START-TO-END SIMULATIONS FOR THE BESSY LOW AND MEDIUM ENERGY FEL LINE INCLUDING ERRORS *

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Abstract

Contrary to storage rings, where the electron bunch properties are damped to equilibrium values, every bunch in a linac driven single pass free electron laser (FEL) will show a characteristic profile from its passage through the injector and the linac. Based on the output of ASTRA and ELEGANT tracking studies, GENESIS calculations have been performed for the BESSY FEL undulators. The effect of timing and charge errors caused by the photo cathode laser, and phase and amplitude errors of the RF fields in the injector and the linac on the FEL radiation were studied. The resulting bunch parameter fluctuations determine the shot-to-shot performance of the FEL. The shot-to-shot parameter variations due to these errors are smaller than or comparable to their variation over the bunch length. The parameter variation along the bunches is imprinted by the typical electron distribution at the end of the gun and the impact of the passed structures. It is independent of the errors. The shot-to-shot variations resulting from the assumed error sources in the FEL output are discussed.

INTRODUCTION

BESSY proposes an FEL project, based on a superconducting CW linac and a cascaded high gain harmonic generation (HGHG) layout for the undulators [1]. Three independent FEL lines are foreseen to cover the spectral range of 51 nm to 1.24 nm. Start-to-end simulations for the normal conducting gun and the 2.3 GeV superconducting linac have been presented, [2]. These studies are extended to the low and medium energy FEL lines, i.e. the bunches extracted at the end of the linac are tracked through the two and three stage HGHG cascades, respectively. At the end of the linac, the bunches show typical parameter profiles, that result from the transverse phase space distributions at the exit of the gun, the energy chirp imprinted for bunch compression, chromatic and coherent synchrotron radiation (CSR) effects in the bunch compressors, and the wake fields in the linac, Fig. 1. The impact of these parameter profiles on the layout of the BESSY FEL is discussed in detail in [3]. Every stage has to be tuned to the properties of the bunch part expected to be used. In HGHG structures, the FEL process is started by the co-propagation of a seeding radiation field with the electron bunch in the first undulator. Due to the adjustment of the stages to a specific part of the bunch, the synchronisation between the seeding field and the electron bunch becomes an issue. Actually, the parameter variation along the undisturbed bunch (no errors) mostly exceeds the fluctuation due to errors within the range of the timing jitter expected from the start-to-end simulations.

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GENERAL LAYOUT

In the photo injector, a long 40 ps FWHM bunch with a charge of 2.5 nC is generated. A 220 m long superconducting CW linac accelerates the bunch to 2.3 GeV. By means of two magnetic bunch compression stages at energies of 220 MeV and 750 MeV this bunch is compressed to about 1 ps FWHM with a flat top of 700 fs and a peak current of 1.8 kA. A fast kicker extracts the bunches at 1.02 GeV for the low energy FEL line, covering the wavelength range from 51 nm to 10.3 nm. At 2.3 GeV the bunches are distributed between the medium and the high energy FEL lines, serving the range of 12.4 nm to 2 nm and from 2.5 nm to 1.2 nm respectively. The undulator section of the BESSY FEL consists of variable gap pure permanent magnet undulators. The last radiators and final amplifiers will be variable polarisation devices. The modules are 1.6 to 3.6 m long. Modulators consist of a single module only, while the radiators are composed of 1to 3 modules. The final amplifiers consist of up to 5 modules. The dispersive sections as well as the fresh bunch chicanes are build up of four identical dipoles and are roughly 2 m long. The Ti:Sa seeding laser will be tunable between 230 and 460 nm and will deliver 20-30 fs pulses with a 1 kHz repetition rate.

SIMULATION TECHNIQUES AND LINAC RESULTS

For the simulation of the electron bunch 25.000 macro particles were tracked through the injector using the ASTRA program [4]. The linac was modelled using ELEGANT [5]. Here the number of tracked particles was raised to 100.000. In detailed start-to-end simulations, the effects of errors in injector and linac were investigated to determine the tolerances. Additionally, they delivered valuable information on the impact of those errors on the bunch quality at the entrance of the undulators. Tab. 1 lists the rms error values applied in these studies.

100 bunches were tracked through the injector and linac with randomly distributed errors. The rms values of the relevant bunch parameters that result at the end of the linac are listed in the second column of Tab. 2. The first column lists the corresponding design values. The energy, the slice emittance and the slice energy spread are averaged over the whole bunch for each simulation. The spread in the mean energy and emittance over 100 runs is negligible. The av-

Table 1: Cathode laser, injector and linac tolerances used in the start-to-end simulations

cathode laser	jitter bunch charge (rel.)	0.25 ps $1 \cdot 10^{-2}$
injector gun	phase amplitude (rel.)	0.2 deg $2 \cdot 10^{-3}$
linac cavity	phase amplitude (rel.)	0.1 deg $3 \cdot 10^{-3}$

erage energy spread varies up to 20 %. For the slice current the rms value was taken over the simulated slices. It varies as a function of the longitudinal position in the bunch. The deviation of the peak current from the design value is up to 8% and large for slices located at the centre of the bunch. Note, that the applied errors lead to a considerable jitter of 75 fs rms in the arrival time of the bunches. Due to this jitter, the seeding radiation will hit most of the bunches not at the nominal, but at a position shifted by up to 75 fs, approximately half the distance between two consecutive bunch parts in Fig. 1. Due to the parameter variations along the bunch, the timing jitter leads to a change in the parameters of the part of the bunch actually interacting with the seeding radiation.

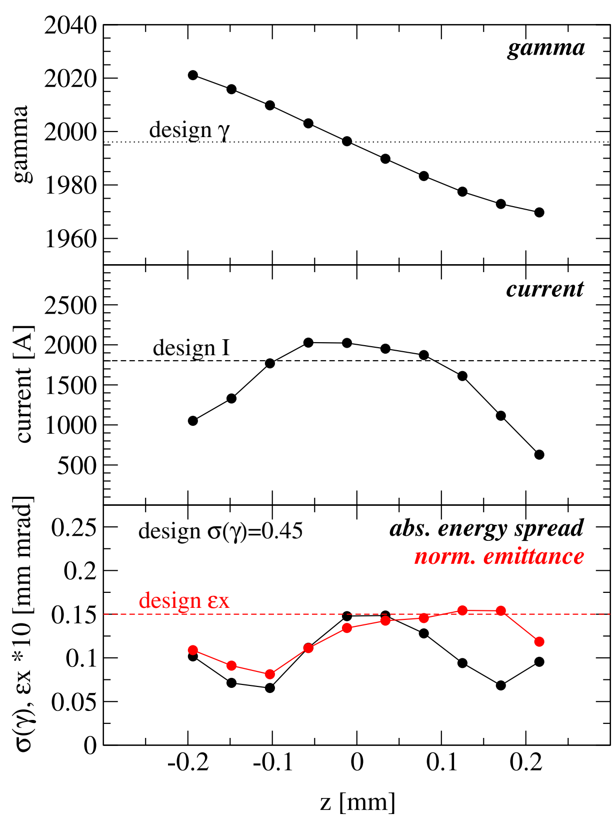

Figure 1: Parameter profile of the bunch at the beginning of the low energy FEL line, when no errors are applied. The profiles are similar for the ME-FEL at $\gamma = 4500$.

The parameter changes for an undisturbed bunch (no errors applied) that has an timing offset with respect to the seed laser of 75 fs are collected in the third column in Tab. 2. The change in central energy exceeds the deviation due to errors by a factor of ten. The shift is over 0.1% for the medium energy FEL line, and almost 0.25% for the low energy FEL line at $\Delta t = 75$ fs. The change in the emittance is twice the deviation due to errors, while the energy spread is hardly effected, even for the low energy case. The current varies up to 6%, the same order of magnitude expected due to errors.

It has to be expected that the dominant effect of the errors anticipated for the cathode laser, injector and linac will be the resulting arrival time jitter rather than the bunch parameter variations.

Table 2: Bunch parameter variations at the end of the linac extracted from start-to-end simulations. The design values, the rms values of 100 simulations and the variations expected for an undisturbed bunch shifted by 75 fs are listed

	design value	rms value	variation per 75 fs
bunch energy (MeV)	2300/1020	0.25	2.5
sliced norm. emittance (mm mrad)	1.5	0.07	0.14
sliced rel. energy spread 2300/1020 MeV	$1 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$2/6 \cdot 10^{-6}$
slice current (A)*	1800	40-150	100
timing offset (fs)	0	75	-
* rms values per slice along the bunch			

ELEGANT-TO-GENESIS [6] was used to convert the phase space data produced by ELEGANT into averaged slice information for GENESIS, which in turn produces populated slices with the corresponding average properties. During this transfer, the information about the arrival time of the bunches is not conserved. To overcome this problem, not the complete bunch at the end of the linac was transfered to GENESIS. A nominal arrival time was fixed, where the bunches were cut off. Three or four 100 fs long consecutive bunch sections, for the low and medium energy FEL line respectively, were then conveyed to GENESIS input. The seeded as well as the unseeded parts of the bunch were tracked through the cascades, to take effects of spontaneous radiation into account. The seed is assumed to be a Gaussian pulse with a peak power of 500 MW. Drift sections were taken into account, and the dispersive sections were modelled by using transfer matrices.

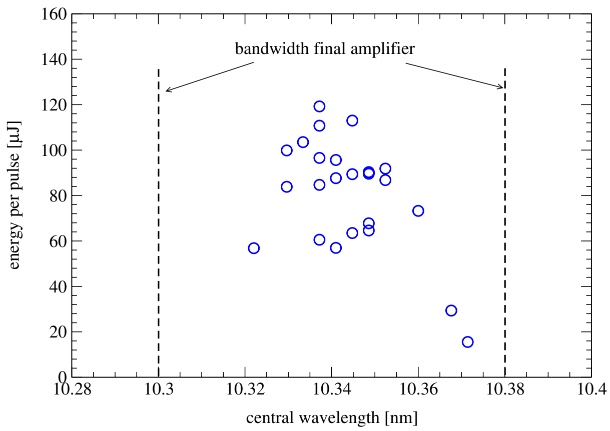

Figure 2: Energy per pulse as a function of the central wavelength delivered by the final amplifier in the low energy FEL line for 24 error simulations.

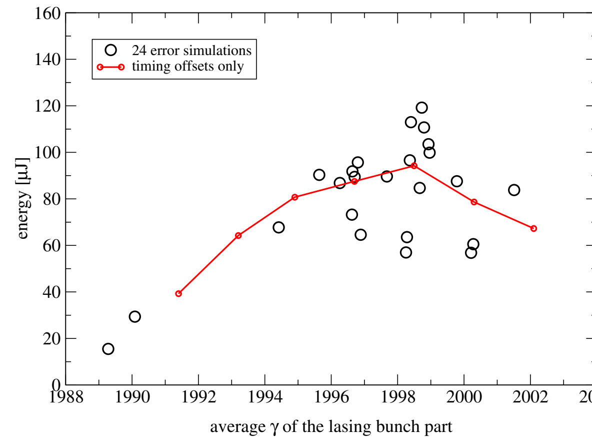

Figure 3: Pulse energy as a function of the averaged γ of the radiating bunch part in the final amplifier for 24 bunches. γ is proportional to the arrival time.

RESULTS

Low Energy FEL Line

Due to the immense CPU time required for one passage even through the two stage FEL line, only a set of 24 arbitrarily chosen bunches were investigated so far. The results are presented in Fig. 2. It depicts the energy per pulse delivered by the final amplifier as a function of the central wavelength of the spectrum. The figure also marks the bandwidth of the final amplifier of $4 \cdot 10^{-3}$. There is a certain spread in the central wavelength, due to the errors, but it covers only approximately half of the bandwidth. This is different to a SASE device, where due to the stochastic process the central wavelength of the spectra will eventually cover the whole bandwidth, even without errors. In two cases, the central wavelength exceeds 10.365 nm. These are bunches with an extraordinarily large shift of the central energy of almost 0.4 %. Disregarding these two exceptions, the average energy is 86 μJ per pulse and the rms-deviation is 18 μJ, roughly 20 %. The rms spread in the central wavelength is 0.0086 nm or 0.08%.

It has been mentioned before, that the deviation in the bunch parameters due to timing offsets are of the order of magnitude or even larger than the variation due to errors. Therefore it is interesting to look for correlations between the arrival time and the output fluctuations. Due to the almost linear energy chirp on the bunch, the arrival time is proportional to the mean energy of the bunch parts radiating in the final amplifier. The red line in Fig. 3 represents the energy per pulse for simulations without errors, but an arrival time offsets of up to 120 fs as a function of the mean energy of the bunch part radiating. The black circles represent the 24 simulations with errors. Although the statistics are poor, the graph indicates a correlation between the pulse energy and arrival time for larger timing jitter. For small timing offsets the fluctuations due to errors dominate. In Fig. 4 the red curve again represents the results yielded by the undisturbed bunch with offsets in the arrival time. The central wavelength of the pulses is plotted, again as a function of the mean energy of the relevant bunch part. Here the effect of the errors is less pronounced and clearly a reduction in the timing jitter would immediately translate into a reduction of the jitter in the central wavelength. Note that the resulting spread in the wavelength is much smaller than one would expect from the resonance condition, which predicts a quadratic dependence of the resonant wavelength on the bunch energy. This is due to the stabilising effect of seeded HGHG structures as discussed in [3].

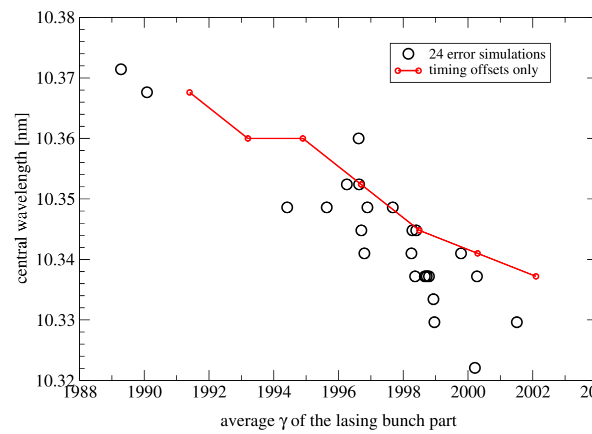

Figure 4: Central wavelength as a function of the averaged γ. A reduction in the arrival time jitter would reduce the spread in the wavelengths.

Medium Energy FEL Line

The medium energy FEL line, consisting of three stages, is being investigated in the same manner as the low energy line. Two new phenomena have been encountered so far:

1) The relative energy spread calculated by start-to-end

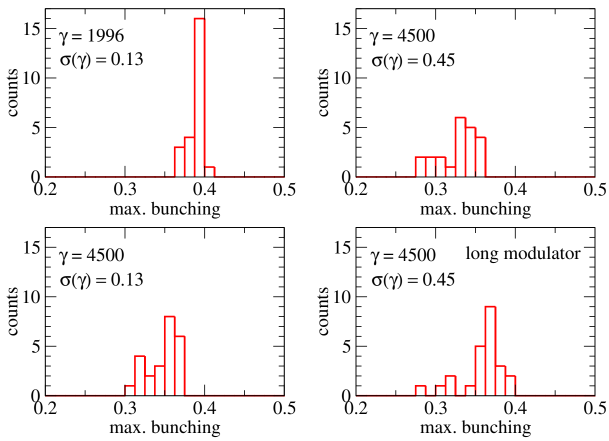

Figure 5: Histograms of the maximal bunching yielded after the first modulator and dispersive section: Top left: Low energy FEL line. Top right: Medium energy line (ME), high energy spread. Bottom left: ME, low energy spread. Bottom right: ME, high energy spread, but long modulator.

simulations is of the order $3 \cdot 10^{-5}$. The design value has been set to $1 \cdot 10^{-4}$, to cope with CSR and longitudinal space charge effects. When the bunches extracted from the start-to-end simulation were tracked through the structure, bunching started to build up in the unseeded, fresh parts of the bunch on the level of the energy modulation that is supposed to be imprinted by the seed. The radiators in the medium energy FEL line are much longer than in the low energy line, so that spontaneous synchrotron radiation in combination with the unexpectedly small energy spread started the SASE process. While it is possible to optimise the structure for the smaller energy spread, a laser heater is planned to be integrated in order to be able to control the energy spread, so that the simulations were repeated for a manually increased energy spread in the order of the design value.

2) Although the undesired bunching disappeared for the increased energy spread, a large spread in the resulting intensity of the output occurred. Already after the first modulator and dispersive section, the spread in the achieved bunching exceeded that of the low energy line, see Fig. 5, upper row. The seeding pulse is assumed to be identical. The length and K value of the first modulator in the medium energy line have roughly been doubled to fit to the higher energy. Still the bunching achieved at the end of the first modulator is less than in the low energy line. This has been compensated by rising the strength of the dispersive section. It turns out, though, that a longer interaction between the seed and the bunches reduces the error sensitivity. In Fig. 5, bottom right, the results are depicted for a longer modulator. Most cases reach bunching factors between 35 and 40%. The graph bottom left depicts the case of the smaller energy spread and the short modulator. The influence of the energy spread is small. Work on the three stage FEL line is being continued.

CONCLUSION

Complete start-to-end simulations were performed for the two stage low energy line, and are in progress for the three stage medium energy line of the BESSY FEL project. After adjusting the layout of the HGHG cascades to the parameter profiles of the bunches extracted from start-to-end simulations, satisfactory results were achieved for the low energy FEL line. The shot-to-shot fluctuations in central wavelength can be improved by reducing the time jitter of the bunches with respect to the seeding radiation. The spread in the energy per pulse results from the error distributions and is 20% rms. The work on the medium energy FEL line shows the importance of being able to control the energy spread of the beam in order to avoid unwanted bunching of the unseeded parts of the bunch. The length of the modulators plays an important role for the spread of the achieved bunching in error simulations. Start-to-end simulations are of fundamental importance in the design of cascaded HGHG FELs, as the layout of the stages depends strongly on the expected bunch properties.

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] "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, FEL2004, proc.

[3] "Impact of Realistic Bunch Profiles and Timing Jitter on the Output of the BESSY Low Energy FEL Line", B. Kuske, M. Abo-Bakr, A. Meseck, BESSY, Berlin, Germany, FEL2005, this proc.

[4] "ASTRA User's Manual", K. Flottmann, http://www.desy.de/mpyflo.

[5] "ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulation", M. Borland, Advanced Photon Source LS-287 (2000).

[6] ELEGANT-TO-GENESIS http://www.aps.anl.gov/ /asd/oag/manuals/SDDStoolkit/node32.html

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