BENEFITS FROM BESSY FEL HIGHER HARMONIC RADIATION*

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Abstract

In the FEL process, bunching and coherent radiation are produced at the FEL resonant frequency as well as at higher harmonics. BESSY proposes a linac-based cascaded High-Gain Harmonic-Generation (HGHG) free electron laser (FEL) multi-user facility [1]. The BESSY soft X-ray FEL will be seeded by three lasers tunable in the spectral range of 230 nm to 460 nm. Two to four HGHG stages downconvert the seed wavelength to the desired radiation range of 1.24 nm to 51 nm. As a surplus, higher harmonic radiation is intrinsically produced in each FEL stage. Radiation on a higher harmonic of the FEL frequency is of interest because it bears the possibility to reduce the number of FEL stages. This paper details extensive studies of the higher harmonic content of the BESSY High-Energy-FEL (HE-FEL) radiation. Important aspects of FEL interaction on higher harmonics as resulting from theory and from numerical simulations are discussed. For the case of the BESSY HE-FEL, methods for improving the harmonic content are presented. These methods are examined as to their influence on FEL output power, pulse duration and spectral bandwidth. Focus is laid on the application of higher harmonic radiation for the sake of seeding.

INTRODUCTION

The BESSY soft X-ray FEL [1] uses a cascade of two to four stages to downconvert the initial seed wavelength to the desired output wavelength range. In each stage, seed radiation and electron beam interact in an undulator called modulator. There the electron beam is modulated in energy which is converted into spatial bunching in a dispersive section. The bunched beam then enters a second undulator, called radiator, which is set to a higher harmonic of the seed frequency. At the end of the radiator, the radiation pulse is extracted to seed a new HGHG stage. In final amplifiers that are set in resonance with the radiation emerging from the last radiators, the FEL process is brought to saturation.

Due to strong linear interaction, microbunching on the resonant frequency of the radiator grows quickly. For higher harmonics, linear amplification is significantly smaller so that only nonlinear interaction remains as the main driving force of higher harmonic bunching [2, 3]. Nonlinear effects are strong in the high gain regime and drive bunching on all even and odd harmonics. As the higher harmonic gainlengths are typically of the order of $L_{Gn} = L_{G1}/n$, n being the harmonic number and L_{G1} being the gain length of the fundamental mode, bunching on higher harmonics develops more quickly and saturates earlier than the fundamental [4].

In [5], the typical amount of higher harmonic radiation was already shown for the BESSY HE-FEL. It was illustrated that slight alterations of the undulator parameter can enhance radiation on higher harmonics while supressing the fundamental. This way, the pulse power in the third and fifth harmonic can be increased significantly. For the BESSY HE-FEL, the fifth harmonic of the first stage radiator is of critical interest because it could be applied directly as a seed for the third stage, bearing the option to simplify the overall FEL design. However, seeding not only requires high levels of power that are needed to overcome the shot-noise level of the electron beam, but also exerts some contraints on the temporal distribution, spectrum and phase of the seed pulse [6]. We will show in this paper that by carefully optimizing the higher harmonic content of the HE-FEL first stage radiator, the higher harmonic pulses can be modified in these key properties.

Simulation of Higher Harmonics

Following the idea detailed in [5], all simulations were performed with the 3D-code GENESIS [7]. GENESIS simulates the FEL process with regard to one wavelength which is usually the FEL resonant wavelength λ_1. For λ_1 GENESIS calculates all relevant radiation properties such as output power and spectrum. It also computes the electron beam parameters that result from FEL interaction such as microbunching on the fundamental wavelength but also bunching on higher harmonics of λ_1. At any point within the simulation, the electron parameters can be extracted and up-converted to one of the higher harmonic frequencies.

In [5], this method was successfully applied to illustrate third harmonic bunching and emission in the BESSY HE-FEL final amplifier. We also showed some initial ideas for enhancing the harmonic content of the first stage radiator. As detailed in [1], the BESSY HE-FEL consisists of four full HGHG stages. Nominally, two initial stages are neccessary to reduce the seed wavelength of 279.5 nm to 11.18 nm[1]. In the first stage, the radiator is set to the fifth harmonic of the seed wavelength. The generated FEL pulse is then used to seed the second stage where the same harmonic number is used, altogether supplying for a factor 25 in down-conversion. A radiation pulse at 11.18 nm can also be achieved using the fifth harmonic of the output emission of the first stage radiator.

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[1] Please note that the term nominal in this paper refers to the BESSY HE-FEL parameters and output properties as are detailed in [1].

HARMONIC CONTENT 1. RADIATOR

From numerical studies [8] and experiments [9] it is known that the fifth harmonic usually saturates at about 0.5% of the fundamental power. In [5] it was shown that slightly changing the undulator parameter K already helps to increase the power on the fifth harmonic way above that level. For the studies, the first radiator was extended until sufficient fifth harmonic bunching could be observed. At a radiator length of 7 m, the particles were extracted, up-converted, and inserted back into the undulator with an optimized undulator parameter K and a visible increase in fifth harmonic output power. These studies were pursued further showing that by carefully selecting the undulator parameter K, the fifth harmonic can be brought to power levels as shown in Fig. 1. They reach about half the power at 11.18 nm that is achieved by the nominal design with a second HGHG stage.

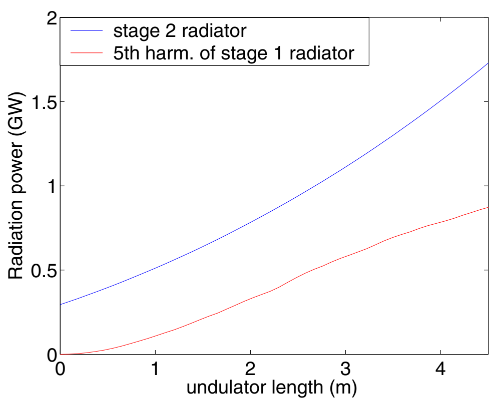

Figure 1: Evolution of peak power of fifth harmonic radiation in first stage radiator with optimized undulator K parameter, red line. K changed by 0.3% of its nominal value. Results are compared to peak pulse power in original stage two radiator, blue line, with same resonant wavelength 11.18 nm.

Note that with the variation of the undulator parameter, the radiation pulse temporal distributions are sligthly varied as well. However, they still remain mirror images of the fifth harmonic bunching that is attained in the extended first radiator. Hence, while the peak power of the fifth harmonic radiation could be increased by further optimization of the undulator parameter, the power distributions still ressemble those depicted in [5].

OPTIMAL ELECTRON BEAM SIZE

According to FEL theory, there are two electron beam size related effects counteracting FEL efficiency. On the one hand, the FEL parameter ρ is inversely proportional to β, where $\beta = \sigma^2/\varepsilon$, σ being the rms transverse electron beam size and ε being the beam emittance. As the FEL radiation power scales directly with ρ, output power is higher for smaller beam sizes. On the other hand, the beam emittance is constant so that small beam sizes are accompanied by large angular divergences $\sigma' = \varepsilon/\sigma$. These act as an energy spread (also referred to as an effective phase spread [10]) and reduce FEL interaction efficiency. Thus the emittance induced energy spread has to be kept below the level of natural energy spread in the electron beam. While the emittance effect is a critical issue in a Self Amplified Spontaneous Emission FEL, it is usually not very dominant in seeded HGHG-FELs. However, the emittance effect does play a role when extending the radiator. The electron beam is now prebunched and has a considerably higher energy-spread. As a result, the threshold for the phase spread introduced by the angular divergence is much higher and allows to reduce the electron beam size. The impact of reducing β can best be seen in Fig. 2 which compares microbunching on the fifth harmonic for different electron beam sizes.

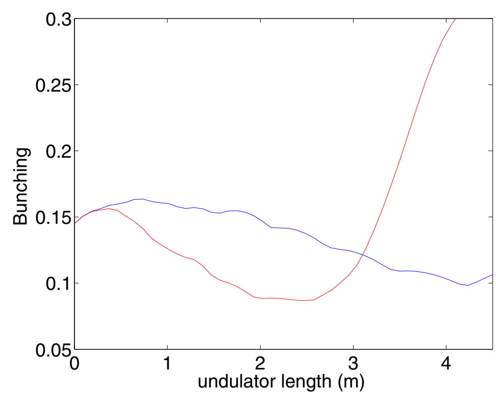

Figure 2: Evolution of bunching on fifth harmonic along extended radiator for nominal electron beam size, blue, and optimized electron beam size, red.

With the nominal (absent) electron beam focusing, bunching gets lost in the course of the radiator, Fig. 2, blue line. When focusing to smaller electron beamsizes, red line, bunching also decreases initially but then increases remarkably in the second half of the undulator. As a consequence, the output power at the radiator end is enhanced significantly, Fig. 3.

Note that in the simulation procedure explained above, only the electron beam properties were extracted and converted to the fifth harmonic. Higher harmonic radiaton, which is also produced in the course of the FEL process in the first radiator, is not calculated by GENESIS and has to be found through an estimate. It can then be added to the simulations in order to correctly consider the most important effects of higher harmonic interaction. A first estimate of the higher harmonic pulse was found by extracting the fundamental pulse with the power P_1 and scaling it to the approximate fifth harmonic radiation pulse. The peak power P_5 of the fifth harmonic at saturation is approximated as $P_5 = 0.5\%$ of P_1. This gives peak powers in the range of MWs that barely overcome the 10 kW-level of background radiation. When reproducing all simulations

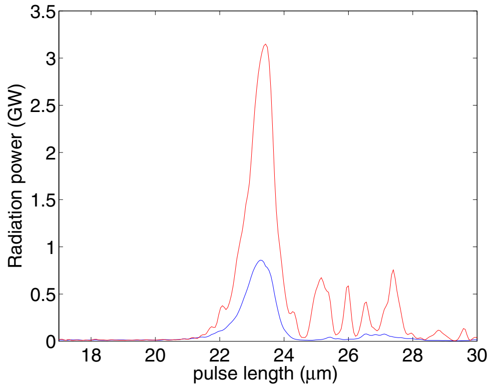

Figure 3: Temporal power distribution of fifth harmonic radiation at radiator end for nominal electron beam size, blue, and optimized electron beam size, red.

and seeding with the estimated fifth harmonic radiation, the effect on the output is negligable.

OPTIMAL UNDULATOR PROPERTIES

Nonlinear harmonic interaction not only occurs in planar undulators, but also develops in helical undulators. Since in helical undulators the electrons couple more effectively to the fundamental wavelength as well as to all higher harmonics [2], they generally provide for a higher level of microbunching and radiation. As a side-effect, the electron beam travelling through a helical undulator develops a higher level of energy spread, too, which degrades FEL efficiency. Thus in the design of the BESSY FEL, mostly planar undulators are foreseen. However, with regard to generating a rich harmonic content in the first radiator, a helical undulator is worth considering. The main difference between planar and helical devices is that higher harmonic radiation is only emitted off-axis in a helical undulator. Hence they are usually not applicable for the sake of seeding with higher harmonics, but inserting a prebunched beam into a helical undulator and regarding a certain harmonic as the resonant wavelength one obtains the desired seed radiation in the forward direction.

In the BESSY FEL, helical undulator fields can be achieved without a major change in magnet structure due to the special design of the APPLE [11] type undulators. They allow a wide range of polarizations by shifting the magnets parallel to each other, see also [1].

Either a partially helical or purely helical radiator can be used to generate the harmonic seed. In both cases, the undulator is divided into two parts with different resonant wavelengths. When using a partially helical undulator, the beam is prebunched in a planar device and inserted into a helical undulator. In an all-helical device, both undulator parts are helical. For both cases, microbunching is conserved best when applying strong focusing along the radiator. For a partially helical undulator, Fig. 4 shows that the output pulses at 11.18 nm can reach remarkably high power levels. Note that the pulse width is large as a consequence of improved bunching and additional slippage due to the extension of the radiator.

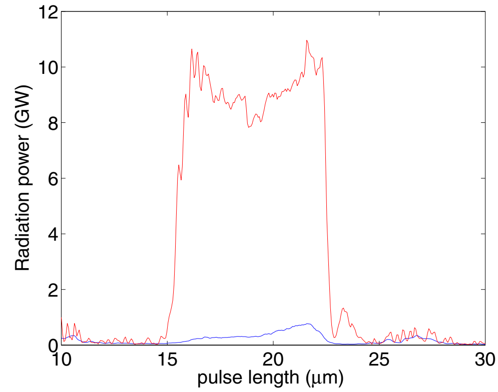

Figure 4: Temporal power distribution of fifth harmonic radiation at radiator end when last radiator part is helical. Compared are power for nominal electron beam size, blue, and optimized beam size, red.

When using a purely helical radiator, the gain in fifth harmonic bunching in the first radiator part is immense. Figure 5 shows how bunching on the fifth harmonic saturates earlier in the helical device with significantly higher bunching. Having shown that higher harmonic bunching can be conserved in the second part of the undulator, the particles are now extracted at 5.5 m were the fifth harmonic bunching factor is well above 15%.

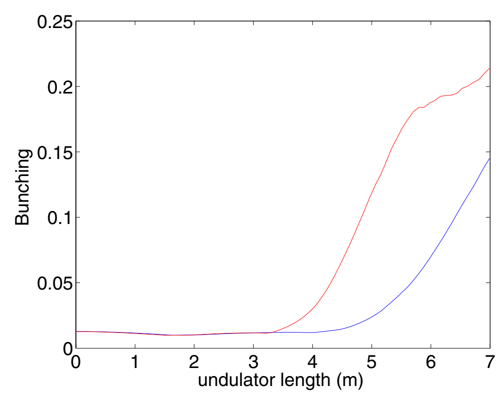

Figure 5: Evolution of fifth harmonic bunching in first stage radiator when using planar undulator, blue, or helical undulator, red.

With the given increase in prebunching and both undulator parts helical, peak powers in the GW-range can easily be achieved. Figure 6 shows one example of a fifth harmonic pulse that can be generated from an all-helical radiator with only slight alterations of the undulator parameter. Compared to the nominal second radiator output, both pulse shape and spectral power distribution, see Fig. 6, bottom, seem well adequate for seeding the next stage.

However, applying the generated pulses for seeding the

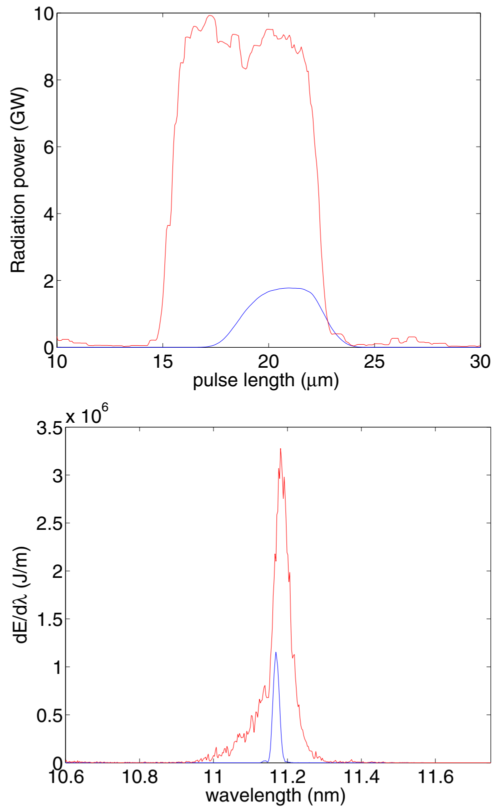

Figure 6: Temporal and spectral power distribution of fifth harmonic radiation pulse for optimized all-helical undulator, red, compared to nominal stage two radiator output, blue. Strong focusing applied along radiator to conserve bunching.

third HGHG-stage shows that the achievable bunching factors are limited. The reason is the increase in energy-spread that is acquired in the third stage modulators. In order to provide for best coupling to the helically polarized undulator radiation that is now used for seeding, the modulators were simulated as helical devices as well. Better coupling of electron beam and radiation brings an increase in microbunching, but it also increases the energy spread degrading the effectiveness of the dispersive chicanes. As a consequence, the bunching factors achieved in the subsequent radiators are low and the radiation powers are limited. Figure 7 shows two pulses as they emerge from the third stage radiators when using well optimized fifth harmonic radiation for seeding. It reveals that short, high power radiation pulses are in fact only achieved with planar undulators.

CONCLUSION

It could be shown that the harmonic output of the BESSY HE-FEL can be enhanced significantly by carefully tuning the undulator parameter and applying strong focusing to the electron beam. Changing the K parameter is technically well feasible by varying the undulator gap in the APPLE III devices. Strong focusing with quadrupoles

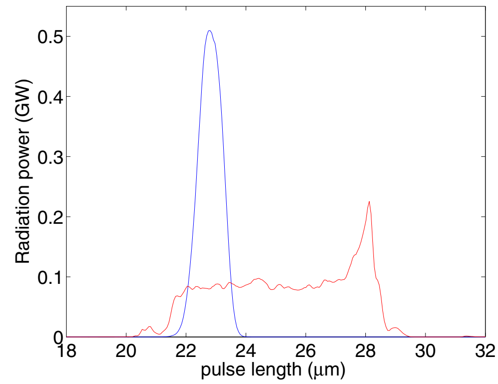

Figure 7: Radiation pulse at end of third radiator when using fifth harmonic radiation of first radiator as a seed. Compared are the powers that can optimally be achieved using all planar undulators, blue, or helical undulator, red.

is easily incorporated in the design and instantly leads to power levels in the GW-range. The same can be achieved on the fifth harmonic of a well optimized helical undulator. Helical field polarization is easily achieved in APPLE type undulators by shifting the magnet rows. When applying the fifth harmonic radiation pulses for seeding, the planar undulator radiation is most suitable. It is connected with the least increase in energy-spread enabling higher bunching in the subsequent FEL stages. While the results are promising, recent start-to-end-simulations [12] reveal that the BESSY FEL electron beam properties tend to vary along the length of the bunch. This influences FEL performance and suggests that in future simulations of higher harmonics, more realistic electron bunches should be taken into account.

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