NONLINEAR HARMONIC GENERATION IN THE BESSY SOFT X-RAY FEL*

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Abstract

Free Electron Lasers (FELs) do not only radiate at the fundamental frequency, they may also radiate coherently at higher harmonics. This process is referred to as nonlinear harmonic generation or NHG. NHG is of high interest, because it extends the output wavelength of FELs to several harmonics of the FEL resonant frequency. In cascaded High Gain Harmonic Generation (HGHG) FELs, harmonic radiation may be used to improve frequency-conversion and reduce the number of HGHG-stages. BESSY proposes to build a cascaded HGHG FEL with three FEL lines [1]. They cover a wavelength range of 51 nm (Low-Energy FEL) to 1.2 nm (High-Energy FEL) and consist of up to four HGHG-stages. In this paper, we present studies of the BESSY High-Energy FEL harmonic content performed with the upgraded version of the simulation code Genesis 1.3 [2].

INTRODUCTION

The BESSY High-Energy (HE-) FEL uses a cascade of four HGHG stages to convert a seed laser of 297.5 nm down to 1.24 nm. Each stage consists of a modulator, dispersive chicane and radiator. Analytic studies [3] predict that the signal-to-noise ratio (SNR) in HGHG FELs decreases by the square of the harmonic nbumber used during conversion. As the total conversion factor in the BESSY HE-FEL is 225, degradation of the radiation due to noise is a critical issue. In order to conserve the excellent temporal coherence of the seeded FEL radiation, a new design is proposed that uses harmonic radiation to reduce the number of HGHG-stages. Its prospects are investigated in this paper.

Harmonic radiation is intrinsically produced during the FEL process in planar undulators and leads to coherent emission at higher harmonics of the FEL resonance [4]. It becomes significant in the high gain regime of an FEL and typically provides for power levels in the range of 1% or 0.1% of the fundamental depending on the harmonic number.

The new design uses harmonic radiation from the first stage radiator. Its fifth harmonic has a wavelength of 11 nm and could hence be applied directly as a seed for the third stage modulator. Figure 3 illustrates the idea.

HARMONIC CONTENT OF FIRST STAGE

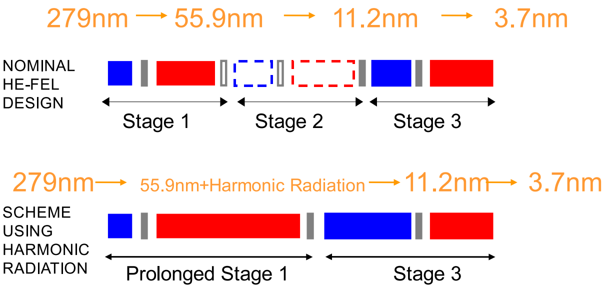

Figure 1: Schematic picture of new proposal for BESSY High Energy FEL: harmonic radiation from first stage radiator could be used to the seed third stage. The second stage could be omitted. Stages 1 to 3 depicted.

The BESSY High Energy FEL first radiator is a planar undulator with the period length of λ_u=92 mm and a total length of 3.69 m. The radiator has to be prolonged significantly to yield sufficient fifth harmonic power for seeding the third stage. The harmonic power in the first radiator then evolves as depicted in Fig. 2.

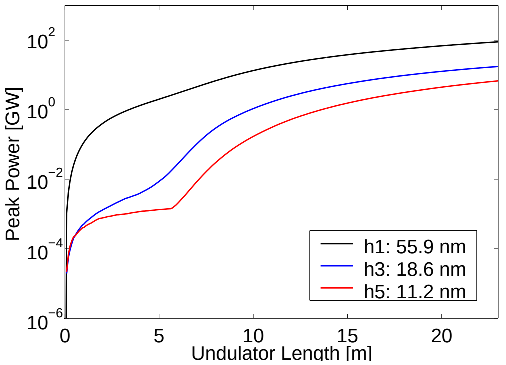

Figure 2: Simulation of BESSY High-Energy FEL radiation power along first radiator. From top to bottom: fundamental, third and fifth harmonic radiation. Simulation performed with new version of Genesis 1.3 [2].

It can be observed that the harmonics start later than the fundamental and enter their exponential gain regime after approximately 5 to 7 m. After that they rapidly reach a significant output power because they have a shorter gain length (higher gain) than the fundamental. This corresponds well to analytic predictions [5].

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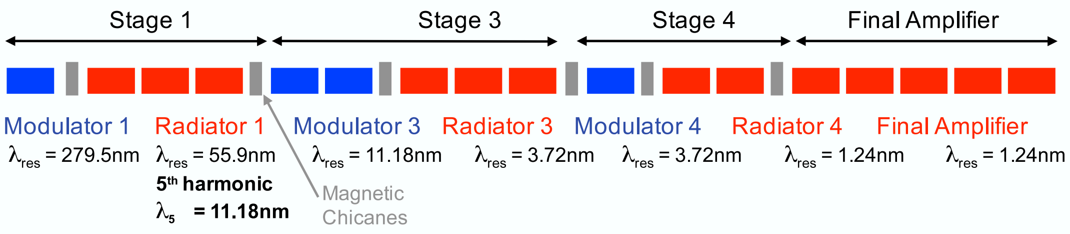

	Mod1	**Rad1**	**Mod3**	**Rad3**	**Mod4**	**Rad4**	**FA**
λ_u [mm]	122	61.2	70	50	50	28.5	28.5
No. of undulator periods	1x18	3x51	2x50	3x56	1x69	2x110	5x110

Figure 3: Schematic view of new design BESSY High Energy FEL with table of undulator properties.

NEW DESIGN

The choice of λ_u and K plays an important role in FEL performance. In order to find the optimal undulator settings for the first radiator with respect to a short gain length and high output power, a range of FEL configurations were studied. The combination of K=6 and λ_u=61.2 mm is a good compromise that reduces the fundamental gain length by about one fourth [6]. With the assumption of a 10 mm undulator gap, this corresponds to a peak flux of 1.6 T in the undulator magnets which is technically feasible [7].

A schematic view of the new design is given in Fig. 3. The radiator length is fixed at 9.4 m (153 periods) where the fifth harmonic power is in the range of 230 MW. Simulation studies of the fresh bunch parts show that this keeps the increase of energy spread at a tolarable level.

The temporal and spectral power distribution of the fifth harmonic at the end of the radiator then evolve as depicted in Fig. 4. However, the fifth harmonic power at the end of the prolonged radiator is about a factor eight lower than the original seed power for the third stage. This requires a careful readjustment of the undulator lengths in all subsequent stages. The total length of the first stage is now 15.5 m including the dispersive section in between modulator and radiator and the fresh bunch chicane after the first radiator. In order to maintain sufficient energy modulation in the third stage modulator, it has to be extended from 30 to 100 periods, equal to about 5 m of undulator. However, the extension of the first and the third stage does not exceed the original length reserved for the second stage.

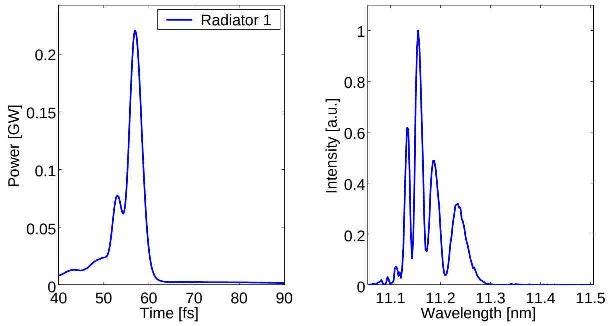

Figure 4: Temporal and spectral power distribution of fifth harmonic radiation of first radiator at 9.4 m. Undulator period 61.2 mm, K=5.98.

RESULTS

Maintaining the nominal undulator configurations for the third and fourth stage, the power at the end of the third and fourth radiator evolves as depicted in Fig. 5. The power

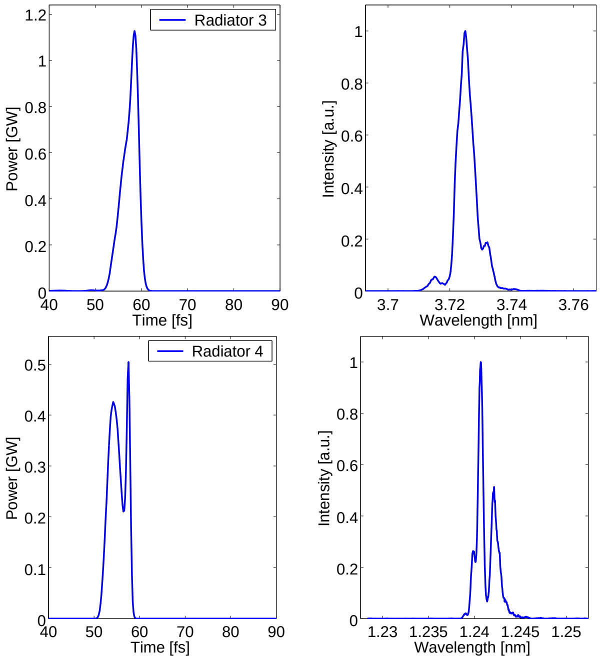

Figure 5: Simulation of temporal and spectral power distribution at end of third radiator, top, and fourth radiator, bottom, in scheme 1.

levels compare well to the output power in the original design. When using the radiation from the fourth radiator to seed the final amplifier, it reaches an output power of 2.5 GW. This slightly exceeds the nominal output power of 1.8 GW. The temporal and spectral power distribution at the end of the final amplifier are depicted in Fig. 6. The output power of the final amplifier in the new design compares well to the output power of the original HE-FEL design. The pulses have become shorter, which is due to the fact that the harmonic pulses at the end of the first radiator are significantly shorter than the fundamental pulses. Radiation from unseeded bunch parts, the background in Fig. 6, left, is also greatly reduced. This can be attributed to the reduced number of HGHG stages. Figure 6, right, shows the improvement of the final amplifier spectrum. The new design results in fewer temporal spikes and the output radiation is concentrated in a smaller bandwidth (30% net reduction), thus showing improved temporal coherence.

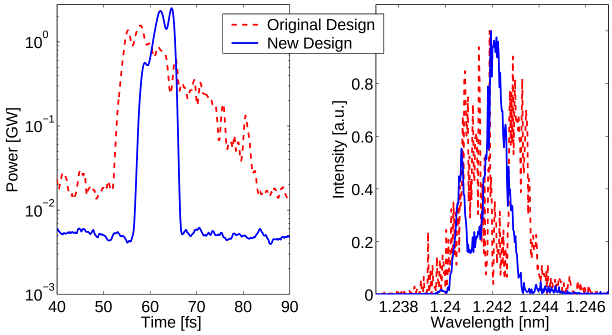

Figure 6: Simulation of temporal and spectral power distribution at end of final amplifier.

However, there are still two peaks visible in the spectrum. The shorter wavelength spike is a sideband which is amplified because it lies within the FEL bandwidth[1]. It already appears in the output of the fourth radiator, see Fig. 5, bottom, which has been used to seed the final amplifier. It probably results from the bunching distribution of the electrons in the radiator. Ref. [1] explains that the electrons can get *overbunched*, meaning that they move too far in the potential bucket, and generate a modulation of the emitted radiation frequency. This could be avoided by readjusting R_{56} in the dispersive chicanes at the expense of output power.

HARMONIC CONTENT OF THIRD STAGE

Harmonic radiation might be used again for an additional change in the design. The third harmonic radiation of the third radiator has a wavelength of 1.24 nm and can be used to directly seed the final amplifier.

However, this idea is more of a theoretical than a practical option. The gain length in the third radiator is significantly longer than in the first radiator (L_{G1D}=1.8 m as opposed to 1 m). This means that the radiator has to be prolonged significantly to yield sufficient fundamental gain for the harmonic power to become noticeable. As a consequence, the total undulator length in this case would exceed the nominal HE-FEL length, which is certainly a drawback. The long undulators also provoke a significant SASE background from the unseeded buch parts. Figure 7 depicts the temporal and spectral profile of the third harmonic at 23 m along the third radiator. The peak power is about a factor of six lower than the output of the fourth radiator in the nominal design. As a result of the degradation of electron beam quality in the long undulator, the spectrum shows several spikes and sidebands.

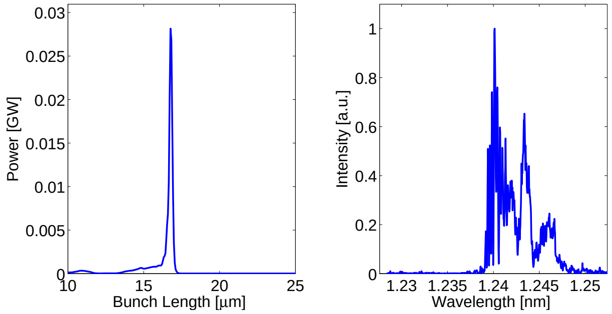

Figure 7: Temporal and spectral power distribution of third harmonic radiation of third radiator at 23 m.

When using the harmonic radiation from the third radiator to seed the final amplifier, the HE-FEL line yields the temporal and spectral power depicted in Figure 8. The final amplifier spectrum is dominated by a spiky SASE spectrum and does not convey the advantages of High Gain Harmonic Generation any more.

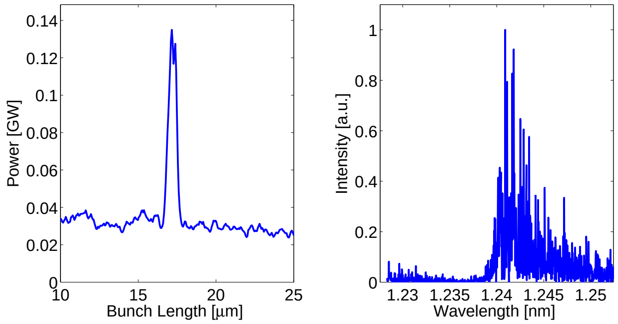

Figure 8: Temporal and spectral power distribution at end of final amplifier when using third harmonic radiation from stage three.

CONCLUSION

The use of harmonic radiation from the first stage for seeding the third stage is a promising option for the BESSY High Energy FEL. The simulation studies performed with

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[1] The relative FEL bandwidth of the order of the FEL parameter ρ which is about 1e-3 in the final amplifier.

the new version of Genesis [2] show that it is a feasible option and yields an output power and spectral bandwidth comparing well to the original design. Moreover, the new scheme that uses harmonic radiation has a number of benefits:

1. The complexity of multi-stage cascading is reduced as the number of HGHG stages decreases from four to three. This can be expected to greatly improve the practicability of the proposed machine both during commissioning as well as during operation.
2. The constraints on the electron beam are relaxed. The BESSY Soft X-Ray FEL implements the serial use of the fresh-bunch technique in each HGHG stage [8]. As a consequence, a long electron bunch with a high current region in the range of several hundreds of femtoseconds is required[2]. In order to reach a peak current of 1.75 kA current along the entire bunch, an initial bunch charge of 2.5 nC needs to be generated in the injector. Saving one HGHG-stage reduces the required bunch length by a few hundred femtoseconds. The bunch charge could be lowered to 1.5 to 2 nC such that the effects of space charge could be reduced. As a consequence, the beam emittance decreases and the FEL efficiency is enhanced.
3. The total undulator length decreases. This is beneficial due to two reasons: a) the FEL pulses are less prolonged by slippage in the undulators. This results in shorter output pulses. b) The fresh parts of the electron beam are less degraded in energy-spread before they come to use in their corresponding stages. This improves the quality of the electron beam and the FEL performance.

However, it has to be noted the experimental experience with harmonic emission in the soft X-ray regime is still small. FEL theory also shows that harmonic radiation is critically dependant on strong FEL gain on the fundamental. If a only a few of the relevant electron beam parameters (e.g. peak current or energy-spread) do not meet the expectations, the first radiator might saturate significantly later and not yield high intensity harmonic emission as predicted. Experiments with harmonic emission from HGHG FELs should hence be conducted to further investigate this issue.

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[2] The length was chosen to allow for seeding five consecutive bunch parts, accounts for slippage of FEL radiation in the radiators and includes a safety margin for timing difficulties.