The Output Performance of the BESSY* Multi-stage HGHG-FEL

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Abstract

BESSY proposes a linac-based cascaded High-Gain Harmonic-Generation (HGHG) free electron laser (FEL) multi-user facility, covering the VUV to soft X-ray spectral range. A photoinjector and a superconducting CW linac will feed three independent FEL-lines delivering variable polarized light. As the efficiency of the interaction between the radiation and the electron beam is higher in a helical undulator, one would tend to prefer such a device for the HGHG stages. Also a higher K-value of the modulators seems to be advantageous. This is not necessarily the case. We present simulation studies for the BESSY-HGHG-FEL and discuss the output performance for “helical stages” and increased K-values of the modulators.

INTRODUCTION

The BESSY soft X-ray FEL is planned as a HGHG FEL multi-user facility. The target photon energy range is from $24\,eV$ up to $1\,keV$ with a peak-brilliance of about $10^{31} photons\,/sec/mm^2/mrad^2/0.1\%\,BW$, i.e. a peak powers in the order of GWs for pulse lengths less than $20\,fs$ (rms). The polarization of the output radiation will be variable. Two to four HGHG stages are necessary to reduce existing laser wavelengths to the desired range of the BESSY FEL. Each stage consists of an modulator - dispersive section - radiator structure, for more details on the HGHG-stages see [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. The technical design report for the BESSY soft X-ray FEL was published recently [1]. As the efficiency of the HGHG-stages depends strongly on the proper choice of the undulator parameters, such as period length, K-value, total length and magnet field configuration, the study of their influence on the FEL output is of major interest. In this paper, we present simulation studies for the output performance of helical and planar stages and increased K-value of the modulators.

PLANAR AND HELICAL UNDULATOR STAGES

In a planar undulator the transverse wiggle motion of electrons in one plane causes a longitudinal oscillation which gives rise to generation of higher harmonics of the resonant wavelength and reduces at the same time the synchronization between electron position and phase front of the fundamental frequency. In a helical undulator, the electrons oscillate in both transverse directions with a phase shift of $\pi/2$. This leads to a constant longitudinal velocity. Therefore, the synchronization of the phase front and electron positions at the fundamental frequency is almost perfect whereas the coupling to higher harmonics is reduced compared to the planar case. In the HGHG scheme, the magnetic field configuration of the modulator must be chosen according to the polarization of the seed field, e.g. a helical device for a circular polarized seed, whereas the radiator using only the prebunched electron beam can be chosen independently of the seed field polarization. For variable polarized output of a HGHG-line only the last radiator and the final amplifier need variable polarization. The previous stages can consist of pure helical or pure planar devices. At the first view, one would tend to prefer helical stages for the HGHG-lines, because the perfect synchronization of the ponderomotive wave and the electrons enhances the efficiency of the radiator, while the higher bunching on the fundamental wavelength, driving the bunching at the harmonics [3], makes it adequate as modulator. On the other hand, the increases of the total energy spread of the seeded part of the beam, due to the interaction of the seed field with the electrons, is larger in a helical modulator. This reduces the output performance of the following radiator [4] compared with the case of a planar modulator.

In figure 1 the bunching factors of a planar modulator with a helical one are compared. The bunching factor at the fundamental frequency at the end of the modulator and the bunching factor on the fifth harmonic after the dispersive section are shown for the BESSY low energy HGHG-line. For the same seed power the impressed modulation is higher in a helical modulator but, as mentioned before, the generated total energy spread is also higher for a helical modulator, see figure 2. A comparison of the output performance of planar and helical radiators is shown in figure 3, where, in addition to pure helical and planar stages, the combination of helical and planar devices are also depicted. Obviously, the output performance depends rather on the radiator itself than on the modulator. The higher bunching achieved in a helical modulator does not lead to a higher output power in a planar radiator, due to the higher energy spread at the radiator entrance. In turn, the lower bunching achieved in a planar modulator combined with the lower energy spread and a helical radiator leads to a performance comparable to a full helical stage.

The output performance of a HGHG-FEL is determined by the output properties of the last radiator. This is insensitive to the field configuration of the corresponding modulator and thus independent on the magnetic configuration of the previous stages. Note that, in general the radiators are

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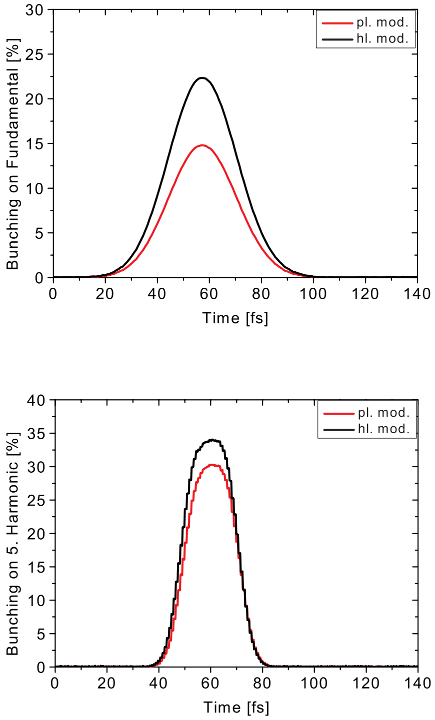

Figure 1: Comparison of the bunching factors of planar and helical modulator for the first stage of the BESSY low energy HGHG-line. Bunching at the fundamental at the end of the modulator (top) and bunching at the fifth harmonic after the dispersive section (bottom).

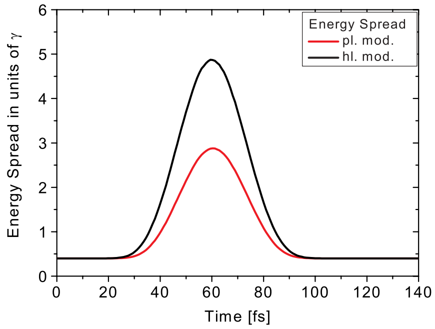

Figure 2: Total energy spread at the entrance of the radiator after helical and planar modulators.

somewhat shorter for pure helical stages, and that tuneable helical-undulators are technically more challenging.

HIGHER K-VALUE

A large bunching factor achieved in the modulator, can increase the output of the radiator and can enhance the efficiency of the HGHG stage. As the bunching, i.e. the energy modulation impressed by the seed, increases with the K-value [4], it seems to be advantageous to apply high K-value modulators. A higher K-value can be achieved for example by reducing the gap. In this case the undulator period has to be reduced according to the resonance condition in order to obtain the same resonant wavelength.

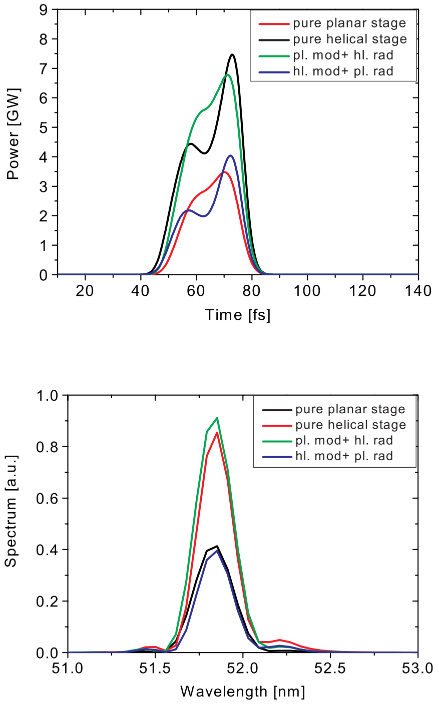

Figure 3: Comparison of the output performance of planar and helical radiators. The radiator power (top) and spectrum (bottom) are shown for different combinations of helical and planar devices.

Figure 4 shows the bunching achieved with the same seed field for modulators with various K-values of 4.97, 5.33, and 5.77 respectively. The increase of the bunching at the fundamental and fifth harmonic are visible, whereas the increase of the energy spread is rather moderate compared to the case of a helical modulator, see figure 5. The performance of the radiator for the three prebunched cases is shown in figure 6. An increase of the K-value of 7%, from 4.97 to 5.33, enhances the bunching on the fifth harmonic of about 4% and leads to a 20% increase of the radiator output, whereas a K-value increase of 16%, from 4.97 to 5.77, leads to 7% more bunchig on the fifth harmonic and 57% more output power. In order to achieve a noticeable output improvement of the HGHG stages an increase of the K-value of about 16% is necessary.

The magnetic field and thus the K-value of an undulator depends exponentially on a second order polynomial of the gap size [5]. Therefore, a strong reduction of the gap is necessary to obtain a significant increase in the K-value. The BESSY-HGHG-lines are tuneable to cover the desired wavelength range, i. e. each undulator serves a certain

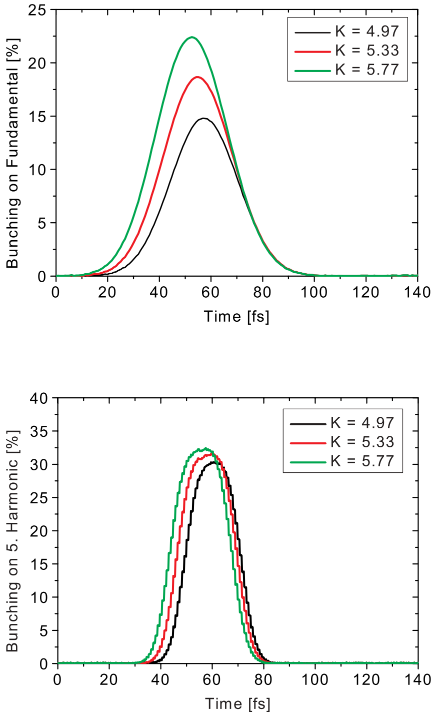

Figure 4: Comparison of the bunching factors of modulators with various K-values for the BESSY low energy HGHG-line. Bunching at the fundamental at the end of the modulator (top). And bunching at the fifth harmonic after the dispersive section (bottom).

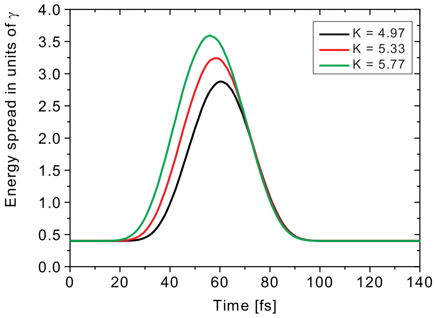

Figure 5: Total energy spread at the entrance of the radiator after modulators with various K-values.

range of wavelengths. This is provided by altering the undulator gaps where the longest wavelength is achieved by the smallest (minimum) gap. An increase of the K-value of about 16% reduces the minimum gap from $10\,mm$ to $2\,mm$. Such a small gap leads to a reduction of the central beam energy due to a strong increase of the wakefields [1] and makes a more sophisticated collimation system necessary to protect the undulators from electron beam losses.

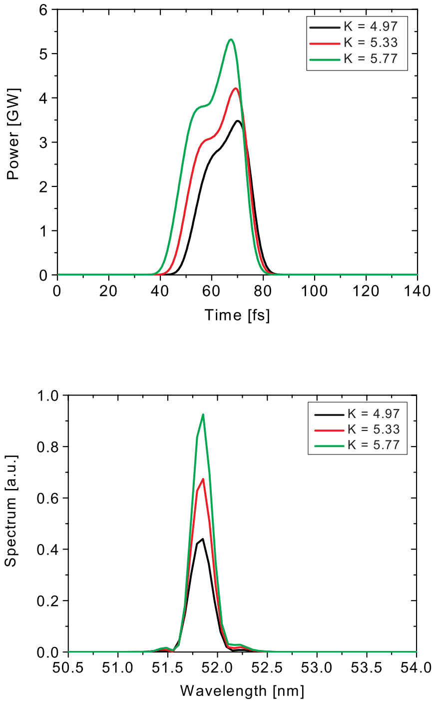

Figure 6: Comparison of the performance of a radiator fed by modulators with various K-values. The radiator power (top) and spectrum (bottom) are shown.

CONCLUSION

The output properties of the last radiators which feeds the final amplifiers determine the output performance of the BESSY HGHG-FEL. As the radiator is insensitive to the magnetic field configuration of the previous stages, it is not necessary to favor the helical stages over the planar. The HGHG-lines of the BESSY-FEL consist of tuneable planar stages. A noticeable output improvement of a HGHG stage can be achieved by a significant increase of the K-value of the modulator. An increase of the K-value by reducing the modulator gap leads to a reduction of the central beam energy due to the wakefields and makes a more sophisticated collimation system necessary. Therefore the minimum gap of the BESSY-FEL undulators is set to $10\,mm$, which moderates wakefields and relaxes the requirements for the collimation system.

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