HARMONIC CONTENT OF THE BESSY* FEL RADIATION

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Abstract

The BESSY soft X-ray FEL is planned as a High-Gain Harmonic-Generation (HGHG) FEL facility. The associated tunable seed lasers will cover the spectral range of 230 nm to 460 nm. Cascaded HGHG stages will be used to reduce the seed wavelength to the desired wavelength range of 1.24 nm $\leq \lambda \leq 51$ nm. Using the harmonic content of the high-intensity radiator output the number of necessary HGHG stages can be reduced. Moreover the higher harmonic content of the final amplifier extends the spectral range and thus is of high interest to the user community. In this paper, the higher harmonic content of the final output as well as of the radiator ouputs are investigated. The main parameters such as output power, pulse duration and bandwidth as well as their suitability for seeding are discussed.

INTRODUCTION

BESSY proposes the construction of a linac-based seeded FEL multi-user facility. The Technical Design Report for the BESSY soft X-ray FEL was published in 2004 [1]. The FEL facility will consist of three undulator lines with three experimental stations each. The independent HGHG-FEL lines deliver reproducible ultra short pulses in the photon energy range of 24 eV to 1 keV with a peak-brilliance of about 10^{31} photons/sec/mm^2/mrad^2/0.1% BW. The polarization of the output radiation will be variable. A photoinjector and a superconducting 2.3 GeV CW linac will feed the FEL lines. Each line will be seeded by a tunable laser. The seed is of a Gaussian profile with a peak power of 500 MW, and a pulse duration of about 15 fs (rms).

Two to four HGHG stages are necessary to reduce the laser wavelength to the desired range. Each stage consists of an undulator - dispersion - undulator structure. In the first undulator, the so-called modulator, the interaction with a radiation field (provided by the seed laser) leads to an energy modulation of the electron beam on the seeding radiation frequency. The following dispersive section converts this energy modulation into a spatial modulation, or bunching, which includes bunching on higher harmonics of the seed frequency. The second undulator, the radiator, is set in resonance with a chosen harmonic of the seed. The prebunched beam then radiates coherently at the harmonic wavelength. The radiator output of each stage is used as a seed for a next stage. The last radiator is followed by the final amplifier. It is seeded at the desired wavelength and the amplification process is brought to saturation.

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The key process in a high gain FEL is the strong microbunching at the fundamental frequency. Due to the nonlinear interaction not only the bunching at the fundamental but also the bunching at the higher harmonics is driven by the exponential gain of the fundamental radiation field [2, 3, 4]. This leads to remarkable power levels at the harmonics frequencies, which are experimentally proven [5, 6]. While the linear amplification of the higher harmonics is always smaller than the fundamental, the nonlinear amplification driven by the fundamental radiation field grows faster and dominates in the exponential gain regime. As the growth rate of the harmonics scales with the harmonic number times fundamental growth rate, the harmonics saturate before the fundamental but at lower level. Using this fact, a proper tapering can be found which maximises the output at a given harmonic and suppresses the gain of the fundamental frequency. In this way, the relation between harmonics and fundamental radiation can be improved.

Simulation studies presented in this paper investigate the harmonic content of the output for the final amplifier and the first radiator of the BESSY High-Energy (HE) FEL-line, and the suitability of the radiator harmonics for seeding. The HE-FEL consists of four HGHG-stages and delivers photons with an energy range of 500 eV to 1 keV.

SIMULATION STUDIES

The studies have been performed using the 3-D simulation code GENESIS [7]. GENESIS calculates the fundamental output power, the microbunching at the fundamental and at higher harmonics, and also the radiation output of a prebunched beam at a given harmonic. However it cannot simulate the power of the harmonics and fundamental simultaneously. Therefore, the output power and the effect of the tapering have been calculated in different runs, as follows. In a preliminary run the fundamental radiation has been simulated for an undulator with the nominal K-parameter, i.e. an extended radiator or a final amplifier. At the point, just before the chosen harmonic saturates, the particle and radiation-field distributions have been extracted. They then were used as input for two further runs using a similar undulator with small variation in the K-parameter. In these runs, the growth of the fundamental using field and particle distributions, and the growth of the chosen harmonic using only the particle distribution were calculated. Obviously, the influence of the fundamental radiation on the harmonic is missed in the last case, but as the nonlinear interaction depends on the fundamental growth rate which is suppressed by the tapering, the effect can be neglected.

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Final Amplifier

The seed used for the final amplifier had a Gaussian profile with a peak power of 150 MW, and a pulse duration of about 12 fs (rms). The third harmonic of the fundamental wavelength of 1.24 nm was chosen for the simulation studies. It saturated after 7.13 m with a maximum bunching of 5 %.

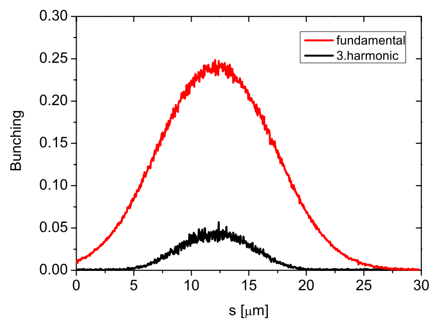

Figure 1: Comparison of the bunching factors of the fundamental and third harmonic for the final amplifier of HE-FEL after 7.13 m. Bunching along the electron beam is shown.

Figure 1 shows the bunching on the fundamental and third harmonics after 7.13 m. The K-parameter of the tapered undulator section varies about 14 % from the nominal case. The maximum harmonic output was reached after 2.85 m in the tapered undulator section. Figure 2 shows the power distribution of the third harmonic and of the fundamental at the saturation point of the third harmonic. The power distributions for the tapered and nominal case are depicted. The maximum power of the harmonic is about a factor of 10 higher for the tapered case. While the harmonic radiation benefits clearly from the tapering, the fundamental radiation is suppressed, as expected. The pulse length of the third harmonic is reduced which is not surprising as we use the harmonic of the radiation.

First Radiator

In order to investigate the suitability of the radiator harmonics for seeding, the output power of the second radiator in HE-line has been compared to the power of the fifth harmonic of the first radiator. The first radiator of the HE-line was extended in order to achieve the saturation of the harmonics. The rest of the undulators and the laser seed had the nominal parameter as described in TDR. The fundamental wavelength of the first radiator amounts to 55.9 nm. The fifth harmonic with a wavelength of 11.2 nm saturates at 6.99 m. The K-parameter of the tapered undulator section varies about 1 % from the untapered case. The maximum harmonic output was reached after 2.48 m in the tapered undulator section. Figure 3 compares the radiation power distributions of the second radiator and the fifth harmonic of the first radiator.

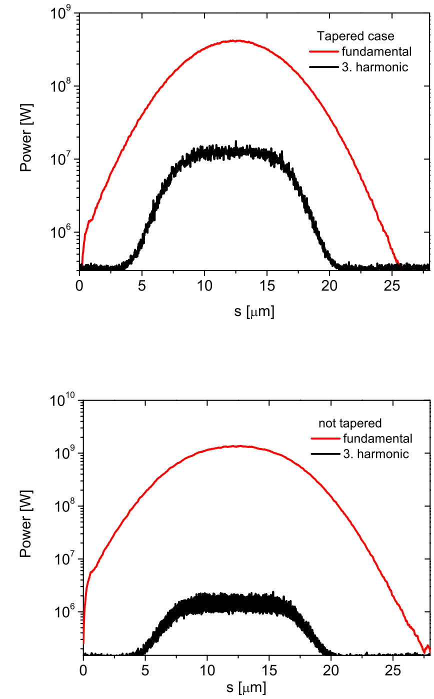

Figure 2: The power distribution of the third harmonic and of the fundamental at the saturation point of the third harmonic. The power distributions for the tapered (top) and untapered (bottom) case are depicted.

The spontaneous emission in the extended first radiator increases the energy spread of the electron beam and leads in connection with the high K-value, which is suitable for the fundamental, to the higher background for the harmonic radiation.

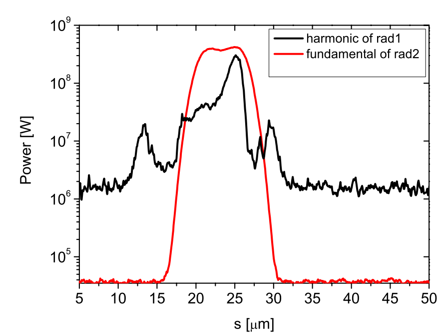

Figure 3: Comparison of the power distributions of the second radiator and the fifth harmonic of the first radiator after the tapered section.

The spectral purity of the fifth harmonic is poor, but the peak spectral power has a remarkable amount of 60 % of the second radiator peak power, see figure 4. The loss of the spectral purity is not caused by the tapering, as the comparison of the harmonic output in tapered and untapered undulators clearly shows. The harmonic radiation is more sensitive to the noises of the fundamental radiation and the electron distribution.

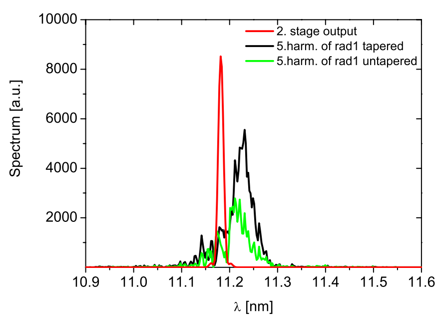

Figure 4: Spectral power distributions of the fifth harmonic of the first radiator and of the fundamental of the second radiator are shown. The spectral distribution of the fifth harmonic is depicted for the tapered and untapered case.

The fifth harmonic radiation was used to seed the third modulator. Figure 5 shows a comparison of the bunching factors achieved by seeding with the harmonic radiation and the second radiator output.

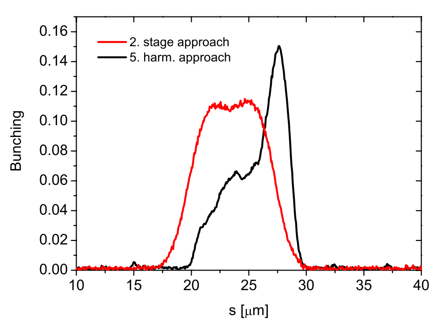

Figure 5: Comparison of the bunching factors achieved by the harmonic radiation and the second radiator output.

The output power and the spectrum of the third radiator are shown in figure 6. A comparison between the power distributions achieved by the fifth-harmonic approach and the regular case suggests that the results are very similar. Only the background of spontaneous emission seems to differ. This can be explained by the fact that in the regular case the electrons have to pass through the second stage. However, the logarithmic plot of the spectral distribution shows, that spectral purity of the fifth-harmonic approach is very poor.

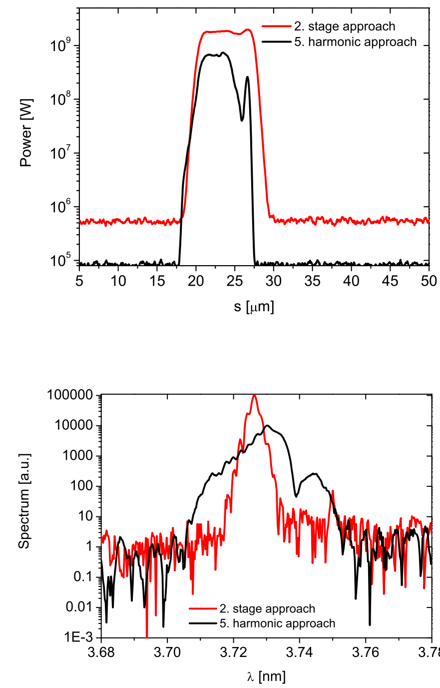

Figure 6: Power distribution and spectrum of the third radiator are shown.

CONCLUSION

The small changes in K-parameter necessary for the tapering are easily achievable by gap variation in each undulator section of the BESSY-FEL. Therefore an enhancement of the harmonic radiation in final amplifier and radiators is feasible. Despite the poor spectral purity, the results for the fifth-harmonic approach are encouraging. Further simulation studies are necessary to decide about the suitability of the radiator harmonics for seeding. In these studies the radiation at the fundamental and harmonics should be calculated simultaneously, as possible with a modified version of GENESIS.

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