THE BESSY SOFT X-RAY FEL: A SEEDED HGHG FEL*

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Abstract

Reproducibility, high power and short pulse length combined with variable polarization and tunable wavelength are required to open new frontiers for the soft X-ray users. To provide radiation with such extraordinary properties, BESSY has been designing a seeded FEL based on the high-gain harmonic-generation (HGHG) concept [1]. The seeding with an external tunable laser ensures the reproducibility of the full-coherent radiation. The combination of so-called HGHG stages, used to down-convert the seed wavelength, and a final amplifier provides for the high power and superior spectral properties. Furthermore, the HGHG concept and the fresh bunch technique planned for the BESSY FEL mitigate the effects of parameter variation along the bunch which are expected from realistic assumptions of the Gun and LINAC structure. The design concept of the BESSY soft X-ray FEL will be presented and the stabilizing effect of HGHG stages and the benefits from the fresh bunch technique and the final amplifier will be discussed.

INTRODUCTION

The BESSY Soft X-Ray FEL is designed as a multi-user facility consisting of three independent FEL lines based on HGHG-concept. Each line is seeded by a tunable laser covering the spectral range of 230 nm to 460 nm. The target wavelength ranges from 51 nm to 1.24 nm with peak powers up to a few GWs and pulse lengths less than 20 fs (rms). The polarization of the fully coherent radiation will be variable.

In the HGHG-FEL approach the light output is derived from a coherent subharmonic seed field. Consequently the optical properties of the HGHG-FEL output reflect the characteristics of the high-quality seed. The benefit is a pulse with selectable short duration, a high degree of stability and control of the central wavelength and bandwidth. Cascades of two to four HGHG stages are planned to reduce the existing laser wavelength to the target range of the BESSY-FEL. The planned “fresh bunch” technique [2] prevents the final output from the electron beam heating effect of FEL interaction in the upstream stages, ensuring the high output power and the spectral quality.

The optimization of an HGHG-line includes the proper choice of the seeding radiation, the electron beam parameters, the harmonic cascade, the undulator parameters and the strength of the dispersive section. In the following the steps taken during the optimization process will be described.

All calculations have been performed with the time-dependent 3D simulation code GENESIS [3].

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THE HIGH-GAIN-HARMONIC GENERATION

Several HGHG stages are necessary to reduce the seed laser wavelengths availabel today to the desired spectral range. Each stage consists of an undulator - dispersion - undulator structure. In the first undulator, the so called modulator, the interaction with a radiation field (e.g. provided by an external laser) leads to an energy modulation of the electron beam with the period of the seeding wavelength. The following dispersive section converts this energy modulation into a spatial modulation, or bunching, that includes bunching on higher harmonics of the seeding frequency. The fundamental of the second undulator, the so called radiator, is set in resonance with the chosen harmonic. The prebunched beam then radiates at the harmonic wavelength with high efficiency. The radiator output is used as the seed for the next stage. 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.

In a cascaded HGHG scheme the necessary seeding power for each stage is produced by adjusting the output power of the previous stage. The output power of the radiator is proportional to the square of the bunching factor, b_n, of the entering electron beam [4]:

$$p_{out} \sim b_n^2.$$

The bunching factor for the n^{th} harmonic of the seed laser is given by:

$$\begin{aligned} b_n &= \langle \exp(i\,n\,\theta_j) \rangle^2 \\ &= \exp\left(\frac{-1}{2} n^2 \sigma_\gamma^2 \left(\frac{d\theta}{d\gamma}\right)^2\right) J_n\left(n \Delta\gamma \frac{d\theta}{d\gamma}\right) \\ &= \exp\left(\frac{-1}{2} \sigma_\gamma^2 \left(\frac{d\psi}{d\gamma}\right)^2\right) J_n\left(\Delta\gamma \frac{d\psi}{d\gamma}\right), \end{aligned}$$

where θ is the ponderomotive phase of the electron beam in the modulator, $\psi = n\theta$ is the phase in the radiator, $\Delta\gamma$ is the maximum energy modulation generated in the modulator, σ_γ is the energy spread of the electron beam, $\frac{d\theta}{d\gamma}$ is the strength of the dispersive section and J_n is the n^{th} order Bessel function.

Large bunching factors can be achieved when the energy modulation impressed by the seed dominates the energy spread of the electron beam. Hence, for a reasonable performance of an HGHG stage the energy modulation induced by the seed should fulfill the following inequality [4]:

$$\Delta\gamma \geq n\sigma_\gamma. \tag{1}$$

When the radiation size at the entrance of the modulator and the transverse size of the electron beam are matched, the energy modulation of the electron beam scales with the seed power, p_{seed}, seed wavelength, λ_s, the modulator length, L_{mod}, the electron beam energy, γ, and the undulator parameter, K, as [4]:

$$\Delta\gamma \sim \frac{K}{\gamma}\, L_{mod} \sqrt{\frac{p_{seed}}{\lambda_s}}. \tag{2}$$

The modulator length should not exceed twice its power gain length in order to avoid an increase in energy spread due to the spontaneous radiation. For given electron beam energy and seed wavelength, and a fixed modulator length, the energy modulation, $\Delta\gamma$, can be controlled by the undulator parameter, or the seeding power, p_{seed}, both of which have their technical limits. The dispersive section has to be adjusted according to the energy modulation, reached in the modulator, taking the effective dispersion in the modulator and radiator into account. The total dispersive strength is given by [4, 5]:

$$\frac{d\psi}{d\gamma} \approx -\frac{n\, 2\pi L_{mod}}{\lambda_{um}\gamma} + \left(\frac{d\psi}{d\gamma}\right)_{dis.sec.} - \frac{4\,\pi L_{rad}}{\lambda_{ur}\gamma}, \tag{3}$$

where λ_{um} and λ_{ur} are the modulator and radiator period length, and L_{rad} is the length of the radiator.

Due to the interaction of the electron beam with the seed, the effective energy spread of the electron beam entering the radiator is given by

$$\sigma_{\gamma eff} = \sqrt{\sigma_\gamma^2 + \frac{(\Delta\gamma)^2}{2}}. \tag{4}$$

An increased energy spread causes an enhanced gain length and therefore extends the necessary length of the radiator. The “fresh bunch” technique is employed to limit the growth of energy spread from stage to stage in a cascaded HGHG FEL. In this approach the seeding pulse is significantly shorter than the electron bunch. As a result the harmonic generation process, and with it the enlargement of the energy spread applies only to a fraction of the bunch. After passing the first HGHG-stage the resulting radiation is shifted to a “fresh” part of the bunch which was not affected by the seed. A theoretical treatment of the HGHG-scheme can be found in [4, 5].

SEEDING RADIATION AND ELECTRON BEAM PROPERTIES

Contrary to a continuous seed pulse as used for the DUV-FEL [6, 7], in the case of a Gaussian-shaped pulse the electrons do not experience the seed peak power during the whole transition through the modulator. Since the integrated power experienced by electrons should be in the same order of magnitude to induce the same amount of bunching, the Gaussian-shaped seed pulse needs a higher peak power. For example, the $30\,MW$ continuous power with a wavelength of $800\,nm$ used for the DUV-FEL where the modulator has 10 periods, corresponds, according to equation 2, to a seed power of $90\,MW$ for a seed wavelength of $266\,nm$, and the same number of modulator periods. A Gaussian-shaped seed with $266\,nm$ wavelength and $15\,fs$ rms pulse duration would require a peak power of $1.3\,GW$ in a 10 periods modulator to induce the same bunching. Since the modulator can be chosen longer for the $266\,nm$ seed radiation, using a proper modulator of 18 periods a peak power of $400\,MW$ is sufficient. Note, to suppress the noise degradation effects [8] a higher peak power should be preferred.

The wavelength of the seed radiation within the range provided by the laser is deduced from the desired final wavelength and the harmonic cascade. Out of the several combinations of harmonics that can be used to provide the desired wavelength range in each particular HGHG-line, the one requiring the minimal number of stages is chosen. The accessible harmonic content in the bunching dropps off with rising harmonic numbers and photon energies, limiting the usable harmonics to the first five. The fifth harmonic is used in the early stages, where, due to the long wavelength, enough power and thus bunching can be obtained with acceptably short radiator lengths. Later stages use the third harmonics. The harmonic combination can change when the gaps are moved and the resonant wavelengths vary.

The planned tunable seed laser covers the spectral range of $230\,nm$ to $460\,nm$ with a Gaussian profile, a peak power of $500\,MW$ and a pulse length of about $15\,fs$ (rms), for more details see [1].

The energy of the electron beam has to fulfill the resonance condition, equation 5, for the whole HGHG-line with the minimum possible gain length. The nominal values of the electron beam parameters, extracted from start-to-end simulations, are listed in Table 1. The electron beam at the entrance of the HGHG-lines has a normalized transverse emittance of $1.5\,mm\,mrad$, a relative energy spread less then 0.02%, and an average current of about $2\,kA$ at the “flat top”. The duration of the flat top amounts to $730\,fs$. For the presented calculation an electron bunch with transverse Gaussian distributions is assumed.

OPTIMIZATION OF UNDULATOR PARAMETERS

The resulting resonant wavelength of the FEL, λ, depends on the undulator period length, λ_U, the K-value and the electron beam energy γ in units of the electron's rest

Parameter	High-energy	Medium-energy	Low-energy
ϵ_n [mm mrad]	1.5	1.5	1.5
I_{peak} [kA]	1.75	1.75	1.75
E [GeV]	1.63-2.3	2.3	1.02
Δ E/E [%]	0.01-0.014	0.01	0.02
Δt [fs]	730	730	730

Table 1: The nominal electron beam parameters at the entrance of the first modulator used in the simulation studies.

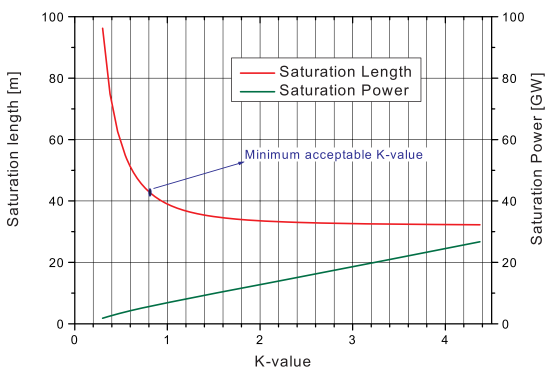

Figure 1: Saturation length and power as functions of the K-value for the final amplifier of the medium-energy HGHG-FEL. The FEL performace deteriorates with decreasing K-value.

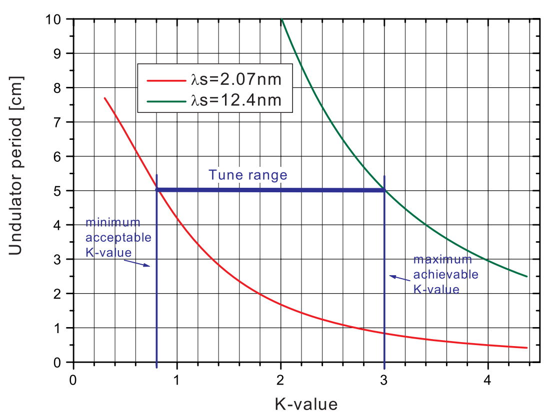

Figure 2: The undulator period as function of K-value for the final amplifier of the medium-energy HGHG-FEL. The tune range is limited by the minimum acceptable and maximum achievable K-value. With an undulator period of $5\,cm$ the desired wavelength range can be covered by gap variation.

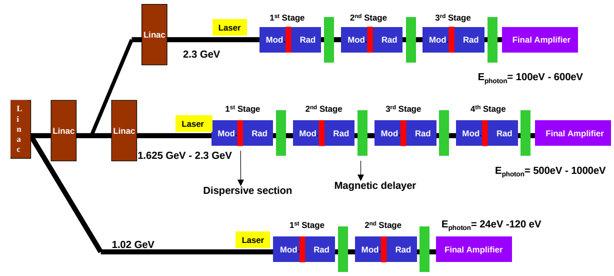

Figure 3: The BESSY HGHG multi user FEL-facility will consist of three HGHG-lines to cover the target wavelength range.

mass:

$$\lambda = \frac{1}{2\,\gamma^2}\,\lambda_U\,(1+K^2). \tag{5}$$

The maximum achievable K-value is limited by the permanent magnet undulator technology. The minimal gap is set to $10.4\,mm$ according to impedance considerations.

The minimum acceptable K-value is set to 0.8 as the interaction between the radiation field and the electron beam suffers from too small K-values. Figure 1 shows the saturation length and power as functions of the K-value for the final amplifier of the medium-energy HGHG-FEL. The deterioration of the FEL performance with decreasing K-parameter is obvious.

The undulator period length is chosen such, that the desired wavelength range can be completely covered within the given range of K-parameter. Figure 2 shows the tune range for the medium-energy HGHG-FEL as an example. With an undulator period of $5\,cm$ the desired wavelength range can be covered. Once the period length, λ_U, is fixed, the resonant wavelength can be altered by adjusting the gap of the undulator.

LAYOUT OF THE HGHG UNDULATOR SECTION

The BESSY HGHG multi user FEL-facility will consist of three undulator-lines to cover the target photon energy range from $24\,eV$ to $1\,keV$ ($51\,nm \geq \lambda \geq 1.2\,nm$). The "low-energy" HGHG-FEL operates in two stages at a beam energy of $1.02\,GeV$ delivering photons in a spectral range of $24\,eV$ to $120\,eV$. An energy of $2.30\,GeV$ is chosen for the "medium-energy" HGHG-FEL. A cascade of three stages covers the energy range of $100\,eV$ to $600\,eV$. The "high-energy" HGHG-FEL operates at variable electron beam energies of $1.625\,GeV$ to $2.30\,GeV$. It delivers in four stages photon energy ranges from to $500\,eV$ to $1000\,eV$. Figure 3 shows a schematic view of the BESSY HGHG multi user FEL-facility. A description of the electron source, linac and compressor scheme providing electron beams with the required properties can be found in [1].

Each of the three HGHG-lines consist of several stages and a final amplifier. In order to optimize an HGHG-stage

Table 2: High Energy HGHG-FEL

Stage	*MODULATOR*			*RADIATOR*		
	λ_U $[mm]$	P #	L [m]	λ_U $[mm]$	P #	L [m]
1	122	18	2.196	92	40	3.680
2	92	22	2.024	70	86	6.020
3	70	30	2.100	50	180	9.000
4	50	69	3.450	28.5	225	6.413
Final				28.5	630	17.955

Table 3: Medium Energy HGHG-FEL

Stage	*MODULATOR*			*RADIATOR*		
	λ_U $[mm]$	P #	L [m]	λ_U $[mm]$	P #	L [m]
1	122	18	2.196	92	40	3.680
2	92	22	2.024	70	104	7.280
3	70	30	2.100	50	231	11.550
Final				50.	393	19.650

Table 4: Low Energy HGHG-FEL

Stage	*MODULATOR*			*RADIATOR*		
	λ_U $[mm]$	P #	L [m]	λ_U $[mm]$	P #	L [m]
1	80	20	1.600	62	56	3.472
2	62	26	1.612	50	69	3.450
Final				50	162	8.100

the lengths of the modulator und radiator as well as the strength of the dispersion section has to be adjusted. The modulator has to be long enough to imprint the necessary energy modulation according to the equation 1. The strength of the dispersion has to be adjusted according to the energy modulation with respect to the total dispersion given in equation 3. The radiator length has to be chosen suitable to deliver the required power for the next stage. Note, that the effective energy spread generated in the modulator determines the efficient of the radiator according to equation 4. The main parameter of the modulators and radiators for each HGHG-line are listed in tables 2, 3 and 4. Listed are undulator period length, λ_u, number of periods, P, and undulator length, L.

Magnetic delayers shift the electron bunch with respect to the radiation field between the HGHG stages and ensure that the radiation field interacts always with a undistrubed part of the bunch in the modulator. Quadrupoles and phase shifters are planned between the stages as well as between the undulator segments of the radiators and the final amplifier to focus and match the electron beam.

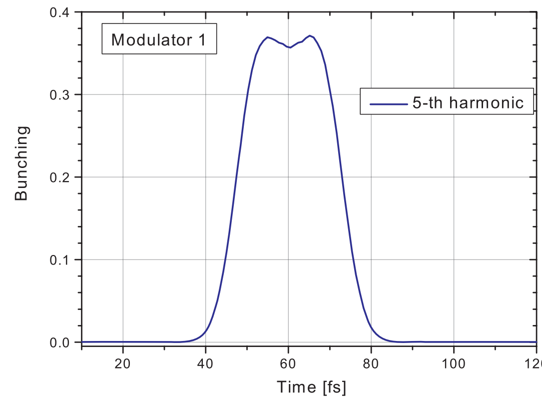

Figure 4: Bunching on the fifth harmonic after the first dispersion section for the high energy HGHG

POWER AND SPECTRUM OPTIMIZATION

For the optimization of the HGHG-FEL performance, the adjustment of the bunching, by setting the modulator length and the dispersion strength, is of major importance. The laser seed interacts with electrons at the rear of the bunch. Due to the slippage effect only a part of the interacting electrons experience the full power of the Gaussian shaped seed. Optimizing the modulator length and dispersive section to a somewhat reduced power level the output of the following radiator can be maximised. In this case the electrons at the center, which experience the full power sufficiently long are somewhat overbunched.

Figure 4 shows the bunching after the first dispersion section for the high energy HGHG. The overbunching causes a power dip in the radiation pulse provided by the first radiator, as shown in figure 5a. Figure 5b shows the corresponding radiation spectrum. The overbunched electrons fulfill synchrotron oscillations in the ponderomotive bucket. The resulting modulation of the emitted radiation frequency causes the side spikes (sidebands) [9].

The more electrons are overbunched the stronger is the growth of the sidebands. This effect is repeated in the following stages, where the slippage shifts the sidebands to one side. In this way the number of sidebands in the spectrum adds up from stage to stage. The higher the harmonic numbers in the cascade the stronger are the sidebands. For example in the case of the medium-energy HGHG-FEL the sidebands for $\lambda_s = 2.07\,nm$ with harmonic numbers $5{\times}5{\times}5$, figure 7, are much stronger than for $\lambda_s = 12.4\,nm$ with harmonic numbers $3 \times 3 \times 3$, see figure 6.

The side spikes can be avoided by optimizing the stages for the seed peak power. In this case the output of the following radiator is reduced. The bunching is of more Gaussian shape. The resulting radiation power and pulse length are reduced compared to the overbunched case. An example of such a spectrum purity optimized case is shown in

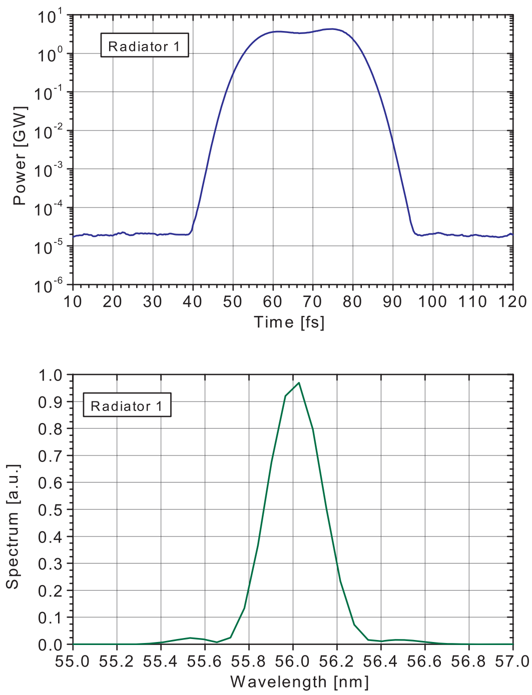

Figure 5: Simulation results for the first radiator of the high-energy HGHG-FEL a)the time resolved power distribution (top) and b) the spectral power distribution (bottom).

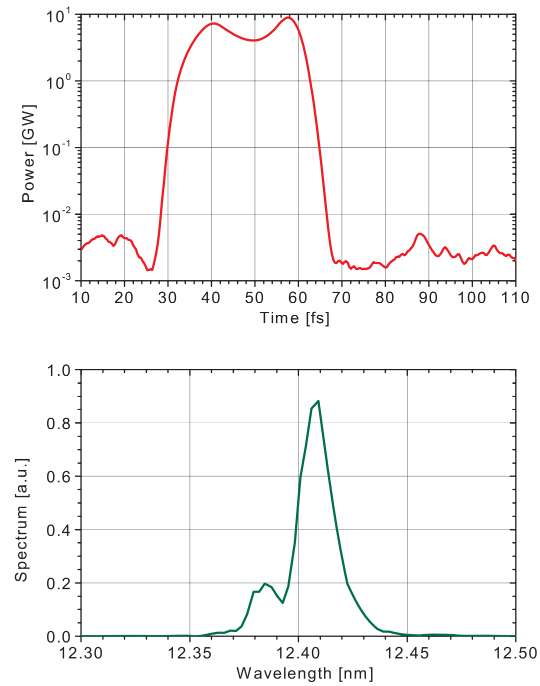

Figure 6: Simulation results for the medium-energy HGHG-FEL, $\lambda_s = 12.4\,nm$ the time resolved power distribution (top) and the spectral power distribution (bottom) are calculated.

figure 8, where the power and spectral distribution of a purity optimized and a power optimized case are displayed in the same graph for comparison.

The details of the cascades for the boundary wavelengths of each HGHG-line are summarised in [1].

PERFORMANCE CALCULATIONS

For the performance calculations the seeding radiation properties and electron beam parameters are chosen according to the considerations of the previous sections.

In order to obtain reliable results, the slippage effects in the undulators and the radiation diffraction in the fresh bunch sections have to be taken into account. The first effect lengthens the pulse, whereas the second one reduces the power density on axis which is relevant for the energy modulation in the following modulator. The time-dependent mode of GENESIS [3] used for the simulation allows an adequate treatment of this effects.

In spite of the short lengths of the modulators and radiators, see Tables 2-4, the degradation of the unseeded part of the bunch due to the emission of incoherent radiation can not be neglected. The resulting increase of the energy spread and decrease in the central energy from stage to stage are shown in figure 9 for the high-energy case.

The relative increase of the energy spread at the entrance of the second modulator is only 0.2%, but it increases to

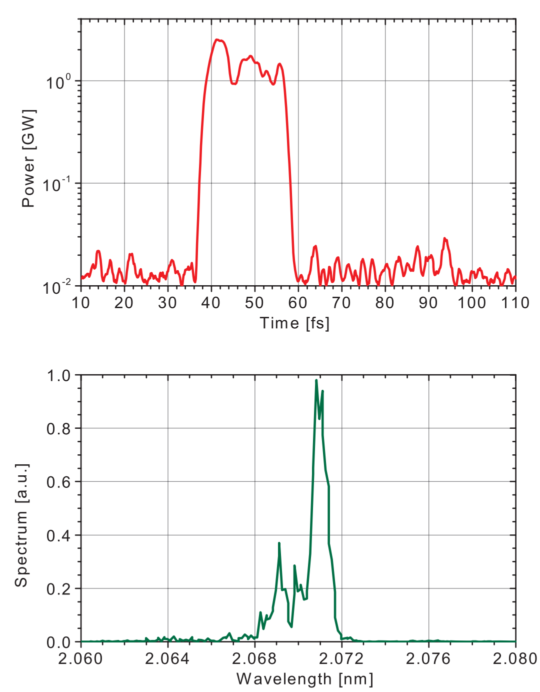

Figure 7: Simulation results for the medium-energy HGHG-FEL, $\lambda_s = 2.07\,nm$ the time resolved power distribution (top) and the spectral power distribution (bottom) are calculated.

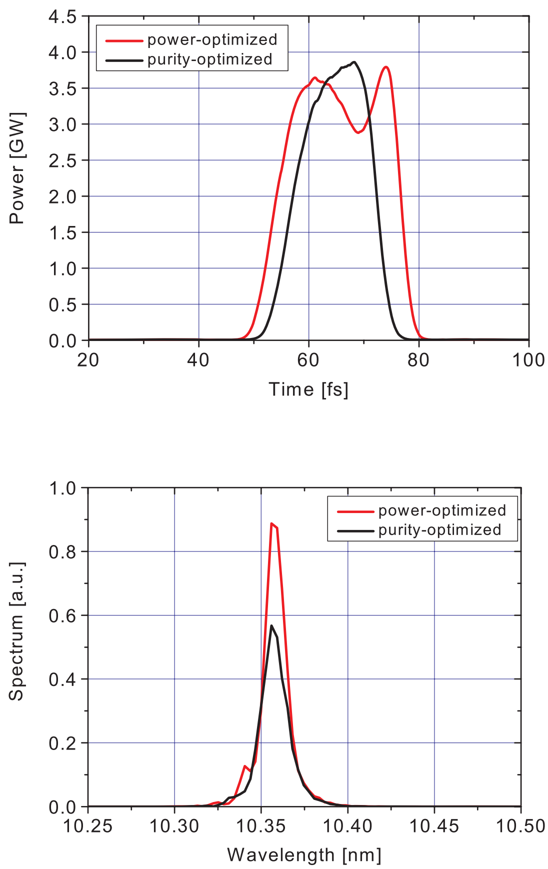

Figure 8: Simulation results for the low-energy HGHG-FEL, the power and spectral distributions of a purity-optimized case and a power-optimized case.

Table 5: The performance of the three HGHG-line for the boundary wavelengths

	LE-FEL		*ME-FEL*		*HE-FEL*	
λ $[nm]$	10.33	51.00	12.40	2.07	2.48	1.24
$Power$ $[GW]$	3.5	14.0	9.0	1.5	1.3	1.5

4% at the fourth modulator. The loss in the central energy at the entrance of the fourth modulator is about 0.45% which is larger than the bandwidth of about 0.2% of the fourth radiator and the final amplifier. This means that the following radiator and amplifier have to be readjusted to meet the resonance condition for the lower central energy.

This loss of the electron beam quality causes a reduction in the maximum bunching and a deterioration of the spectral properties of the radiation. Tracking the electrons through all the previous undulators, this effect has been taken into account. The performance of the three HGHG-lines for the boundary wavelengths are summarised in the Table 5.

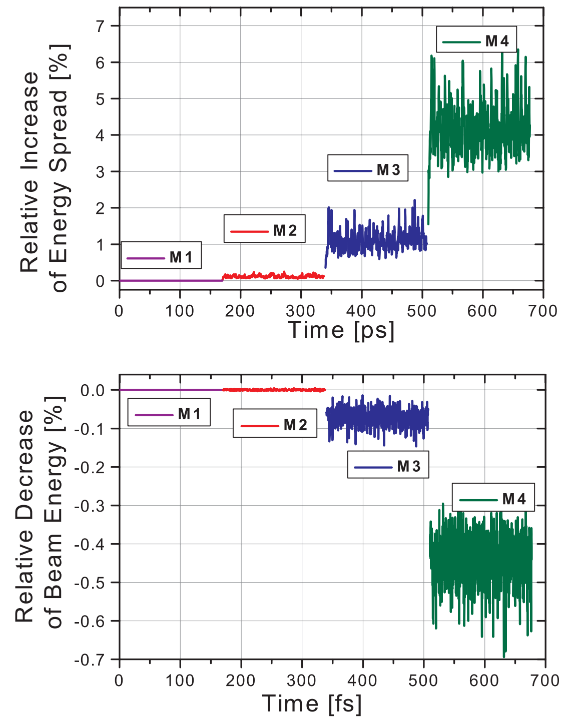

Figure 9: Degradation of the unseeded part of the bunch for the high-energy HGHG-FEL, the relative changes in energy spread (top) and the central energy (bottom) at the entrace of modulators, M1 to M4, are shown.

S2E BUNCHS AND SELF-STABILIZING

Start-to-end simulations for the BESSY FEL show variation of the electron beam parameter along the bunch [10]. The possibility to adjust the undulator gaps and the strengths of the dispersive sections independently, mitigates the effects of the parameter variations [11]. Each stage can be optimized according to the particular parameters of the interacting part.

Furthermore, the concept of the final amplifier allows to use the asymmetry of the detuning curve to reduce the output degradation due to the combination of the energy chirp and the arrival-time jitter of the bunch [12]. The energy chirp, induced for the bunch compression, combined with the arrival-time jitter, due to gun and LINAC errors, causes a mismatch between the central energy of the interacting part of the bunch and the resonance energy. This leads to a fluctuation of the FEL output power. Adjusting the final amplifier to a somewhat reduced K-value, stabilizes the output power, as the average energy of the interacting electrons is somewhat higher then the resonance energy.

CONCLUSION

BESSY has been designing a seeded FEL based on a cascaded high-gain harmonic-generation concept. Simulations with start-to-end bunchs including all relavant effects show that the BESSY FEL meets the user requirements with respect to pulse duration, tunability, spectral purity and power. Furthermore, simulation studies including errors in the gun and LINAC attest to the advantages of the HGHG concept planned for the BESSY FEL.

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