

FIRST OPERATION OF A HARMONIC LASING SELF-SEEDED FEL

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Abstract

Harmonic lasing is a perspective mode of operation of X-ray FEL user facilities that provide brilliant beams of higher energy photons for user experiments. Another useful application of harmonic lasing is so called Harmonic Lasing Self-Seeded Free Electron Laser (HLSS FEL) that improves spectral brightness of these facilities. In the past, harmonic lasing has been demonstrated in the FEL oscillators in infrared and visible wavelength ranges, but not in high-gain FELs, and not at short wavelengths. In this paper we report on the first evidence of the harmonic lasing and the first operation of the HLSS FEL at the soft X-ray FEL user facility FLASH in the wavelength range between 4.5 nm and 15 nm. Spectral brightness was improved in comparison with Self-Amplified Spontaneous emission (SASE) FEL by a factor of six in the exponential gain regime. A better performance of HLSS FEL with respect to SASE FEL in the post-saturation regime with a tapered undulator was observed as well. The first demonstration of harmonic lasing in a high-gain FEL and at short wavelengths paves the way for a variety of applications of this new operation mode in X-ray FELs.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) down to the Ångström regime opens up new horizons for photon science. Even shorter wavelengths are requested by the scientific community.

One of the most promising ways to extend the photon energy range of high-gain X-ray FELs is to use harmonic lasing which is the FEL instability at an odd harmonic of the planar undulator [1–5] developing independently from the lasing at the fundamental. Contrary to the 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 radiation if the fundamental is suppressed. The most attractive feature of saturated harmonic lasing is that the spectral brightness of a harmonic is comparable to that of the fundamental [5].

Another interesting option, proposed in [5], is the possibility to improve spectral brightness of an X-ray FEL by the combined lasing on a harmonic in the first part of the undulator (with an increased undulator parameter K) and on the fundamental in the second part of the undulator. Later this concept was named Harmonic Lasing Self-Seeded FEL (HLSS FEL) [6]. Even though this scheme is not expected to provide an ultimate monochromatization of the FEL radiation as do self-seeding schemes using optical elements [7, 8], it has other advantages that we briefly discuss below in the paper.

Harmonic lasing was initially proposed for FEL oscillators [9] and was tested experimentally in infrared and visible wavelength ranges. It was, however, never demonstrated in high-gain FELs and at a short wavelength. In this paper we present the first successful demonstration of this effect at the second branch of the soft X-ray FEL user facility FLASH [10, 11] where we managed to run HLSS FEL in the wavelength range between 4.5 nm and 15 nm.

HARMONIC LASING

Harmonic lasing in single-pass high-gain FELs [1–5] is the amplification process in a planar undulator of higher odd harmonics developing independently of each other (and of the fundamental) in the exponential gain regime. The most attractive feature of the saturated harmonic lasing is that the spectral brightness (or brilliance) of harmonics is comparable to that of the fundamental [5]. Indeed, a good estimate for the saturation efficiency is $\lambda_w / (hL_{\text{sat},h})$, where λ_w is the undulator period, h is harmonic number, and $L_{\text{sat},h}$ is the saturation length of a harmonic. At the same time, the relative rms bandwidth has the same scaling. In other words, reduction of power is compensated by the bandwidth reduction and the spectral power remains the same.

Although known theoretically for a long time [1–4], harmonic lasing in high-gain FELs was never demonstrated experimentally. Moreover, it was never considered for practical applications in X-ray FELs. The situation was changed after publication of ref. [5] where it was concluded that the harmonic lasing in X-ray FELs is much more robust than usually thought, and can be effectively used in both existing and future X-ray FELs. In particular, the European XFEL [12] can greatly outperform the specifications in terms of the highest possible photon energy: it can reach the 60–100 keV range for the third harmonic lasing. It was also shown in [13] that one can keep sub-Ångström range of operation of the European XFEL after CW upgrade of the accelerator with a reduction of electron energy from 17.5 GeV to 7 GeV. Another application of harmonic lasing is a possible upgrade of FLASH with the aim to increase the photon energy up to 1 keV with the present energy 1.25 GeV of the accelerator. To achieve this goal, one should install a specially designed undulator optimized for the third harmonic lasing as suggested in [14].

HARMONIC LASING SELF-SEEDED FEL

A poor longitudinal coherence of SASE FELs has stimulated efforts for its improvement. Since an external seeding seems to be difficult to realize in the X-ray regime, a so called self-seeding has been proposed in [7, 8]. There are alternative approaches for reducing bandwidth and increasing spectral brightness of X-ray FELs without using optical

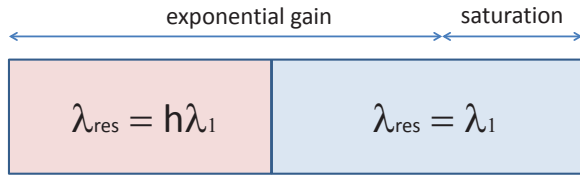


Figure 1: Conceptual scheme of a harmonic lasing self-seeded FEL

elements. One of them [15, 16] suggests to use chicanes inside the undulator system to increase slippage of the radiation and to establish long-range correlations in the radiation pulse. Another method was proposed in [5] and is based on the combined lasing of a harmonic in the first part of the undulator (with increased undulator parameter K) and of 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. This concept was named HLSS FEL (Harmonic Lasing Self-Seeded FEL) [6]. Note that a very similar concept was proposed in [17] and was called a purified SASE FEL, or pSASE.

Typically, gap-tunable undulators are planned to be used in the X-ray FEL facilities. If the maximal undulator parameter K is sufficiently large, the concept of harmonic lasing self-seeded FELs 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 h -th sub-harmonic of the second part which is tuned to a wavelength of interest λ_1 . 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 is resonant to the wavelength, previously amplified as the harmonic. The amplification process proceeds in the fundamental harmonic 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 its harmonic number) but the saturation power is still as high as it is in the reference case of lasing at the fundamental in the whole undulator, i.e. the spectral brightness increases.

The enhancement factor of the coherence length or, 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 [6]:

$$R \simeq h \frac{\sqrt{L_w^{(1)} L_{\text{sat},h}}}{L_{\text{sat},1}}. \quad (1)$$

Here h is harmonic number, $L_{\text{sat},1}$ is the saturation length in the reference case of the fundamental lasing with the lower K -value, $L_w^{(1)}$ is the length of the first part of the undulator, and $L_{\text{sat},h}$ 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

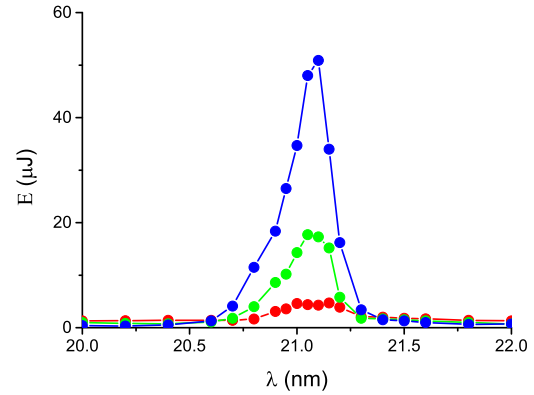


Figure 2: Scan of the resonance wavelength of the first part of the undulator consisting of one undulator section (red), two sections (green), and three sections (blue). Pulse energy is measured after the second part of the undulator tuned to 7 nm.

the help of phase shifters [4, 5] in order to increase $L_w^{(1)}$. However, for the sake of simplicity, we did not use this option in our experiments.

Despite the fact that the bandwidth reduction factor (1) is significantly smaller than that of self-seeding schemes using optical elements [7, 8], the HLSS FEL scheme is very simple and robust, and it does not require any additional installations, i.e. it can always be used in existing or planned gap-tunable undulators with a sufficiently large K -value.

One more advantage of the HLSS FEL scheme over the SASE FEL (and in many cases over a self-seeded FEL) is the possibility of a more efficient use of a post-saturation taper for an improved conversion of the electron beam power to the FEL radiation power [6, 18]. This makes us believe that HLSS FEL will become a standard mode of operation of X-ray FEL facilities.

OPERATION OF HARMONIC LASING SELF-SEEDED FEL AT FLASH

The first soft X-ray FEL user facility FLASH [10, 11] 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 [19]. 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. This makes it possible to study the HLSS FEL scheme with the 3rd harmonic seeding. The details of our measurements can be found in [20].

On May 1, 2016 we were able to successfully perform the first test of HLSS FEL at FLASH2. Electron energy was 948 MeV, charge 0.4 nC. Initially we tuned 10 undulator sections to a standard SASE, operating in the exponential gain regime at the wavelength of 7 nm (rms K parameter was 0.73); the pulse energy was 12 μJ . Then we detuned

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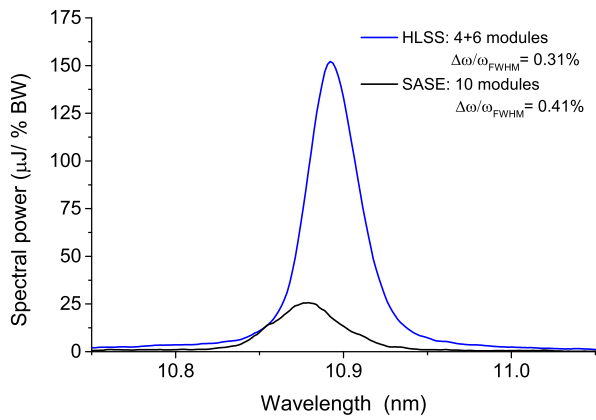


Figure 3: Spectral density of the radiation energy for HLSS FEL configuration (blue) and for SASE FEL (black).

the first section, tuned it to the third subharmonic (rms K was 1.9) 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 three undulator sections was 40 nJ, i.e. it was far from saturation (which was achieved at the 200 μJ level). This means, in particular, that the nonlinear harmonic generation in the first part of the undulator is excluded.

One can see from Fig. 2 that the effect is essentially resonant. For example, in the case when three undulator sections were scanned, the ratio of pulse energies at the optimal tune, 21.1 nm, and at the tune of 20 nm is $51 \mu\text{J}/0.3 \mu\text{J} = 170$. We claim that there can be only one explanation of the effect that we observe in Fig. 2: 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 three 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 [4–6, 18].

In the next runs in 2016 at different wavelengths (between 4.5 nm and 15 nm) we were able to demonstrate an improvement of the longitudinal coherence in HLSS regime with respect to SASE case as well as a better performance in the post-saturation taper regime.

In June 2016 the electron energy was different 757 MeV and we lased at 11 nm. We also used a different charge, 0.25 nC, in this experiment. The undulator settings were similar to the previous case: we used ten undulator modules, rms K-parameter was 0.73 in SASE mode and 1.9 in the first part of the undulator in HLSS mode. The difference with the previous measurements was that we detuned four undulator modules in HLSS regime.

The spectra in Fig. 3 are the results of averaging over 50 single-shot spectra in each case. One can see that HLSS FEL indeed has a smaller bandwidth, 0.31%, as compared to

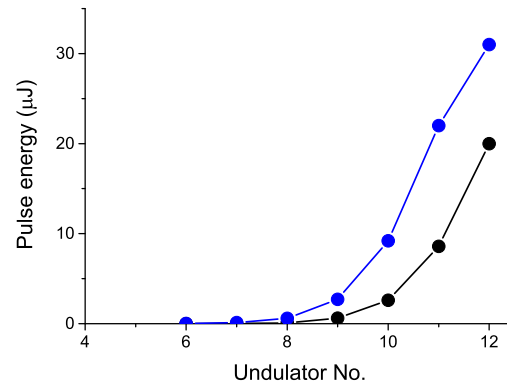


Figure 4: Radiation pulse energy versus position in the undulator for HLSS (blue) and for SASE (black) at 15 nm. Post-saturation taper was optimized for both cases.

0.41% in the case of SASE FEL. The bandwidth reduction factor is 1.3 from this measurement. The spectral power, however, differs by a factor of six due to an additional increase of pulse energy in HLSS regime. This happens because the 3rd harmonic lasing at 11 nm has a shorter gain length than lasing at the same wavelength on the fundamental. An expected bandwidth reduction factor (or coherence enhancement factor) R from formula (1) can be estimated at 1.7. The discrepancy can be explained by the energy chirp in the electron beam.

Another method of determination of an improvement of the longitudinal coherence (independent of the presence of the frequency chirp in FEL pulses) is based on statistical measurements of the FEL pulse energy along the undulator length. we obtain an estimate for the coherence enhancement factor in the end of the exponential gain regime: $R \approx 1.8 \pm 0.3$ [20]. This is in a good agreement with already presented theoretical estimate $R \approx 1.7$.

In November 2016 we set up HLSS FEL as a configuration with four first undulators tuned to 45 nm and the last eight undulators tuned to 15 nm. The electron energy was 645 MeV, the charge was 100 pC, the rms value of K was 1.9 in the first part of the undulator and 0.73 in the second part. We reached FEL saturation in SASE and HLSS modes, and applied post-saturation taper to improve FEL efficiency. The result is presented in Fig. 4 from which one can conclude that HLSS FEL indeed performs better in this operation mode than the SASE FEL. We can, therefore, forecast that HLSS may become a standard mode of operation of the X-ray FEL user facilities with gap-tunable undulators, providing an improvement of the longitudinal coherence, a reduction of the saturation length and a possibility of a more efficient post-saturation tapering.

It is also important to note that the first evidence of harmonic lasing in a high-gain FEL and at a short wavelength (down to 4.5 nm) paves the way for a variety of applications of this effect in X-ray FEL facilities [5, 6, 13, 14].

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