HARMONIC LASING SELF-SEEDED FEL

E.A. Schneidmiller, M.V. Yurkov, DESY, Hamburg, Germany

Abstract

Numerical studies of the recently proposed concept of a harmonic lasing self-seeded FEL are presented. A gap-tunable 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. 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 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. Application of the undulator tapering in the deep nonlinear regime would allow to generate higher peak powers approaching TW level. The scheme is illustrated with the parameters of the European XFEL.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) [1–3], based on self-amplified spontaneous emission (SASE) principle [4], 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 [5–7]. A particularly simple in technical realization self-seeding scheme [7] is now in operation at the Linac Coherent Light Source (LCLS) [8].

There are alternative approaches to reducing bandwidth and increasing spectral brightness of X-ray FELs without using optical elements. One of them (called iSASE [9]) uses chicanes within an undulator system to increase slippage of the radiation and thus a coherence time. Another approach was proposed by us [10] 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. Therefore, we suggest here to call this concept HLSS FEL (Harmonic Lasing Self-Seeded FEL). Recently, a very similar concept was proposed in [11]: a purified SASE FEL, or pSASE. The authors of [11] performed numerical simulations of

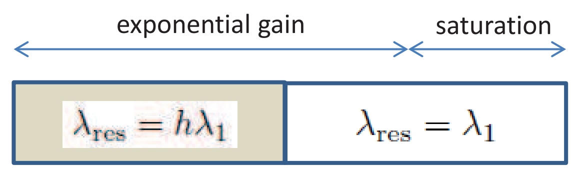

Figure 1: Conceptual scheme of a harmonic lasing self-seeded FEL.

this scheme[1] to confirm the validity of the concept. It was proposed in [11] to have three sections of the undulator: the harmonic lasing section (with increased K-value) is placed in between of the two sections with lower K. We notice here that simply by exchange of the first two sections (smaller K and larger K), both operating as linear amplifiers, the pSASE concept is reduced to our original concept [10]. In other words, pSASE FEL is a more complicated version of the HLSS FEL.

In this paper we present the results of numerical simulations of the HLSS FEL scheme with the parameters of the European XFEL.

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.

Harmonic lasing in single-pass high-gain FELs [10, 13–15] is the radiative instability at an odd harmonic of the planar undulator developing independently from lasing at the fundamental wavelength. Contrary to nonlinear harmonic

[1] Very recently the pSASE scheme was also simulated in [12].

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generation (which is driven by the fundamental in the vicinity of saturation), harmonic lasing can provide much more intense, stable, and narrow-band FEL beam. In our recent study [10] we came to the conclusion that the harmonic lasing in X-ray FELs is much more robust than usually thought, and can be widely used at the present level of accelerator and FEL technology. We found that for typical parameters of X-ray FEL facilities the gain lengths of several odd harmonics can be comparable to that of the retuned (to the same wavelength) fundamental. This finding was the base for the proposed concept (now we call it HLSS FEL) of bandwidth reduction and brilliance improvement [10] that we study numerically in this paper.

Let us consider 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. The rms relative bandwidth at saturation of harmonic lasing scales as $\sigma_\omega/\omega \simeq \lambda_{\mathrm{w}}/(hL_{\mathrm{sat},h})$, where h is harmonic number, λ_{w} is the undulator period, and $L_{\mathrm{sat},h}$ is the saturation length[2]. Note that this scaling and the estimates below are valid when the energy spread effect is not strong. It is also well-known (see, for instance, ref. [16]) that in the exponential gain regime (up to saturation) the bandwidth reduces inversely proportional to the square root of the undulator length. Therefore, since the length of the first part of the undulator $L_{\mathrm{w}}^{(1)}$ is shorter than the saturation length $L_{\mathrm{sat},h}$ of harmonic lasing, an estimate for the bandwidth reduction factor takes the form:

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

Here $L_{\mathrm{sat},1}$ is the saturation length in the reference case of the fundamental lasing with the lower K-value.

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 [10,15] in order to increase $L_{\mathrm{w}}^{(1)}$. However, for the sake of simplicity, in the simulations presented below we do not use this option.

SIMULATION PARAMETERS

We perform numerical simulations of a HLSS FEL using the parameters of the European FEL [17] as an example. We study FEL process in the SASE3 undulator with the help of the simulation code FAST [18]. The main parameters of electron beam and undulator, used in our simulations, are shown in Table 1. We consider lasing at 0.3 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 5th subharmonic of 0.3 nm, i.e. to 1.5 nm. Thus, the fifth harmonic lasing in the first part is responsible for creating the narrow-band seed signal for the second part. The length of the first part is fixed in our simulations at 25 m. We consider two different lengths of the second part: the saturation is achieved within 35 m, and we compare properties of HLSS FEL and a standard SASE FEL (when the whole undulator is tuned to the resonance with 0.3 nm) at saturation. Then we continue with undulator tapering [19] to demonstrate that an increase of the coherence time due to HLSS mechanism provides an advantage over SASE in the achievable FEL efficiency. In our simulations the total length of the undulator in this regime is 175 m (note that the planned length of SASE3 undulator is 105 m). We have chosen such a length for a better comparison of performance of HLSS and SASE in this regime.

[2] The same scaling is approximately valid for FEL efficiency.

Table 1: Electron Beam and Undulator Parameters

Electron beam	**Value**
Energy	14 GeV
Peak current	5 kA
Rms normalized slice emittance	0.4 μm
Rms slice energy spread	1.5 MeV

Undulator	**Value**
Period	6.8 cm
K_{rms} (first part)	5.67
Length of the first part	25 m
K_{rms} (second part)	2.37
Length of the second part	35 m/150 m
Beta-function	15 m

SATURATION

Let us briefly present our expectations from the numerical simulations of the saturation regime. We can use Ming Xie formulas [20], generalized to the case of harmonic lasing [10], to estimate expected bandwidth reduction factor. Assuming that the saturation length approximately equals 20 power gain lengths, for the parameters from Table 1 we obtain the saturation length for the fifth harmonic in the case when the high K-value section was long enough: it would be about $L_{\mathrm{sat},5} \simeq 40$ m. Then we find saturation length for the fundamental in the reference case of lasing in the whole undulator with the reduced undulator parameter: $L_{\mathrm{sat},1} \simeq 53$ m. Thus, for the chosen length of the first part of the undulator $L_{\mathrm{w}}^{(1)} = 25$ m, we obtain from (1) that the bandwidth reduction factor is expected to be $R \simeq 3$.

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 1.5 nm), the 3rd (at 0.5 nm), and the 5th (at 0.3 nm) harmonics (shown in red, green and blue, respectively) in the first part of the undulator with the consequent amplification of the 5th harmonic in the second part of the undulator (now as the fundamental) up to saturation. Power of the 5th harmonic radiation at the exit of the first part is 30 MW. The reference case of lasing on

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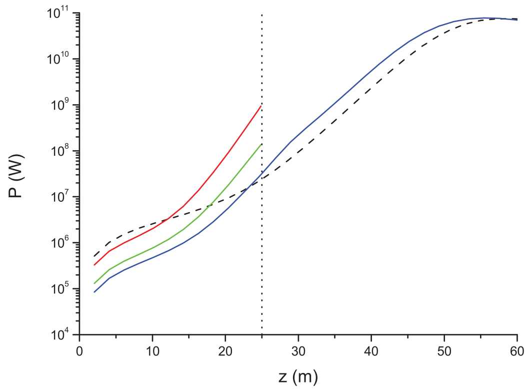

Figure 2: FEL power versus undulator length. In the first part of the undulator (tuned to the resonance with 1.5 nm) the first (red), the third (green), and the fifth (blue) harmonics are shown. The fifth harmonic continues to get amplified in the second part of the undulator (now as the fundamental) tuned to 0.3 nm. A reference case of lasing at 0.3 nm on the fundamental in the whole undulator with constant K-value is shown in dash.

the fundamental at 0.3 nm through the whole undulator is shown with black dash line. Note that in the case of HLSS mode, we slightly tuned the K value of the second part of the undulator such that the maximum of spectral gain curve in both parts have the same wavelength. This is done for the fair comparison with the reference case since the saturation power is about the same in both cases (note that the saturation power in HLSS mode can easily be increased by optimizing the detuning). 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 5th harmonic in the first part of the undulator is shorter than the gain length of the fundamental in the second part.

In Fig. 3 we present a typical distribution of the power versus time for the two modes of operation, taken at saturation points (55 m and 58 m, see Fig. 2). One can see that a time domain picture gets cleaner when one operates the undulator in HLSS mode, and this indicates an increase of coherence length (or, the bandwidth reduction). Detailed studies of statistical properties of the radiation (coherence time, degree of transverse coherence, spectrum width, brilliance etc.) will be published elsewhere.

POST-SATURATION TAPER

It is well-known (see, for example, [21]) 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 [19]. 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.

A possibility to drastically increase the coherence length,

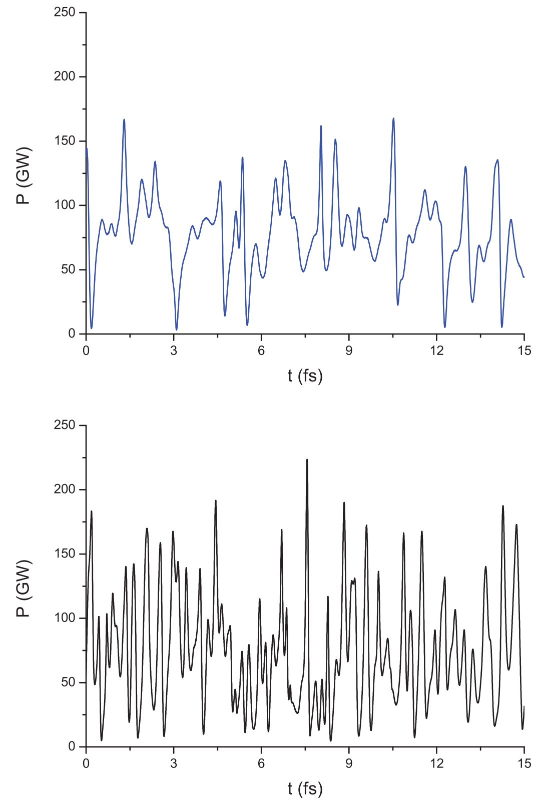

Figure 3: Typical distribution of power versus time at saturation for HLSS mode (upper plot, saturation at 55 m), and for SASE mode (lower plot, saturation at 58 m).

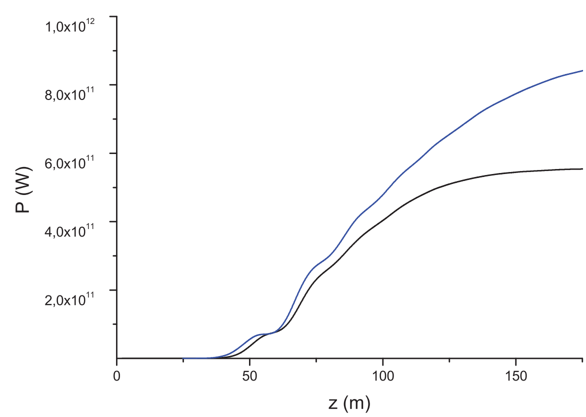

Figure 4: FEL power versus undulator length when the post-saturation taper is applied. HLSS case is shown in blue, and the SASE case - in black.

thus improving the post-saturation taper, is to use self-seeding scheme: this case was studied in [22, 23]. However, even a moderate increase of the coherence time (as in the case of HLSS FEL) might be helpful. We would like to demonstrate this by applying the post-saturation taper to both study cases: HLSS mode and SASE mode. We use linear taper, i.e. the undulator parameter decreases linearly

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along the undulator length starting slightly earlier than the saturation point. In each case the taper strength was optimized, and it turned out that a stronger taper is optimal for the HLSS case. In Fig. 4 one can see the evolution of power as a function of the undulator length in both study cases. The power in the case of HLSS configuration is 0.85 TW, and it exceeds SASE power by 50 %.

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