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HARMONIC LASING OF THE EUROPEAN XFEL IN THE ÅNGSTRÖM REGIME

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Abstract

Harmonic lasing is an opportunity to extend the photon energy range of existing and planned X-ray FEL user facilities. Contrary to nonlinear harmonic generation, harmonic lasing can provide a much more intense, stable, and narrow-band FEL beam. Another interesting application is Harmonic Lasing Self-Seeding (HLSS) that allows to improve the longitudinal coherence and spectral power of a Self-Amplified Spontaneous Emission (SASE) FEL. This concept was successfully tested at FLASH in the range of 4.5 - 15 nm and at PAL XFEL at 1 nm. In this contribution we present recent results from the European XFEL where we successfully demonstrated operation of HLSS FEL at 5.9 , thus pushing harmonic lasing for the first time into the ngström regime.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) down to the ngström 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.

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].

Harmonic lasing was initially proposed for FEL oscillators [7] and was tested experimentally in infrared and visible wavelength ranges. It was, however, not demonstrated in high-gain FELs and at a short wavelength until the successful experiments [8] at the second branch of the soft X-ray FEL user facility FLASH [9,10] where the HLSS FEL operated in the wavelength range between 4.5 nm and 15 nm. Later, the same operation mode was tested at PAL XFEL at 1 nm [11]. In this paper we report on recent results from the European XFEL [12] where we successfully demonstrated operation of HLSS scheme at 5.9 .

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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 $\lambda_w/(hL_{sat,h})$, where λ_w is the undulator period, h is harmonic number, and $L_{sat,h}$ 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 not 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 the existing and future X-ray FELs. In particular, the European XFEL [13] can greatly outperform the specifications in terms of the highest possible photon energy: it can reach 60-100 keV range for the third harmonic lasing. It was also shown [14] that one can keep sub-ngström 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 [15].

HARMONIC LASING SELF-SEEDED FEL

A poor longitudinal coherence of SASE FELs stimulated efforts for its improvement. Since an external seeding seems to be difficult to realize in X-ray regime, a so called self-seeding has been proposed [16, 17]. There are alternative approaches for reducing bandwidth and increasing spectral brightness of X-ray FELs without using optical elements. One of them was proposed in [5], it is based on the 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

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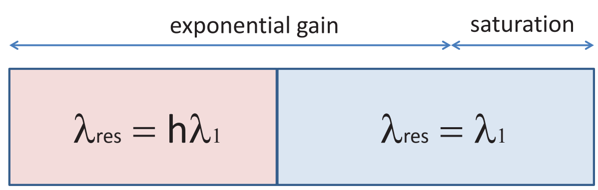

Figure 1: Conceptual scheme of a harmonic lasing self-seeded FEL.

is seeded by a narrow-band signal generated via a harmonic lasing in the first part. This concept was named HLSS FEL [6].

Typically, gap-tunable undulators are planned to be used in X-ray FEL facilities. If the maximal undulator parameter K is sufficiently large, the concept of harmonic lasing self-seeded FEL can be applied (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. 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 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 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]:

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

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

Despite the bandwidth reduction factor (1) is significantly smaller than that of self-seeding schemes using optical elements [16, 17], 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 range of accessible K-value.

HARMONIC LASING SELF-SEEDING AT THE EUROPEAN XFEL

The European XFEL is a X-ray FEL user facility, based on superconducting accelerator [12]. It provides ultimately bright photon beams for user experiments since 2017. Two hard X-ray undulators (SASE1 and SASE2) and one soft X-ray undulator (SASE3) are presently in operation [18]. Harmonic lasing experiment was performed in the SASE3 undulator on April 19, 2019.

The electron beam energy was 14 GeV and the bunch charge was 250 pC. SASE3 undulator consists of twenty one 5 m long undulator segments plus intersections containing quadrupoles and phase shifters between the segments [19]. The undulator has a period of 6.8 cm and the K-values can be changed between 4 and 9 in the specified working range. Shortly before our experiment, the beam based alignment of SASE3 undulator was done.

The experiment was performed as follows. As a preparation step, we defined the number of undulator segments to be tuned to the third subharmonic of 2.1 keV radiation that was our target photon energy. We set the undulator K value to 8.74 and lased at 700 eV on the fundamental. As it is described above, in the first part of the undulator we have to avoid the nonlinear harmonic generation what means that we have to stay three or more orders of magnitude below saturation. We have found that five undulator segments satisfy this condition.

Then we set the undulator K-value to 4.91 and had a normal SASE operation at 2.1 keV (wavelength 5.9). We choose twelve undulator segments to stay at the onset of saturation. The pulse energy was measured at 700 μJ with X-ray gas monitor (XGM) detector [20, 21]. In the same way as it was done in the earlier experiments at FLASH [8], we closed gaps of first five undulator segments one by one such that the undulator K became 8.74, and the resonance photon energy was 700 eV (wavelength 17.7). In other words, we moved to the configuration, shown on Fig. 1, with $h = 3$, five segments in the first part of the undulator and seven segments in the second part. As soon as K in each of the

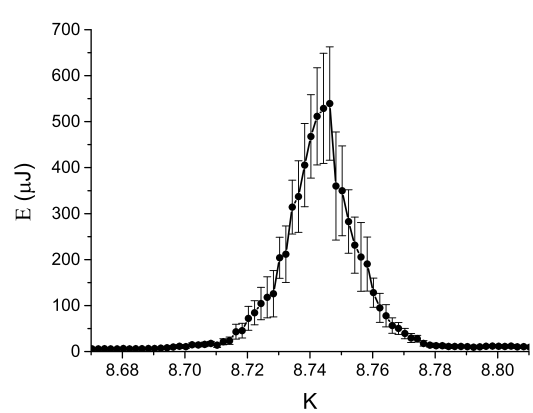

Figure 2: Scan of the K-value of the first part of the undulator consisting of five undulator segments, tuned to 700 eV. Mean pulse energy and its standard deviation are measured after the second part of the undulator tuned to 2.1 keV. FEL operates in "5+7 segments HLSS" mode.

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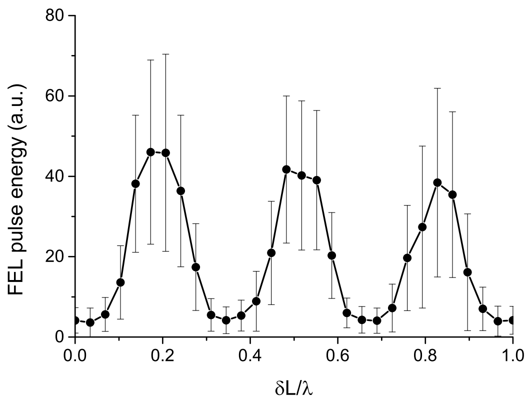

Figure 3: Synchronous scan of phase shifters after first four undulator segments. FEL pulse energy is measured after the second part of the undulator tuned to 2.1 keV. Mean pulse energy and its standard deviation are plotted versus a delay measured in units of the fundamental wavelength in the first part (tuned to 700 eV). FEL operates in "5+6 segments HLSS" mode.

first five segments deviates from the original value of 4.91, we observe a strong reduction of pulse energy, measured with an XGM. However, when K approaches the value of 8.74, the pulse energy almost recovers. For "5+7 HLSS" configuration we measured 550 μJ, i.e. about 20% less than for a normal SASE with twelve undulators tuned to 2.1 keV. This is not what we expected: in theory, the harmonic lasing has an advantage over lasing on the fundamental at the same wavelength[1] as soon as the energy spread is not too big [5]. However, in practice the harmonic lasing is more sensitive to the undulator phase errors and settings of phase shifters between the undulator sections etc. In any case, we can conclude that gain lengths were comparable in our experiment.

We performed a scan of the K-value of the first part of the undulator, tuned to 700 eV, and measured pulse energy after the second part, tuned to 2.1 keV. The result is presented in Fig. 2 where one can see a sharp resonance. Taking into account the above mentioned fact that lasing on the fundamental at 700 eV was too weak to produce nonlinear harmonics, we can conclude that we have the 3rd harmonic lasing in the first part of the undulator at 2.1 keV that continues as lasing on the fundamental in the second part.

An independent confirmation of harmonic lasing is the result of a scan of phase shifters in the first part of the undulator, presented in Fig. 3. For this scan, we used six undulator segments in the second part in order to increase senstitivity of the system by reducing saturation effects. We performed synchronous scan of phase shifters after first four undulator segments over a range in which the fundamental radiation at $\lambda = 17.7$ slips over the electron beam by a single cycle. If we seeded the second part of the undulator by the nonlinear harmonic generation in the first part, the phase shifter scan would result in a single cycle. However, one can clearly see three cycles in Fig. 3 which proves that we had harmonic lasing.

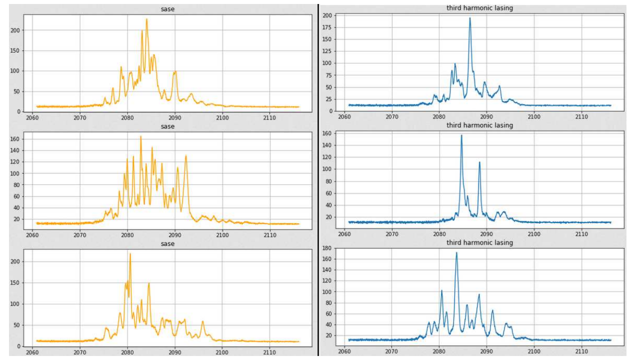

Figure 4: Single-shot spectra for SASE (left column) and HLSS (right column). Plots show spectral intensity (in arbitrary units) versus photon energy (in eV). HLSS operates in "5+7 segments" configuration.

The purpose of HLSS scheme is to increase FEL coherence time and to reduce bandwidth. From formula (1) we estimate the coherence enhancement factor $R \simeq 2$ for our experimental conditions. An increase of the coherence time results in a corresponding reduction of the number of longitudinal modes with respect to the SASE case. In the frequency domain we should then observe a reduction of the average number of spikes in single-shot spectra. In an ideal case, we could also expect a reduction of the average bandwidth by a factor of two, to the level of 0.1% FWHM. Unfortunately, a reduction of the average bandwidth was not possible in our case since the bandwidth is strongly affected by the energy chirp of the electron bunches.

To measure spectra, the SASE3 monochromator [22] was used in spectrometer mode: the spectral distribution of the soft X-rays was converted into visible light in a YAG:Ce crystal located in the focal plane of the monochromator and was recorded by a CCD. To resolve spikes in single shot spectra, we recordered the spectra in 3rd diffraction order with a 50 l/mm grating.

We took a series of spectra for HLSS configuration (five segments at 700 eV and seven segments at 2.1 keV) as well as for standard SASE with twelve segments at 2.1 keV. As expected, the average spectrum width was dominated by the chirp and was the same in both cases, 0.6% FWHM. However, we could clearly observe a reduction of number of spikes in the spectra. This is illustrated by Fig. 4 where one can see three representative shots for each configuration (a quantitative analysis will be published elsewhere).

Finally, we conclude that Harmonic Lasing Self-Seeded FEL was successfully operated at the European XFEL in the ngström regime.

[1] And this was observed in the experiments at FLASH [8]

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