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REVERSE UNDULATOR TAPERING FOR POLARIZATION CONTROL AND BACKGROUND-FREE HARMONIC PRODUCTION IN XFELS: RESULTS FROM FLASH

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Abstract

Nonlinear harmonics in X-ray FELs can be parasitically produced as soon as the FEL reaches saturation, or can be radiated in dedicated afterburners. In both cases there is a strong background at the fundamental since it is much stronger than the harmonics. One can get around this problem applying the recently proposed reverse undulator tapering. In this contribution we present recent results from FLASH where the second and the third harmonics were efficiently generated with a low background at the fundamental. We also present the results for a high-contrast operation when the afterburner is tuned to the fundamental.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) [1–3] based on the self-amplified spontaneous emission (SASE) principle [4], opens up new horizons for photon science. One of the important requirements of FEL users in the near future will be polarization control of X-ray radiation. Baseline design of a typical X-ray FEL undulator assumes a planar configuration which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from using a circularly polarized radiation. There are different ideas for possible upgrades of the existing (or planned) planar undulator beamlines.

As a cheap upgrade one can consider an installation of a short helical afterburner as it was done at LCLS where a so called DELTA undulator was installed behind the main undulator [5]. However, to obtain high degree of circular polarization one needs to suppress powerful linearly polarized radiation from the main undulator. A method for suppression of the linearly polarized background from the main undulator was proposed in [6] is an application of the reverse undulator taper. It was shown that in some range of the taper strength the bunching factor at saturation is practically the same as in the reference case of the non-tapered undulator, the saturation length increases moderately while the saturation power is suppressed by orders of magnitude. Therefore, the proposed scheme is conceptually very simple (see Fig. 1): in a tapered main (planar) undulator the saturation is achieved with a strong microbunching and suppressed radiation power, then the modulated beam radiates at full power in a helical afterburner tuned to resonance. This method (in combination with the spatial separation) was used at LCLS to obtain a high degree of circular polarization [7] and is routinely used now in user operation.

Obviously, the afterburner (helical or planar) can be tuned to a harmonic of the main undulator. In this case the harmonics can be efficiently generated with a low background at the fundamental.

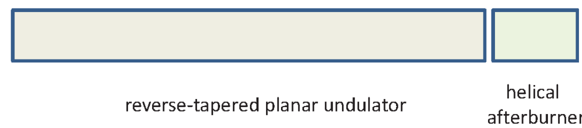

Figure 1: Conceptual scheme for obtaining circular polarization at X-ray FELs.

In this paper we present experimental results from FLASH [1, 8, 9] where a high contrast between the radiation from the "afterburner" (the last two undulator sections) and from the reverse-tapered undulator was demonstrated recently. Also, the results on an efficient background-free production of high harmonics from the afterburner are presented.

POTENTIAL APPLICATIONS OF REVERSE TAPER IN HIGH-GAIN FELS

Polarization Control

Undulators of X-ray FEL user facilities are usually planar, and the FEL radiation is linearly polarized. However, there is a strong interest from users in obtaining circularly polarized radiation, or, more generally, to have full polarization control. To achieve this goal one can install a short variable-polarization afterburner, and to suppress a strong linearly polarized background from the main undulator. Reverse tapering seems to be an ideal solution to this problem since it does not require any additional installations. Moreover, not only FEL power is suppressed, but also the energy modulations are strongly reduced in comparison with on-resonance operation [6] . Thus, fully bunched electron beam with small energy modulations can more efficiently radiate in the afterburner.

Efficient Background-Free Generation of High Harmonics

The afterburner can also be tuned to a harmonic of the main undulator. In this case a powerful background-free generation of this harmonic can be expected. Indeed, the modulated electron beam at saturation contains harmonics of density, and the energy modulation is small. Therefore, these density harmonics exist longer in the radiator (planar or helical), and a significant intensity can be produced at a selected harmonic. At the same time, the radiation at the fundamental and at harmonics of the main undulator is strongly suppressed (a suppression is much stronger for harmonics than for the fundamental), i.e. the background is small. In particular, if a helical afterburner is tuned to the

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second or the third harmonic of the main undulator, a high degree of circular polarization should be expected. Let us note that the method of harmonics production can be used for SASE FELs as well as for seeded (self-seeded) FELs (the latter case was recently considered in [10]).

It is also worth noticing that, in principle, one does not need a dedicated afterburner for an operation of this scheme. Instead, it is sufficient to have a gap-tunable undulator with the largest part being reverse-tapered and a smaller last part tuned to a second or third harmonic. In this case one can reach a shorter wavelength than in a standard SASE mode of operation of an X-ray FEL user facility. A promising configuration could use, for example, a radiation at the third harmonic of the afterburner using the second harmonic of the beam density, produced in the reverse-tapered main undulator. Such an operation mode was recently tested at FLASH, the results will be published elsewhere.

REVERSE TAPER EXPERIMENTS AT FLASH

The first soft X-ray FEL user facility FLASH [1, 8, 9] was upgraded to split the electron pulse trains between the two undulator lines so that the accelerator with maximum energy of 1.25 GeV now drives both lines. In a new separate tunnel, a second undulator line, called FLASH2, with a variable-gap undulator was installed, while a new experimental hall has space for up to six experimental stations [9]. The gap-tunable undulator of FLASH2 consists of twelve 2.5 m long sections with the undulator period of 3.14 cm and the maximum rms K-value about 1.9.

High Contrast Radiation at the Fundamental of the Afterburner

In the experiment on January 23, 2016 we used the first ten undulator sections as a main undulator with reverse tapering, and the last two sections played the role of the afterburner, i.e. they could be tuned to a resonance with the incoming microbunched beam. In what follows we will simply call them afterburner even though they are not a dedicated device.

The electron energy during the measurements was 715 MeV, and the FEL wavelength was 17 nm. The rms value of K in the first section was 1.06 (corresponding to the undulator gap of 14.5 mm), and the depth of reverse taper over 10 undulator sections was 10% (note that the step-tapering was used, i.e. the parameter K was constant inside each section). The bunch charge was 0.3 nC, and the other parameters of electron beam (peak current, emittance etc.) were not measured due to a parallel operation with the other undulator line, FLASH1. For this reason we present here only experimental results without a comparison with simulations.

In Fig. 2 the gap scan of the two last undulator sections (afterburner) is shown. When the undulators are completely open, the pulse energy is slightly below 1 microjoule. When they are tuned to the resonance with the incoming microbunched beam, the pulse energy becomes 200 μJ (to be compared with 260 μJ in an untapered undulator with 12 undulator sections). Note that the rms K parameter in this case is 1.11 which is the mean of the initial value, 1.06, and the final value, 1.17, of the rms K in the reverse-tapered undulator section. This result is in agreement with the predictions of the theory of an FEL with slowly varying parameters [11].

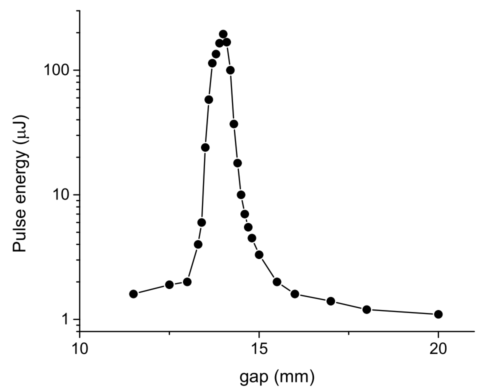

Figure 2: Gap scan of the afterburner (last two undulator sections). For a completely open gap the pulse energy is below 1 μJ.

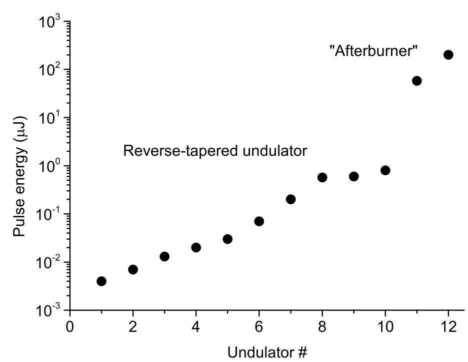

Figure 3: FEL pulse energy versus undulator number. First ten undulators are reverse-tapered, last two sections are tuned to the resonance with the incoming microbunched beam.

We also measured the FEL gain curve in this configuration, it is shown in Fig. 3. One can see again that the high contrast (in excess of 200) between the radiation intensity from the afterburner and from the reverse-tapered undulator is measured. The gain curve in Fig. 3 looks similar to that simulated in [6] for the European XFEL [12].

We repeated the reverse taper experiment at the same wavelength but at a higher electron energy (930 MeV) on March 12, 2016. Rms undulator parameter was 1.6, and the ten undulator sections were reverse-tapered by 5%. In this case the pulse energy was 0.25 μJ, while after tuning the 11th and the 12th sections to the resonance it reached 60 μJ, i.e. the contrast above 200 was demonstrated again.

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Background-Free Generation of Harmonics in the Afterburner

On March 12, 2016 we were also able to observe the generation of the second harmonic from the afterburner while the main undulator was reverse-tapered [13].

A dedicated experiment was performed on October 10, 2016 with the aim to demonstrate an efficient generation of the 2nd and the 3rd harmonics in the afterburner. The electron energy was 852 MeV, the charge was 0.3 nC, and the wavelength for the untapered case was set to 25.5 nm with the rms K parameter of 1.9. The first nine undulator sections were then 5% reverse-tapered, and the following two sections played the role of the afterburner. When the afterburner sections were completely opened, the background from the reverse-tapered main undulator was measured at the level of 0.9 μJ. When we tuned the afterburner sections to 26.2 nm, the pulse energy was 132 μJ, i.e. a contrast above 100 was measured. Then we tuned the afterburner to the second and the third harmonics of the main undulator and a wavelength scan (or, K-scan) of the undulator around the corresponding resonances was performed. The results are presented in Fig. 4 where one can see that the pulse energy reached 41 μJ when the afterburner was tuned to 13.2 nm, and 10 μJ for the 8.8 nm tune. Note that in the latter case the rms K-value was 0.75 only, i.e. one could have expected a better result if a dedicated optimized afterburner with a shorter period and a larger K-value had been used. We should also note the fact that a small background on the fundamental at the detectors (and, in the future, at a user experiment) from the reverse-tapered main undulator can be further reduced by using small apertures since the fundamental has a larger divergence. Thus, we have demonstrated that the reverse tapering in the main undulator can be used for an efficient, background-free, generation of harmonics in the afterburner.

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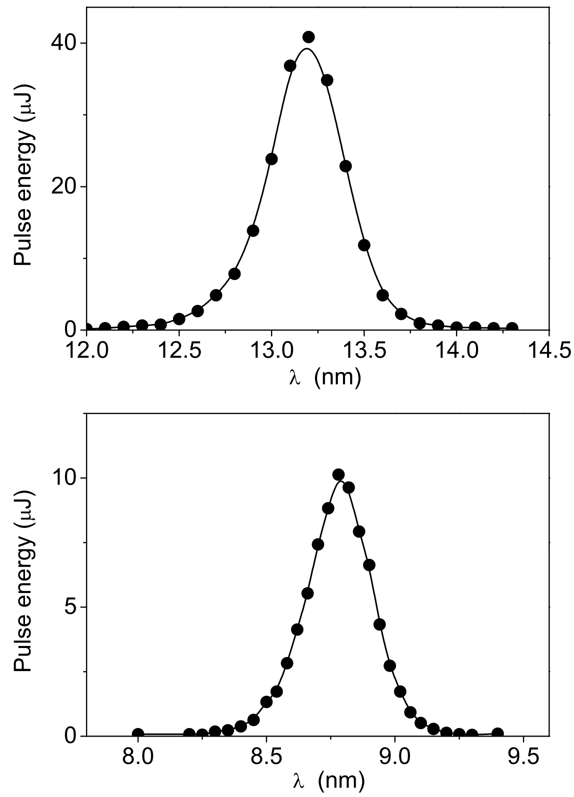

Figure 4: Radiation pulse energy of the second (left plot) and the third (right plot) harmonics radiated in the afterburner versus the resonance wavelength of the afterburner. A small background from the fundamental is subtracted.

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