THE INFLUENCE OF THE SEED PULSE SHAPE ON THE OUTPUT PERFORMANCE OF THE BESSY * MULTI-STAGE HGHG-FEL

A. Meseck, M. Abo-Bakr, B. Kuske, BESSY, Berlin, Germany

Abstract

The BESSY soft X-ray FEL is planned as a High Gain Harmonic Generation (HGHG) FEL multi-user facility. Three independent FEL-lines, fed by a superconducting CW linac, will be provided to cover the VUV to soft X-ray spectral range. In the HGHG scheme, the properties of the radiation output are dominated by the characteristics of the laser seed. In this connection, the influence of the laser pulse shape on the output characteristics, in particular on the output spectrum is of high interest. We present simulation studies for the BESSY-HGHG-FELs and discuss the output performance for different shapes of the laser pulse.

INTRODUCTION

Based on the experience with its third generation lightsource, BESSY proposes a linac-based cascaded HGHG-FEL multi-user facility. The target photon energy ranges from 24 eV to 1 keV with a peak-brilliance of about 10^{31} photons/sec/mm^2/mrad^2/0.1% BW, i.e. a peak power of up to a few GW for pulse lengths less than 20 fs (rms). The polarization of the output radiation will be variable. The technical design report for the BESSY soft X-ray FEL was published recently [1].

The BESSY HGHG multi-user FEL facility will consist of three undulator lines to cover the target photon energy range. Each line is seeded by a tunable laser covering the spectral range of 230 nm to 460 nm. The pulses are assumed to have a Gaussian profile, a peak power of 500 MW, and a pulse duration of about 15 fs (rms).

Two to four HGHG stages are necessary to reduce existing laser wavelengths to the desired range of the BESSY FEL. Each stage consists of a modulator - dispersive section - radiator structure, for more details on the HGHG-stages see [1, 2]. The last radiator is followed by the so-called final amplifier. It is seeded at the desired wavelength and the amplification process is brought to saturation.

For a Gaussian-shaped seed, only a part of the interacting electrons experience the full power due to the seed shape and the slippage effect. The impressed energy modulation mirrors the Gaussian profile of the seed. The strength of the dispersion section can be adjusted for the peak energy modulation at the center of the seeded part or for a somewhat lower energy modulation including the flanks. The second case provides the maximum output power of the following radiator, since more electrons are optimally bunched. In this case the electrons at the center, which experience the full power of the seed are somewhat overbunched. The overbunched electrons perform synchrotron oscillations in the ponderomotive bucket. The resulting modulation of the emitted radiation frequency causes the side spikes (sidebands) [3]. The more electrons are overbunched the stronger is the growth of the sidebands. This effect is repeated in the following stages. In this way the number of sidebands in the spectrum adds up from stage to stage. Due to the slippage in the radiators and final amplifier, the sidebands are shifted to one side.

The sidebands can be avoided by optimizing the dispersion sections for the peak energy modulation, as described in [4]. In this case the bunching is of more Gaussian shape. The resulting radiation power and pulse length are reduced compared to the overbunched case, since less flank-electrons are optimally bunched. The losses in the integrated power are due to the reduction of the pulse length, i.e. the peak power suffers only slightly. Nevertheless the loss of integrated power and the reduction of the pulse length which inhere in this approach might be undesirable. Therefore other possibilities to avoid the sidebands are of interest.

The sidebands are due to the overbunched electrons in the seeded part of the bunch. The shape of the impressed energy modulation in connection with the strength of the dispersion section determines whether the electrons are overbunched or not. Therefore the sidebands can also be avoided by adjusting the shape of the energy modulation instead of reducing the dispersion strength. In this case one would expect that the integrated power and pulse length do not suffer in spite of more spectral purity. As the shape of the impressed energy modulation is mainly determined by the profile of the laser seed, the shape of the seed pulse can be adjusted to optimize the shape of the energy modulation. Note that, due to the slippage, the impressed energy modulation is not an one-to-one copy of the seed shape.

In this paper, we present simulation studies for different laser-pulse shapes for the BESSY-HGHG-FELs and discuss the output performance in terms of power and spectrum purity. The calculations have been performed with the time-dependent 3-D-simulation code GENESIS [5]. The different laser seed profiles in the time domain are generated with a modified version of the GENESIS output routine. Note, that the chosen seed-pulse shapes should demonstrate the influence of the seed shape in a HGHG-FEL rather than represent realistic laser radiation profiles.

SIMULATION STUDIES

Seed Pulse Shapes

In order to avoid the overbunching and ensure the maximum output power of the radiator a constant energy modulation in the interacting part of the bunch seems to be ben-

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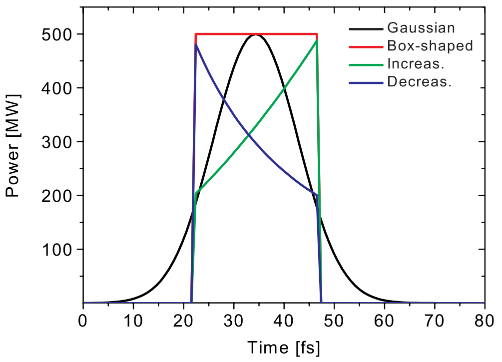

Figure 1: The different shapes of the seed pulses used in the simulation studies.

eficial. Using a box-shaped seed a nearly constant energy modulation of the interacting electrons can be achieved. As the slippage of the seed in the modulator as well as the slippage of the emitted photons in the radiator have to be taken into account, the expected output of the radiator is not box-shaped.

Figure 1 shows the different shapes of the seeds used for the present simulation studies. In addition to the simulations with the Gaussian and the box-shaped seeds, also simulations with increasing and decreasing seed power are performed to investigate the slippage effects.

First Stage

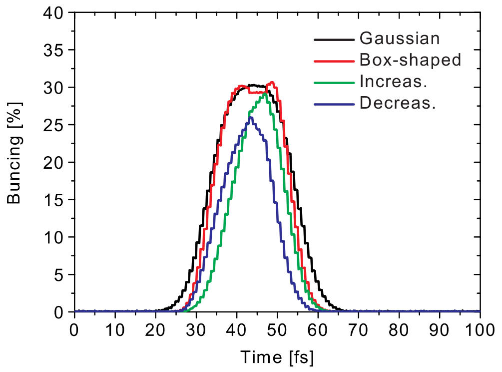

Figure 2: The resulting bunching factors on the fifth harmonic after the first dispersion section of the two-stage HGHG-FEL for different seed cases.

The resulting bunching factors of the fifth harmonic after the first dispersive section for the two-stage HGHG-FEL [1] are shown in figure 2. The dispersion strength is adjusted to maximum radiator power and for retaining pulse lengths if procurable. As expected, the bunching caused by the box-shaped seed is not fully box-shaped. Due to the slippage, there exist electrons in the interacting part, which do not experience the peak power during the whole passage through the modulator. For the maximum power of the following radiator, the strength of the dispersion section has to be adjusted such that these edge electrons are bunched optimally. In this case the central electrons experience a to high dispersion strength, which leads to an over bunching of them. The flanks of the bunching caused by the box-shaped seed are steeper than those of the Gaussian shaped seed, while the flanks of the increasing-power and decreasing power seeds are roughly as steep as those of the Gaussian seed in spite of the upright edges of the corresponding seed shapes.

The bunching maxima of the increasing- and decreasing power cases are shifted relative to each other but this shift is much smaller than the shift by the seed shapes itselfs. The slippage effect seems to mitigate these seed characteristics. Due to the fact that the integrated seed powers for these both shapes are lower than for the Gaussian and box-shaped cases, the resulting maximum bunching factors are

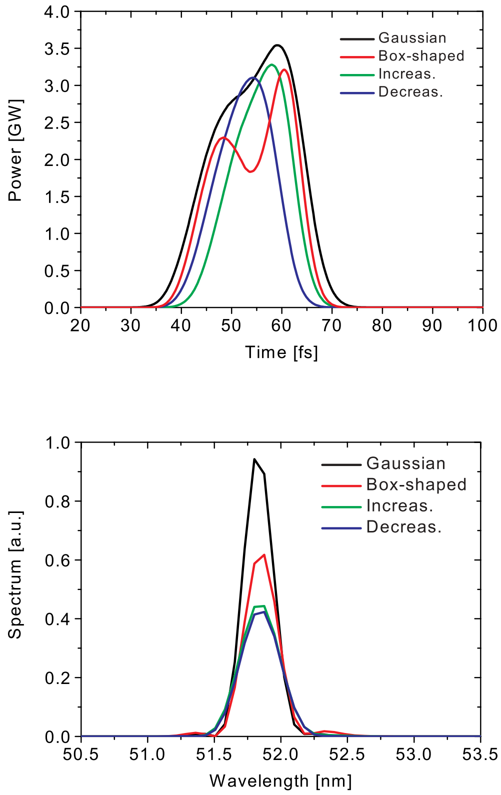

Figure 3: The power distribution (top) and the spectrum (bottom) of the first radiator of the two-stage HGHG-FEL for different seed-pulse shapes.

also lower.

The power distributions and the spectra of the first radiator for different seeds, shown in figure 3, point at the effects of the slippage and overbunching. The higher peaks at the right side of the power distributions for the Gaussian and box-shaped cases are caused by the slippage. The dips in the power profiles originate from the overbunching, which increases during the passage through the radiator. The maxima for the other two seed cases are shifted according to the bunching factors. For these cases, the electrons are not yet overbunched but the radiator outputs are far from the maximum results.

Second Stage

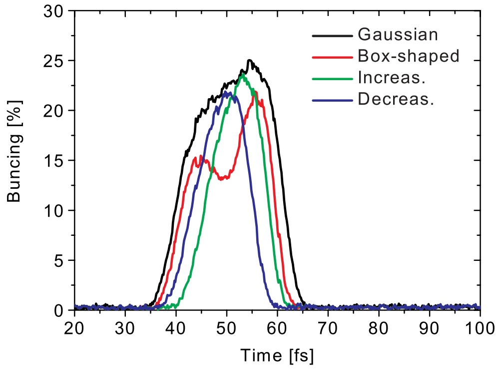

Figure 4: The Bunching on the fifth harmonics after the second dispersion section of the two-stage HGHG-FEL for different seed cases.

The output of the first radiator is used as a seed for the second stage. Figure 4 shows the bunching factors on the fifth harmonics after the second dispersive section for the two-stage HGHG-FEL. The dip in the bunching for the box-shape case is not an overbunching effect but rather it mirrors the shape of the seed radiation, i.e. the output of the first radiator. This can be concluded from the spectrum of the second radiator, figure 5b, where the sidebands are very small. The flanks of the bunching profile for the box-shaped case are no more steeper than the Gaussian case.

Although the peaks of the power distributions for the different seeds, figure 5a, have roughly the same values, the spectral distributions differ strongly. The high sideband in the spectrum of the Gaussian case points to a strong overbunching which is also indicated by the deep dip in the corresponding power distribution. The spectrum of the box-shaped case is pure and its maximum is roughly as high as the Gaussian case. The spectrum of the increasing- and decreasing power cases are also pure but the maximum spectral powers suffer from the reduced pulse length similar to the purity-optimized case described in [4]. The relative shift between the spectral maxima is not only reduced but

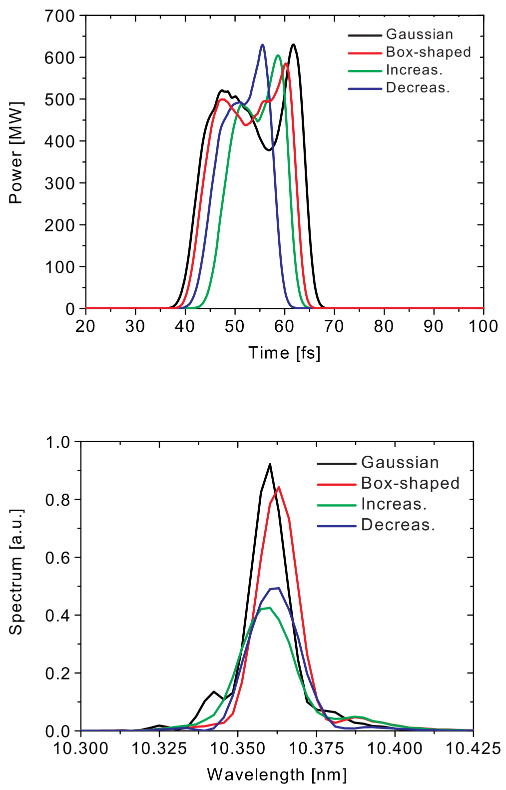

Figure 5: a)The power (top) and b) spectrum (bottom) of the second radiator for different seed-pulse shapes.

also the order of the maxima is changed compared to the spectra of the first radiator.

Final Amplifier

Using the output radiation of the second radiator as seed for the final amplifier, one would expect, that the properties of the radiator outputs dominate the output characteristics of the amplifier. Figures 6a and 6b show that this is true only for the Gaussian and box shaped case. For the increasing- and decreasing power cases, the properties of the radiator outputs are not fully retained during the amplification process. The spectral purity is reduced compared to the radiator output and the shift between the maxima of the spectrum seems to increase.

A comparison of the results of the final amplifier for the Gaussian, box-shaped, and purity-optimized case [4], figure 7, shows that a box-shaped seed leads to a spectral purity as high as a purity-optimized case, i.e. reduced dispersion strengths, while the output power is roughly as high as for a Gaussian seed. Although the pulse duration of the box-shaped case is longer than of the purity-optimized case, it is not as long as the Gaussian case. This might be

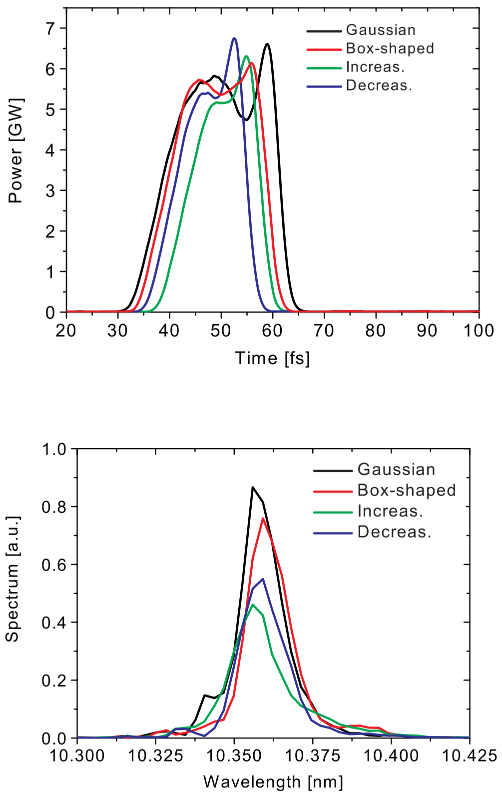

Figure 6: The power and spectrum of the final amplifier for different seed-pulse shapes.

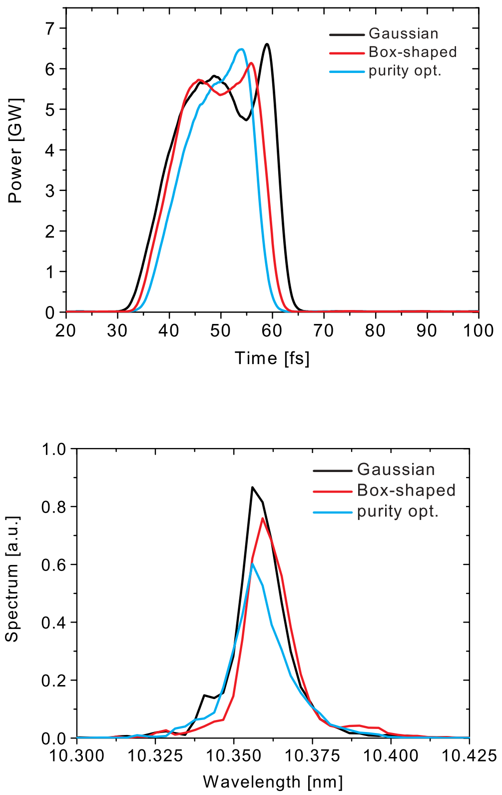

Figure 7: A comparison of the temporal and spectral power of the final amplifier for the Gaussian, box-shaped, and purity-optimized case [4] is shown.

originate from the flanks of the Gaussian distributed seed pulse.

CONCLUSION

The simulation studies show that the performance of a HGHG-FEL can be further optimized by adjusting the seed pulse shape. For the BESSY two-stage HGHG-FEL a box-shaped seed pulse can be used to achieve notable more spectral purity with only a minor loss of power compared with the FEL output for a Gaussian seed. Nevertheless the simulations with the increasing and decreasing seed power show also that due to the slippage, the shape of the radiation pulse changes during the passage through the FEL-line. Therefore the seed pulse shape should be adjusted for each of the three BESSY FEL-lines separately, in order to preserve the benefits of a well adjusted seed.

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