

# IMPACT OF REALISTIC BUNCH PROFILES AND TIMING JITTER ON THE OUTPUT OF THE BESSY LOW ENERGY FEL LINE\*

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## Abstract

In present FEL designs, the undulators are often optimised for an electron bunch with properties constant along the length of the bunch. The mean energy, emittance and other parameters are assumed not to vary from slice to slice. This paper investigates the impact of more realistic bunch properties, extracted from start-to-end simulations of the BESSY FEL [1]. The energy chirp needed for the bunch compression, and the impact of the passed structure imprint typical parameter profiles on the bunch at the end of the linac. Especially in high gain harmonic generation (HG) structures, that use consecutive parts of a long electron bunch, each stage must be adjusted to the expected bunch parameters. Due to this individual adjustment, synchronisation between the bunch and the seeding radiation becomes an issue. Even assuming an on-time seed laser pulse, the changing properties along the bunch in combination with jitter in its arrival time cause varying conditions for the interaction of the electron bunch with the seed laser radiation for every shot. This paper investigates the impact of the expected timing jitter and the realistic bunch profile on the BESSY low energy FEL at  $\lambda = 10\text{nm}$  and outlines counter measures.

## INTRODUCTION

A growing number of proposals for FEL projects consider to use HG structures in order to exploit the advantages that arise from seeding the FEL process, at wavelengths much shorter than what can be provided today by adequate seed lasers, [2]. When the desired wavelength exceeds the usable harmonics of the laser radiation, cascaded structures are considered to further reduce the wavelength. These projects require up to ps-long electron bunches, as the energy spread of a seeded bunch part necessarily increases, and the consecutive unseeded parts of the bunch have to be used in the following stages of the conversion process to shorter wavelength. These long bunches usually exhibit parameter profiles at the end of the linac that are far from being constant. Bunch compression leads to a residual energy chirp, the current only approaches a flat top profile and all other parameters vary along the bunch. As the layout of the HG stages depend on the bunch properties, an adjustment to the results of start-to-end calculation is necessary: The part of the bunch where the seeding laser is supposed to interact with the electrons has to be determined (seeding point) and the following HG stages

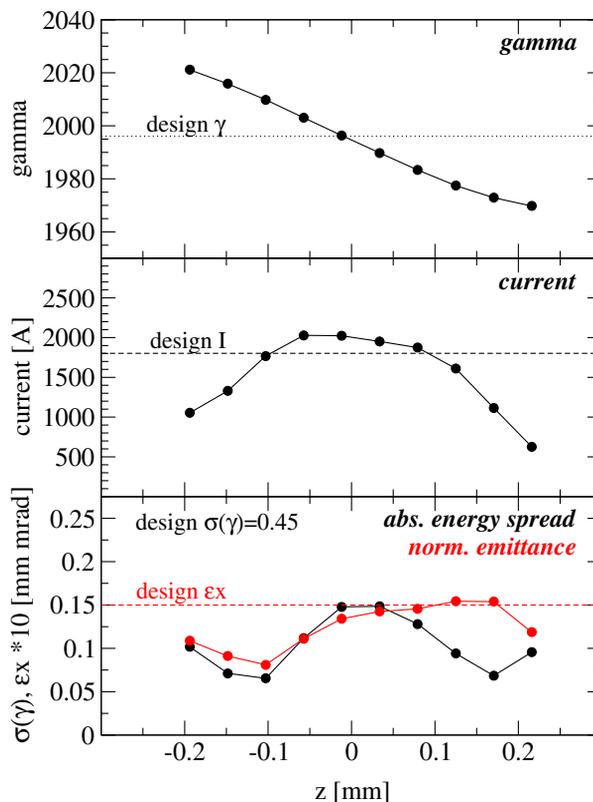


Figure 1: Typical parameter profiles of bunches at the beginning of the two stage low energy FEL line.

have to be adjusted to the properties of the specific bunch part that will be used in this stage. Consequently, deviations from the nominal seeding point, i.e. the effects of different arriving times, have to be investigated.

## BUNCH PROFILE

Start-to-end simulations for the injector of the BESSY FEL have been presented in [3]. Although these studies have been performed to define tolerances for typical injector errors, they revealed essential information for the undulator part of the FEL. They show that independent of the chosen error combination, all bunches show the same typical profile in the main bunch parameters at the end of the linac, Fig. 1. The design parameters used for the original layout of the cascades are indicated in the plot by dashed lines.

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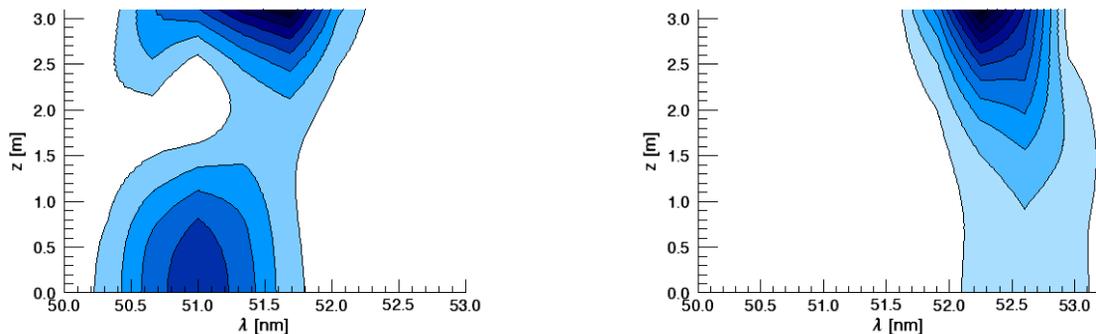


Figure 2: Development of spectra in a modulator. The radiation wavelength corresponds to the wavelength on which the bunching occurs. Despite the different seeding wavelength the final bunching approaches the resonant wavelength of the modulator.

**Energy:** The energy chirp is imprinted on the bunch intentionally, as it is needed for the bunch compression. Due to the necessary final extension of the bunch of some hundreds of fs and to avoid a too large slice energy spread, bunch compressors for HGHG structures do not fully compress the bunch so that a residual energy chirp remains, determined by the desired final bunch length. Five 30 fs long bunch parts are necessary for the four stage high energy FEL line. They are separated by 70 fs and a 125 fs safety margin is added towards the ends of the current flat top region, to cope with timing jitter. The final bunch length is close to 1 ps, the flat top region in the current profile is 750 fs. The average gamma of the bunch parts rises by roughly 0.2% per stage for the low energy line and tuning becomes essential to fulfill the resonance condition. All BESSY FEL undulators will be variable gap undulators. By driving the gaps of the undulators the K-value fitting to the average bunch energy can be chosen. Adjusting the LE FEL line to the expected energy chirp caused variations of less than 1% in the K-value of the undulators compared to the original design.

**Energy Spread:** The energy spread is of special importance in the modulators, as the energy modulation imprinted by the seed must be larger than the energy spread of the beam. In the dispersive section following the modulators, the energy modulation is transformed into spacial bunching. Deviations in energy spread will lead to differences in the depth of the energy modulation. The strength of the dispersion dipoles can be used to optimise the bunching and avoid over bunching. BESSY FEL simulations show a variation of over 50% for the energy spread along the bunch. The average value turned out to be a factor of three smaller in the start-to-end simulations than anticipated as the original design value. The presented calculations were performed with this small energy spread. It has been checked, that also for a larger energy spread the LE FEL line could be adapted. Too small an energy spread starts the SASE process in the unseeded parts of the bunch due to spontaneous synchrotron radiation in long radiators. This has been observed in simulations of the BESSY

medium energy FEL line. Fe., a superconducting wiggler could be installed to increase the energy spread, if necessary. This would also reduce coherent synchrotron radiation (CSR) and longitudinal space charge effects.

**Current:** The seeding power achieved in the radiators depends on the peak current of the active bunch part. Lower current will lead to reduced seeding power and minor bunching in the following modulator. By adjusting the dispersive sections, this can be counteracted to some degree. Over bunching due to increased current can be compensated by reducing the dipole strength.

**Emittance and Beam Dimensions:** The emittance can not be altered in the FEL lines. In combination with the beam optics it determines the transverse beam sizes. Especially for shorter wavelengths it is critical to control the beam size and to guarantee a good overlap between the radiation and the beam. A quadrupole doublet is foreseen after each radiator, to adjust the beam sizes along the FEL lines. When the beam size varies strongly along the bunch, the optics in front of each stage are set to optimise the beam size of the bunch part being used. In the final amplifiers one quadrupole is planned between each module. The necessary adjustment of the optics to the varying beam sizes can be large and requires the use of bipolar power supplies.

The low and medium energy FEL line have been adjusted to the more realistic bunch properties resulting from start-to-end calculations and the achieved output is comparable to the output sought in the original design, proving the flexibility of cascaded HGHG structures.

## STABILISING EFFECTS IN HGHG STRUCTURES

The FEL process in a HGHG structure is started by the co-propagation of the seeding radiation field and the bunch in the first modulator. The seeding wavelength  $\lambda_s$ , the particle energy  $\gamma$  and the K-value of the undulator are linked via the resonance condition

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}(1 + K^2) \quad (1)$$

where  $\lambda_U$  is the undulator period length. In a SASE device,  $K$ ,  $\lambda_U$  and  $\gamma$  determine the resonant wavelength  $\lambda_s$ . In a seeded device,  $\lambda_s$  is fixed by the seeding radiation, and the electrons will absorb or emit energy to match the resonance condition. This process is visualised in Fig. 2, where the development of the spectrum in a seeded modulator is shown for two different seeding wavelengths. Due to the energy modulation, the electrons start to emit coherently at the wavelength of their modulation. Thus, the spectrum shows the wavelength on which the energy modulation, i.e. bunching takes place. In the left plot, the modulator is seeded at 51 nm, somewhat shorter than the resonant wavelength of 51.8 nm. At the beginning, clearly the seeding wavelength at 51 nm dominates, but no amplification occurs. The seeding power diminishes as the electrons absorb energy from the seeding field. The further the process propagates through the modulator, the influence of the seed weakens and the modified beam energy leads to radiation at 51.5 nm. In the right graph, the seeding wavelength is 52.6 nm and longer than the resonant wavelength. The electrons emit energy and the seeding radiation field gets enhanced from the beginning. With the reduced energy the resonant wavelength drifts towards lower values. In both cases the final bunching takes place at wavelengths closer to the desired resonant value than suggested by the seed. The same process occurs when the seeding wavelength is at the design value, but the bunches have different average energies. Bunches with energies above or below the design value will emit and absorb energy of the seeding field and thereby approach the design value. Simulations show [4], that the wavelength shift of the spectrum of the BESSY low energy FEL line due to a mismatch of the central electron energy is roughly 25% of the value deduced from the resonance condition.

## EFFECTS OF ARRIVAL TIME JITTER

According to the assumptions of the start-to-end investigations, the electron bunch arrives with a timing jitter of 75 fs rms. Taking an additional jitter of the seed laser into account, an acceptable performance of the FEL for a total jitter of  $\approx 100$  fs is demanded. Due to the jitter, the seeding radiation will interact with a different part of the electron bunch with every shot. As the HGHG stages are optimised for the parameters of the 'on time' part of the bunch, the optimisation will not match for different arrival times and a degradation in the performance is expected. In order to study this effect in detail, three bunch parts required for a full passage through the two stage FEL line have been cut out of the bunches delivered by start-to-end simulations at the end of the linac. The cuts were then shifted for simulations corresponding to arrival times of multiples of 20fs. Each bunch part is 100 fs long, so that there is a large overlap between the bunches of consecutive simulations. Positive timing offsets correspond to early arrivals, in this case the seed laser will interact with a bunch part with a larger energy, see Fig.1. All calculations have been performed

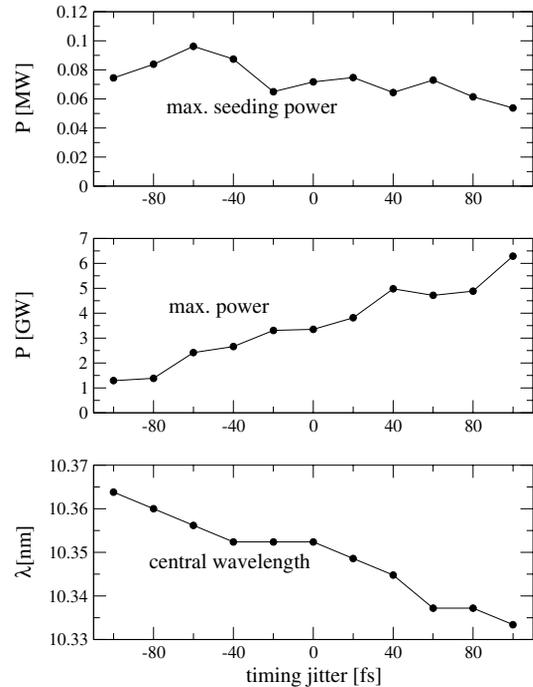


Figure 3: Maximal seeding power (top), max. output power (centre) and central wavelength (bottom) of the final amplifier, as a function of the arrival time offsets of the bunch.

with the FEL code GENESIS 1.3 [5]. For a detailed description of the simulation techniques, see [6].

Fig. 3 shows the seeding power, peak power and the central wavelength yielded by the final amplifier of the two stage, low energy line of the BESSY FEL for the simulated timing offsets. The shift in the resonant wavelength (bottom) simply reflects the changing central energy of the electrons interacting with the seed. The shift is only  $\approx 25\%$  of the value expected from

$$\Delta\lambda/\lambda = -2\Delta\gamma/\gamma. \quad (2)$$

This is due to the stabilising mechanism of HGHG structures. The top graph depicts the maximal power with which the final amplifier has been seeded. It is slightly lower for positive arrival times. On the contrary, the output power (centre), rises almost linearly with positive arrival times. It is almost twice as large for a bunch arriving 100 fs early. This surprising result is a feature of the seeding process, and is linked to the energy exchange between seeding field and electron bunch as explained above. The higher the electron energy, the more the seeding field and consequently the bunching is boosted, and the output power rises as long as the bandwidth of the undulator is not exceeded. Fig. 4 shows the energy, bunching and power development of a single slice at a specific position in an early (bottom row) and a late bunch (top row) in the final amplifier. The slice with the reduced  $\gamma$ -value absorbs energy of the radiation field during the first 5 m in the final amplifier.

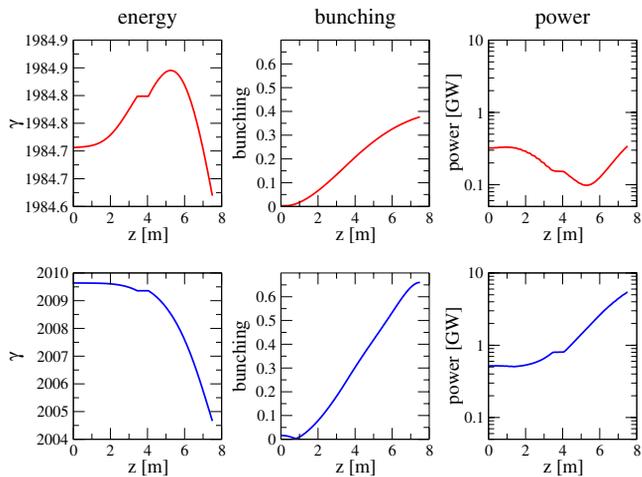


Figure 4: The development of average energy (left), bunching (centre) and power (right) of a specific slice of a late bunch (top) and an early bunch (bottom) as a function of the location in the final amplifier. The energy absorption/emission is clearly visible. The bunching rates achieved for the two cases differ by almost a factor of 2. The power reached at the end of the amplifier is 20 times higher in the case of the early arrival.

Bunching develops only slowly. The power curve shows the absorption of the seeding power by the electrons. Amplification due to the FEL process only starts at the end of the final amplifier. The slice with the higher  $\gamma$ -value emits energy from the beginning on. Bunching increases rapidly, and so does the power. The slow rise of the power in the first 2-3 m of the undulator is attributed to the mismatch between seeding wavelength and electron energy.

## OUTPUT STABILISATION

The fact that an energy higher than the resonant energy leads to a surplus in radiation power can be used to stabilise the final amplifier output. By opening the gap of the undulators slightly, the K-value is reduced as well as the  $\gamma$ -value resonant to the seeding wavelength. The K-value can be chosen such, that most bunches have an average energy exceeding the resonant energy. The results for a K-value reduction of 0.4% is plotted in Fig. 5 for arrival time offsets up to 120 fs. The variation in maximal power within 100 fs has been cut to half. The maximal spectral power is stable within less than 50%.

## CONCLUSION

It has been demonstrated, that cascaded HGHG devices are very flexible structures, that can be adopted to realistic bunch profiles. The variable gap of the undulators, the dispersive sections behind the modulators and the focussing structure provided for other reasons, can be used to adjust the stages to the specific bunch parameters available at the

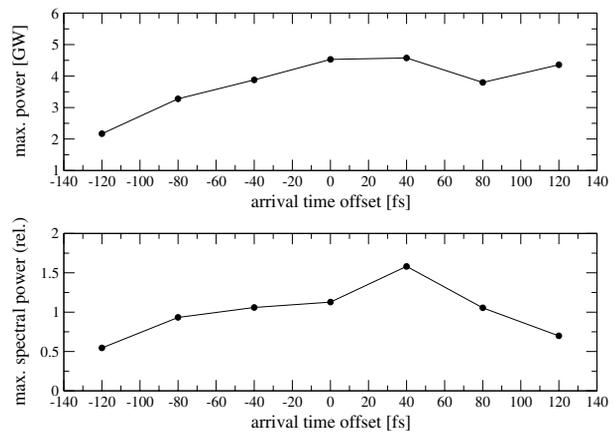


Figure 5: The power (top) and the spectral power (bottom) of the final amplifier can be stabilised with respect to timing offsets by reducing the K-value of the final amplifier.

end of the linac. Due to the repeated seeding process in the cascades, HGHG structures have a smoothing effect on variations in the bunch energy and seeding wavelength. It has been shown, that arrival time offsets lead to variations in the output power, that can be stabilised by tuning the K-value of the final amplifier. The remaining power fluctuation are correlated with the size of the arrival time jitter.

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