IMPACT STUDIES OF BUNCH PARAMETER VARIATIONS ON THE PERFORMANCE OF THE BESSY HGHG FEL*

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Abstract

In the recent past interest has grown in FEL designs offering alternatives to the SASE principle. BESSY proposed a High Gain Harmonic Generation (HGHG) soft X-ray FEL, composed of three independent FEL-lines utilising 2 to 4 HGHG stages. Modulators and radiators in such a scheme are kept short, to stay away from the exponential regime of the FEL process and only the final amplifier (FA) reaches saturation. Therefore, the mechanisms of how the electron beam properties generated by the gun and the linac influence the radiation output differ from what is known in SASE devices. Shot to shot variations and the influence of realistic bunch profiles are considered, as well as requirements arising from the use of the fresh bunch technique.

INTRODUCTION

BESSY recently presented the technical design report for a linac-based soft X-ray FEL, designed as a multi-user facility [1]. Three independent beamlines are planed and will supply photons in the spectral range from $0.02\,keV \leq \hbar\omega \leq 1\,keV$. The FEL is designed as a High Gain Harmonic Generation (HGHG) structure, to avoid the known restrictions of a SASE device and in lack of high-power short-wavelength seeding lasers that could be used for seeding at the desired wavelength. As in every beam based radiation source, the achieved bunch parameters, such as energy, energy spread, emittances, current, and the like, determine the radiation quality. Different to storage rings, not only deviations from design parameters have to be investigated. Due to jitter, mainly in the gun, but also in the linac, bunch properties will vary shot to shot. In addition, as the fresh bunch technique is applied, the longitudinal profile of the bunch is of major importance. In an HGHG cascade, only the final amplifier takes the FEL process to saturation, whereas all other undulators stay in the linear regime. Consequently, the mechanisms of how varying bunch parameters influence the final performance differ strongly from those in the SASE case. Performance improvements in one stage might be lost in the following stage, while minor bunching or less seed power might still lead to adequat output one stage later. The paper will cover different aspects of bunch parameter deviations. All calculations are performed for the two stage low energy FEL line, using the time-dependent computer code GENESIS [2]. Even in this comparatively short set up (the other lines cover three and four stages) the computational efforts are considerable.

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DEVIATION FROM CONSTANT BUNCH PARAMETERS

In the design of the BESSY FEL it was assumed, that the bunch parameters do not vary along the bunch. The design values of the bunch parameters are listed in Table 1.

Table 1: Nominal bunch parameters.

bunch parameter	design value	
energy spread	2.0×10^{-4}	
emittance$_{x,y}$	1.5×10^{-6}	m rad
peak current	2.1	kA
gamma (low energy)	1996.09	
beam size$_{x,y}$	$< 1.0 \times 10^{-4}$	m

When the energy spread, the emittance or the current of the bunch differ from their design values at the end of the linac, it is not possible to retune the FEL in order to improve its performance. These cases will be discussed first. In case of an offset in the central electron energy, it is possible to change the gap of the undulators and restore the design output. Deviations in the central energy will be treated in the next paragraph. Beam sizes and trajectory offsets can be corrected using the optics in front of the FEL and between the HGHG stages, and will not be considered. After a short reminder of how these parameters determine the HGHG process, the effect of their deviations from the design values will be discussed.

Energy spread: The energy spread of the bunch at the end of the linac, σ_γ, is modified during the passage through the undulators due to spontaneous emission of synchrotron radiation. Furthermore, an additional energy modulation is introduced to the bunch by the interaction with the seeding field. For harmonic generation, the imprinted modulation depth $\Delta\gamma$, has to fulfill $\Delta\gamma \geq n\sigma_\gamma$, with n the harmonic number sought in the modulator. Therefore, the larger the energy spread the weaker the bunching on the seeding frequency after the dispersive section. In the radiators, a smaller energy spread supports the amplification process as more particles fulfill the resonance condition.

Emittance: When the transverse emittances, $\varepsilon_{x,y}$, are reduced, the radiation power is concentrated on axis, and the amplification process in the radiators is enhanced. Additionally, the energy spread induced to the bunch during the passage through the undulator is linked to the transverse emittances, as longitudinal energy is tranfered to the transverse velocities. This effect depends on ε_n/λ_s, where ε_n is the normalised emittance and λ_s is the resonant wavelength, i.e. its importance grows with every stage, resp. wavelength reduction.

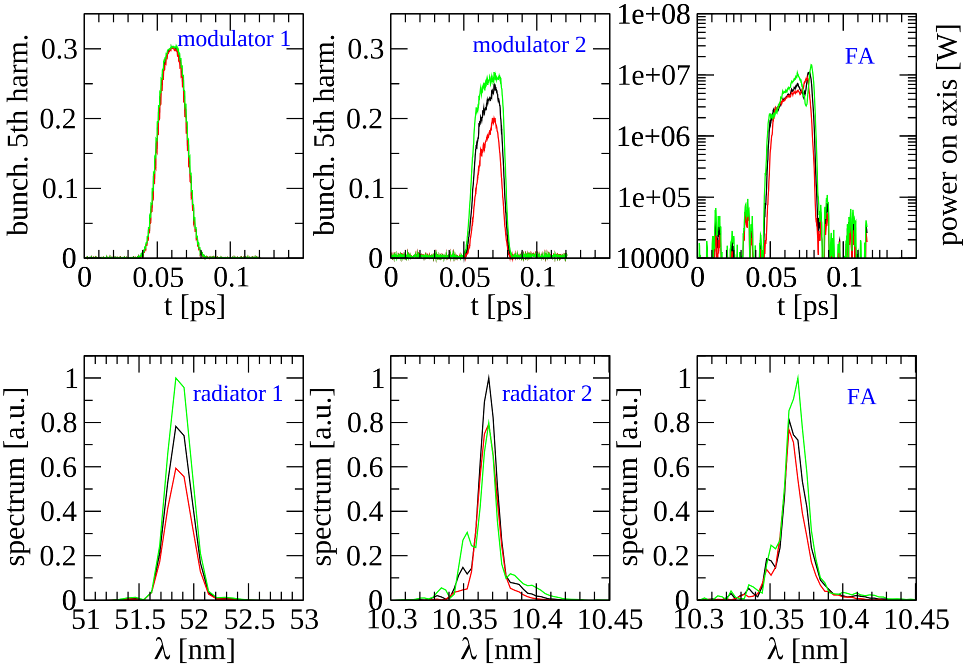

Figure 1: Development of the bunching in the modulators and the spectral power of the radiators and the FA, when the average bunch current is altered by $\pm 10\%$.

Current: The higher the bunch current, the higher is the radiation power emitted by the bunch even far away from exponential gain. The bunching in the modulators is slightly enhanced by the additional radiation. The dominant effect of current changes shows in the radiators, where a higher bunch current directly leads to an increased spectral power.

Fig. 1 shows the development of the bunching in the modulators, and the spectral power of the radiators and the final amplifier for the 2 stage low energy FEL line. The three curves depict the reference case with the design current (black) and two cases with a reduced (green) and a enhanced bunch current (red). A 10% deviation in the bunch current hardly influences the bunching rate created in the first modulator (upper left), but leads to a 30% increase in spectral power emitted by radiator 1 (lower left). The bunching rate produced in the second modulator (center top) reflects the different seed powers of radiator 1. In the case of the higher seeding power, though, the particles are already overbunched, as can be detected from the reduced flat top of the green curve. This overbunching leads to the rise of side maxima and a reduction of the peak power in the spectrum of radiator 2 (center bottom). The peak power in the case of the reduced bunching is similiar, and both lie 20% below the design current. In the final amplifier (right bottom), the reduced current case still reaches the reference spectral power by saturating at a later point in the undulator. The higher current case shows an increase of the spectral peak power by 20% due to the extra current.

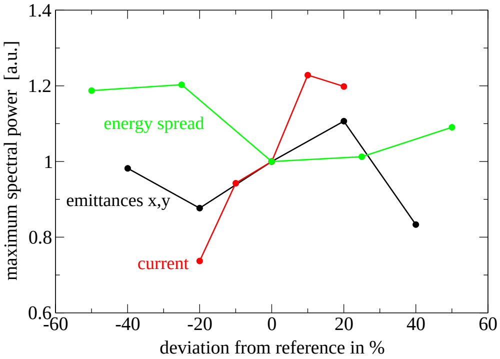

Figure 2: Peak spectral power as a function of bunch parameter offsets in percent.

Fig. 2 shows relatice changes in the peak spectral power at the end of the final amplifier as a function of offsets in the bunch parameters in percent. Clearly, the output power depends strongest on the bunch current. This differs from the SASE experience, where f.e. the emittance has a stronger influence on the power. When the bunch current increases, overbunching limits the performance.

Changes in the energy spread can be large according to start-to-end simulations. The energy spread plays a mayor role in the modulators, in the interaction between the seed radiation and the bunch. The output of the radiators corresponds to the bunching rates created in the previous modulators. While the spectra of radiator 2 still reflect the changing energy spread, the output of the FA increases slightly for deviating σ_γ. The overall change in spectral power is small.

It should be pointed out, that for the design values the saturation point of the final amplifier was chosen well inside the device, leaving space for fluctuations of whatever kind. As a result, a slower amplification process, due to minor parameters might still saturate at a later point, and even at higher power than the reference. An excess of power, due to advantageous bunch parameters might get lost, when the amplification process saturates too early, and overbunching sets in. As the final amplifier consists of 3 undulators only, opening gaps will be too crude to compensate this effect. In a sense this is a stabilising mechanism that reduces the output fluctuations.

In the case of small emittance changes, the results are dominated by the point of saturation in the FA rather then by the emittance value. For growing emittances the expected power reduction sets in. For smaller emittances, overbunching dominates the positive effects, the reduction in spectral peak power is below 20% for $\pm 40\%$ emittance changes.

SHOT TO SHOT VARIATIONS

Jitter in the gun and linac parameters will lead to unavoidable shot to shot variations in the parameters of the bunches reaching the FEL. Start-to-end tolerance simulations [3] predict typical shot to shot rms deviations for the emittance of $0.14 mm\, mrad$, for the energy spread of 0.8×10^{-4} for the low energy FEL line and for the current of $\leq 200\,A$. The studies presented in the previous paragraph cover $\geq 2\sigma$ of the expected variations, so the expected fluctuations in the FA output seem to be tolerable, as long as single error sources are concidered.

Effects leading to shot to shot variations in the transverse size and position of the bunches have not yet been studied.

Whereas constant offsets in the central bunch energy, γ can be counteracted by adjusting the undulator gaps, shot to shot variations of γ could well be problematic, as the resonant wavelength will be shifted, or worse, particles might run out of the resonance condition, and the FEL process might not get started. Start-to-end simulation show, that the expected gamma variations depend on the position inside the bunch and are largest at the head and the tail of the bunch, where rms values of up to 6×10^{-4} can be reached. The resonance condition predicts shifts of the resonant wavelength of

$$\frac{\Delta\lambda}{\lambda} = -2\,\frac{\Delta\gamma}{\gamma} \qquad (1)$$

Fig. 3 shows spectra of the final amplifier of the low energy FEL line, for bunches with the design γ (black) and with central energies shifted by $\pm 1 \times 10^{-3}$ and $\pm 2 \times 10^{-3}$ (solid and dashed lines). As expected, the central wavelength is clearly shifted, but it is shifted by only 6×10^{-4}, about $1/4$ of the expected value. The reason is, that, as long as the seed laser wavelength stays within the bandwidth of the modulator, the energy modulation on the seeding frequency will be enhanced and the following radiator is seeded with the respective harmonics. During the passage through the radiator the central frequency of the spectrum slowly drifts from the harmonics of the seeding frequency towards the resonant wavelength of the radiator. The shorter the radiator, the smaller the wavelength shift. Also in this respect, the HGHG setup is more relaxed than a SASE device. The effects of jitters in the seeding wavelength, though, yet have to be investigated, as well as the influence of shot to shot variations in the beam sizes and trajectories.

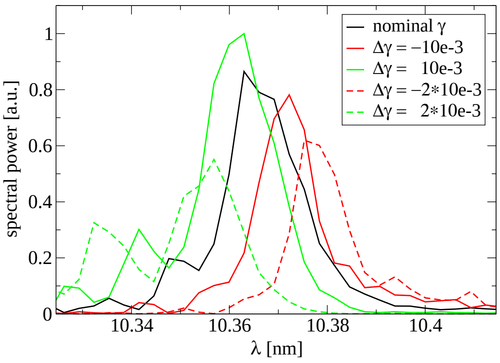

Figure 3: Spectra of the final amplifier for bunches with offsets in the central energy of $\pm 1 \times 10^{-3}$ (solid line) and $\pm 2 \times 10^{-3}$ (dashed line).

REALISTIC BUNCH PROFILE

In order to study the effects of a realistic bunch profile, a bunch with $1.4\,ps$ total length, extracted from start-to-end simulations [3] has been tracked through the low energy FEL line. In such a bunch, all parameters vary slice to slice, f.e. there is an energy chirp needed for the bunch compression and the current distribution approaches a flat top profile. As only small parts of the bunch are used in each HGHG stage, the bunch has been cut into twelve $120\,fs$ long pieces for the simulations. This corresponds roughly to the spacing sought for the fresh bunch technique. As the properties of the seeded part of the bunch spoil during the passage through a HGHG stage, the seeding radiation for the next stage has to be shifted to a fresh, unperturbed part of the bunch. In the two stage HGHG-FEL, f.e., three consecutive parts of the bunch are used. The averaged properties of each of the twelve bunch parts are depicted in Fig. 4. While the central energies (top) vary around the design value (line), the design current of $2100 A$ is only approached by the central four bunch parts (center). The emittances and the energy spread stay well below the design values (bottom). The beam size is twice the design value horizontally, and the first three parts have a considerable horizontal offset (not shown).

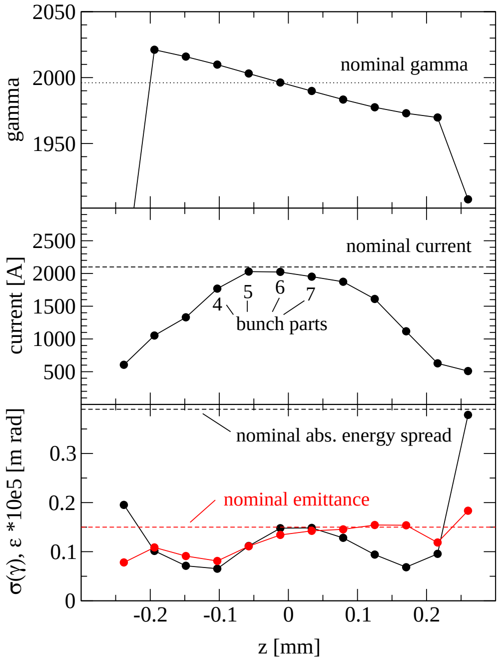

Figure 4: Bunch properties deduced from start-to-end simulations. Above: gamma, center: current, below: absolut energy spread (black) and emittance (red).

In an first attempt, these bunch parts have been tracked through the first HGHG stage, without any readjustment. Fig. 5 shows the resulting spectra of the first radiator. Clearly, the frequency shift due to the energy slope in the bunch is detectable. As above, Eq. 1 is not fulfilled. The achieved peak power basically reflects the current distribution. Part 5 radiates best, but still the peak power is only 60% of the design value, since the resonance condition is not met anymore.

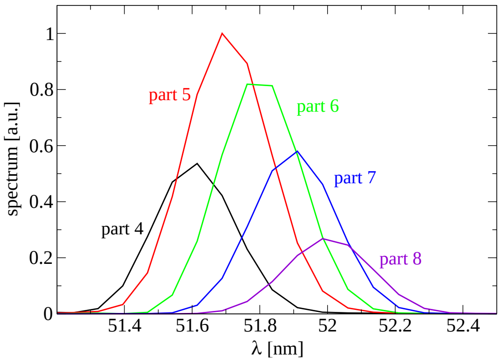

Figure 5: The power spectra of different bunch parts are dominated by the respective current and gamma.

In a second step, the K parameters of the modulators and radiators have been adjusted, each stage to the gamma of the bunch part that is actually used. Although the averaged bunch parameters of part 5 are close to, and better than the design values, it reaches only 80% of the required power in radiator 1. For part 4, the nominal values are reached. Both parts have a $50\mu m$ horizontal offset that has not been compensated. The even smaller emittance of part 4 apparently over compensates the lack of current and the trajectory mismatch.

Although the radiation generated by part 4 is comparable to the reference case, only 80% of the bunching is achieved, when it is used to seed part 5 in the second modulator. In radiator 2, the power rises only slowly for part 5, and finally reaches 1/3 of the expected value. In addition, the central wavelength of the spectrum is shifted by 1×10^{-3} to lower frequencies. This shift is caused by the energy ramp of the bunch, despite the adjustment of the undulators. Due to the ramp, the dispersion sections following the modulators not only transform the energy modulation into bunching, but, in addition compress the bunch, and thus shift the impressed wavelength to lower values. The optimisation of the second stage under these circumstances requires further investigations.

CONCLUSION

The effects of deviant bunch parameters have been studied for the BESSY low energy FEL line. Due to certain 'self stabilizing' effects of HGHG structures, offsets in the averaged bunch parameters are tolerable in the order of magnitude, that is expected from start-to-end simulations. Reductions in the bunching factor or spectral power that occure in the early HGHG stages are at least partly compensated in the final amplifier, by a shifted saturation point. When the early stages function too well, overbunching will limit the final output. First studies using bunches extracted from start-to-end simulations were presented. Unexpected effects like a shift in the resonant wavelength caused by the dispersive sections in combination with the energy chirp of the bunch have to be included in further optimization procedures. Due to the fresh bunch technique, the bunch parameters vary for every HGHG stage, making the analysis of performance limitations and the definition of acceptable parameter tolerances extremely difficult. In further studies the three and four stage FEL lines will be investigated.

REFERENCES

[1] The BESSY Soft X-ray Free Electron Laser, Technical Design Report, March 2004, eds.: D. Krämer, E. Jaeschke, W. Eberhardt, ISBN 3-9809534-0-8, BESSY, BERLIN (2004)

[2] GENESIS 1.3: A Full 3D Time Dependent FEL Simulation Code, S. Reiche, Nuclear Instruments and Methods A429 (1999) p. 243

[3] Start-to-End Injector and Linac Tolerance Studies for the BESSY FEL, M. Abo-Bakr, M. v. Hartrott, J. Knobloch, B. Kuske, A. Meseck, BESSY, Berlin, Germany, this proc.