STUDIES OF HARMONIC LASING SELF-SEEDED FEL AT FLASH2

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Abstract

A concept of the Harmonic Lasing Self-Seeded (HLSS) FEL was recently proposed. A gap-tunable planar undulator is divided into two parts such that the first part is tuned to a sub-harmonic of the second part. Harmonic lasing occurs in the exponential gain regime in the first part of the undulator, also the fundamental stays well below saturation. In the second part of the undulator the fundamental mode is resonant to the wavelength, previously amplified as the harmonic. The amplification process proceeds in the fundamental mode up to saturation. In this case the bandwidth is reduced by a significant factor depending on harmonic number but the saturation power is still as high as in the reference case of lasing at the fundamental in the whole undulator, i.e., the spectral brightness increases. Application of the post-saturation tapering would allow to generate higher peak power than in SASE mode due to an improved longitudinal coherence. We present feasibility study of the application of the HLSS FEL scheme at FLASH2. We also present first experimental evidence of HLSS effect in FLASH2 undulator at 7 nm. This is the first experimental demonstration of harmonic lasing in high-gain FELs.

INTRODUCTION

Successful operation of X-ray FELs, based on self-amplified spontaneous emission (SASE) principle [1], opens up new horizons for photon science. However, a poor longitudinal coherence of SASE FELs stimulated efforts for its improvement. Since an external seeding seems to be difficult in X-ray regime, a so called self-seeding has been proposed [2,3]. There are alternative approaches to reducing bandwidth and increasing spectral brightness of X-ray FELs without using optical elements. One of them was proposed in [4] and is based on combined lasing on a harmonic in the first part of the undulator (with increased undulator parameter K) and on the fundamental in the second part. In this way the second part of the undulator is seeded by a narrow-band signal generated via a harmonic lasing in the first part[1]. This concept was later named HLSS FEL (Harmonic Lasing Self-Seeded FEL) [5].

In this paper we present the results of numerical simulations of the HLSS FEL scheme with the parameters of FLASH2, the second branch of the soft X-ray FEL user facility FLASH [6]. We also present first experimental evidence of HLSS effect in FLASH2 undulator at 7 nm. We would like to stress that it is the first demonstration of harmonic lasing in a high-gain FEL.

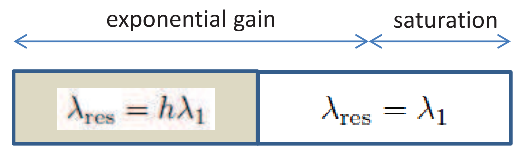

Figure 1: Conceptual scheme of a harmonic lasing self-seeded FEL.

SCHEME DESCRIPTION

Typically, gap-tunable undulators are planned to be used in X-ray FEL facilities. If maximal undulator parameter K is sufficiently large, the concept of harmonic lasing self-seeded FEL can be applied in such undulators (see Fig. 1). An undulator is divided into two parts by setting two different undulator parameters such that the first part is tuned to a sub-harmonic of the second part (and the second part is tuned to a wavelength of interest). Harmonic lasing occurs in the exponential gain regime in the first part of the undulator, also the fundamental in the first part stays well below saturation. In the second part of the undulator the fundamental mode is resonant to the wavelength, previously amplified as the harmonic. The amplification process proceeds in the fundamental mode up to saturation. In this case the bandwidth is defined by the harmonic lasing (i.e., it is reduced by a significant factor depending on harmonic number) but the saturation power is still as high as in the reference case of lasing at the fundamental in the whole undulator, i.e. the spectral brightness increases.

The bandwidth reduction factor (that one obtains in HLSS FEL in comparison with a reference case of lasing in SASE FEL mode in the whole undulator) reads [5]:

$$R \simeq h \frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{\rm sat,1}} \qquad (1)$$

Here h is harmonic number, $L_{\rm sat,1}$ is the saturation length in the reference case of the fundamental lasing with the lower K-value, $L_{\rm w}^{(1)}$ is the length of the first part of the undulator, and $L_{{\rm sat},h}$ is the saturation length of harmonic lasing. We notice that it is beneficial to increase the length of the first part of the undulator. Since it must be shorter than the saturation length of the fundamental harmonic in the first section, one can consider delaying the saturation of the fundamental with the help of phase shifters [4, 8] in order to increase $L_{\rm w}^{(1)}$. However, for the sake of simplicity, in the simulations presented below we do not use this option.

[1] A very similar concept was later proposed in [7]: a purified SASE FEL, or pSASE.

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Table 1: Electron Beam and Undulator Parameters

Electron beam	Value
Energy	700 MeV
Bunch charge	300 pC
Peak current	1 kA
Rms normalized slice emittance	1 μm
Rms slice energy spread	0.2 MeV
Undulator	**Value**
Period	3.14 cm
K_{rms} (first part)	1.9
Magnetic length of the first part	10 m
K_{rms} (second part)	0.73
Magnetic length of the second part	20 m
Beta-function	6 m

SIMULATION PARAMETERS

We perform numerical simulations of the HLSS FEL scheme using the parameters of FLASH2 with the help of the code FAST [9]. The main parameters of electron beam and undulator, used in our simulations, are shown in Table 1. Since the maximum rms value of K equals 1.9, only 3rd harmonic lasing is possible at FLASH2. We consider lasing at 13 nm, so that the K-value in the second part of the undulator is tuned to the resonance with this wavelength. The first part of the undulator is tuned to the resonance with the 3rd subharmonic of 13 nm, i.e., to 39 nm. Thus, the third harmonic lasing in the first part is responsible for creating

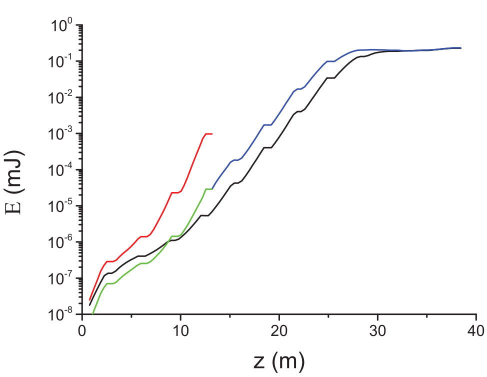

Figure 2: FEL pulse energy versus undulator length. In the first part of the undulator (tuned to the resonance with 39 nm) the first (red) and the third (green) harmonics are shown. The third harmonic continues to get amplified in the second part of the undulator (now as the fundamental) tuned to 13 nm (shown in blue). A reference case of lasing at 13 nm on the fundamental in the whole undulator with constant K-value is shown in black.

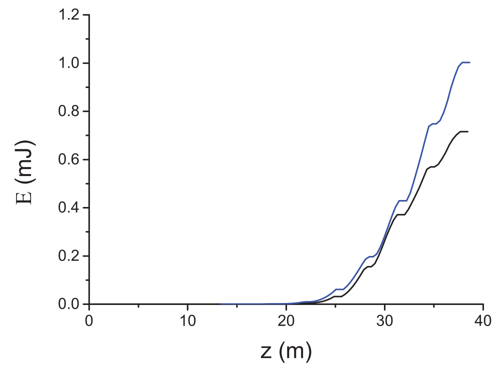

Figure 3: FEL pulse energy versus undulator length when the post-saturation taper is applied. HLSS case is shown in blue, and the SASE case - in black.

the narrow-band seed signal for the second part. The total length of the undulator is about 40 m, the net magnetic length is 30 m.

SATURATION

Now we can present the results of numerical simulations of the HLSS FEL up to the saturation. In Fig. 2 one can see the evolution of the 1st (at 39 nm) and the 3rd (at 13 nm), and the (shown in red and green, respectively) in the first part of the undulator with the consequent amplification of the 3rd harmonic in the second part of the undulator as the fundamental up to saturation (shown in blue). The reference case of lasing on the fundamental at 13 nm through the whole undulator is shown in black. One can notice that the saturation length in the HLSS case is shorter, this is explained by the fact that the gain length of the 3rd harmonic in the first part of the undulator is shorter than the gain length of the fundamental in the second part (see [4] for the explanation). The bandwidth reduction factor at saturation is about factor of 2 in a good agreement with formula (1).

POST-SATURATION TAPER

It is well-known that a high-gain FEL with a monochromatic seed performs better than a SASE FEL in the case when a post-saturation taper is used to increase FEL power. The main reason is a poor longitudinal coherence of SASE FEL: when the slippage of the radiation in the tapered section becomes comparable to the FEL coherence length, the power growth is stopped. Even a moderate increase of the coherence time as in the case of HLSS FEL might be helpful. Moreover, as it was already mentioned, the saturation is achieved earlier in the case of HLSS FEL, i.e. more undulator length is available for tapering. In our simulations we apply quadratic post-saturation taper to both study cases: HLSS mode and SASE mode. In Fig. 3 one can see the evolution of the FEL pulse energy as a function of the undulator length in both study cases. The pulse energy in the case of HLSS configuration reaches 1 mJ, and it exceeds SASE

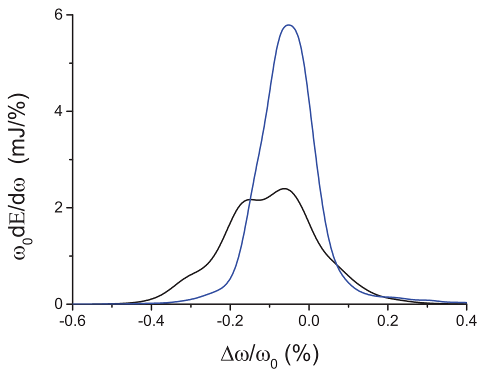

Figure 4: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black).

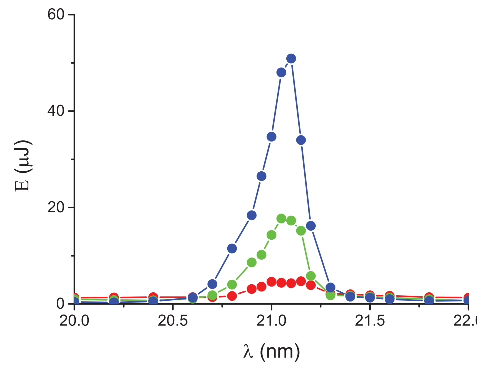

Figure 5: Scan of the resonance wavelength of the first part of the undulator consisting of one undulator section (red), two sections (green), and three sections (blue). Pulse energy is measured after the second part of the undulator tuned to 7 nm.

pulse energy by 40 %. This enhancement factor could be larger if the undulator was longer.

In Fig. 4 we present spectra for both study cases. One can see that the spectral density of the radiation energy is higher for HLSS FEL by a factor of 2.5. This is a combination of the reduced bandwidth (factor 1.8) and an increased pulse energy (factor 1.4). In FLASH2 undulator the considered scheme can only work with the third harmonic, thus the enhancement factor is not so large. When the maximum K parameter is much larger, one can get much higher enhancement by using larger harmonic numbers.

EXPERIMENT AT FLASH2

On May 1, 2016 we were able to successfully perform the first test of HLSS FEL at the second branch of the soft X-ray FEL user facility FLASH2 [6]. Electron energy was 945 MeV, charge 0.4 nC. Initially we tuned 10 undulator sections (each section is 2.5 m long, parameters are presented in Table 1) to a standard SASE, operating in the exponential gain regime at the wavelength of 7 nm; the pulse energy was 12 μJ. Then we detuned the first section (and the pulse energy was reduced to about 1 μJ), tuned it to the third subharmonic and scanned it around 21 nm. We repeated the measurements with the first two sections, and then with the first three sections. Note that the fundamental at 21 nm was also in the exponential gain regime, pulse energy after 3 undulator section was 40 nJ, i.e., it was far away from saturation. This means, in particular, that the nonlinear harmonic generation in the first part of the undulator is excluded.

One can see from Fig. 5 that the effect is essentially resonant. For example, in the case when 3 undulator sections were scanned, the ratio of pulse energies at the optimal tune, 21.1 nm, and at 20 nm is 51 μJ/0.3 μJ = 170. The actual ratio might have been even larger, because the radiation at 21 nm (even being much weaker than 0.3 μJ) is more efficiently detected. We claim that there can be only one explanation of the effect that we observe in Fig. 5: FEL gain at 7 nm is strongly reduced as soon as the first part of the undulator is detuned, and then the gain is recovered (and becomes even larger) due to the 3rd harmonic lasing in the first part as soon as the resonant wavelength is 21 nm.

We should stress that the pulse energy with 3 retuned undulator sections (51 μJ) is significantly larger than that in the homogeneous undulator tuned to 7 nm (it was 12 μJ). This is because the gain length of harmonic lasing is shorter than that of the fundamental tuned to the same wavelength [4], see also Fig. 2. We could not measure and compare the spectra of SASE FEL and of HLSS FEL because the spectrometer was not available during these measurements, but we plan to demonstrate a line narrowing in the near future.

A clear effect, that we observed at FLASH2, allows us to conclude that the harmonic lasing self-seeded FEL works. Moreover, we can state that harmonic lasing in a high-gain FEL was demonstrated for the first time. Thus, the applications of harmonic lasing in X-ray FELs, proposed in [4, 10, 11], can now be considered quite seriously.

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