# 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

*Abstract*

BESSY is proposing a soft X-ray FEL user facility in Berlin, delivering short and stable photon pulses in the wavelength range of 62 nm $\leq \lambda \leq$ 1.2 nm by utilizing up to four cascaded High Gain Harmonic Generation (HGHG) stages [1]. To optimize the FEL performance of the cascaded HGHG stages extensive Start-to-End (S2E) simulations have been carried out. To test the quality of the chosen configuration with respect to the sensitivity towards various error sources tolerance studies from the injector to the linac end have been performed. Procedures and results of these studies are presented.

## INTRODUCTION

Based on it's experiences in operating high brilliant synchrotron light sources the Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) is proposing a 2.3 GeV linac-based single-pass Free-Electron Laser (FEL) user-facility for the wavelength range from 62 nm $\leq \lambda \leq$ 1.2 nm. To generate very short photon pulses of $\leq$ 20 fs duration and to ensure stable radiation output a cascaded High Gain Harmonic Generation (HGHG) scheme has been designed. A detailed description of the BESSY FEL can be found in the recently completed Technical Design Report [1].

Due to the FEL process the quality of the seeded part of the electron bunch, mainly the energy spread, after one HGHG stage is significantly reduced and no longer suitable for further stages. For that reason the "fresh bunch technique" [2] is applied, providing a fresh part of the electron bunch to to all HGHG stages and the final amplifier. Taking timing jitter sources and synchronization limits into account, a flat top pulse of about 700 fs duration is required. In combination with the requested 1.8 kA peak current a total bunch charge of 2.5 nC will be needed.

To deliver such an electron beam to the FEL lines, a very long bunch of 40 ps FWHM duration is generated in the photo-injector. By means of two magnetic bunch compression stages at energies of 220 MeV and 750 MeV in combination with an energy-position correlation in the longitudinal phase space (chirp) the longitudinal bunch density and thus the peak current is increased to the requested values.

Aim of this studies was to verify that compression, timing and energy variations at the linac end due to the expected "shot-to-shot" errors stay within tolerable limits.

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† Michael.Abo-Bakr@bessy.de, Albert-Einstein-Strasse 15, 12489 Berlin, Germany

For that purpose, start-to-end simulations have been performed, beginning at the injector cathode and ending at the first HGHG undulator entrance.

## ERROR SOURCES AND THEIR EFFECTS

In the simulations, errors in the injector and linac part are investigated, that influence mainly the dynamics of the longitudinal phase space. Nevertheless, the horizontal emittance can also be affected due to the peak current dependency of wake field and CSR effects.

**Injector:** for the injector (rf gun and first, eight-cavity "booster" module), timing errors and intensity variations of the photo cathode laser are considered as well as phase and amplitude errors of the rf fields in the injector gun and the booster cavities.

For the main linac tolerance studies, phase and amplitude rf field errors are considered. No error correlation between neighbouring linac cavities is assumed. Vibrations and field strength variations of the magnets on a "shot-to-shot" time level haven't been considered as well as vibrations of the rf modules, which would cause the electron bunches to scan "off axis" transverse electric field components in the cavities. Mechanical vibrations of the cavities are considered within the microphonics simulations, incorporated into our assumptions on cavity phase and amplitude errors.

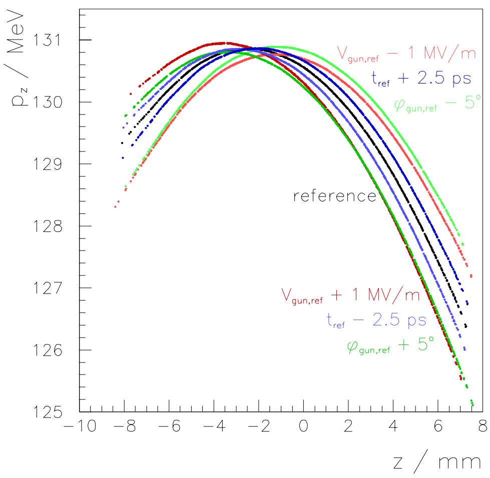


Figure 1: Single error simulations for the BESSY FEL injector: longitudinal phase space at the booster module end for $\pm$2.5 ps timing jitter (blue), $\pm$1 MV/m gun amplitude (red) and $\pm 5^\circ$ gun phase errors (green). The reference curve is also plotted (black).

At the end of the booster module, all injector errors result in a time and energy jitter of the bunch center with respect to the undisturbed bunch. In addition, the momentum position correlation (chirp) is changed, when the bunch passes the booster module with a time or, equivalently, a phase jitter. All injector error sources couple by "time of flight" effects in the non-relativistic part of the injector. Thus the resulting time, energy or chirp jitter at the injector end can not be easily associated to a single error source.

In Figure 1 longitudinal phase space distortions at the end of the booster module due to injector errors are shown. For demonstration exemplary single error types such as $\pm 2.5$ ps timing jitter, $\pm 1$ MV/m gun amplitude and $\pm 5°$ gun phase have been applied. In all cases the mean energy and z-position (for a fixed time of flight) changes as well as the momentum chirp. The effects of gun amplitude and phase errors dominate at the chosen error weighting, while the changes due to the timing jitter are small.

**Main linac:** the effect of injector errors on the final longitudinal phase space at the linac end are illustrated in Figure 2. Both a mean energy jitter and a time jitter of the bunch are investigated.

The main effect of an energy jitter from the injector is the transformation into a time jitter in the bunch compressors and thus at the linac end (upper graph of Figure 2). For an HGHG FEL with several "fresh bunch" stages this causes two problems: to ensure, that the seeding laser hits the electron bunch always in its flat top, high current part, the flat top length has to be increased at both ends by the expected time jitter. If the jitter exceeds the expectations, either the initial seed for the first HGHG stage or the last

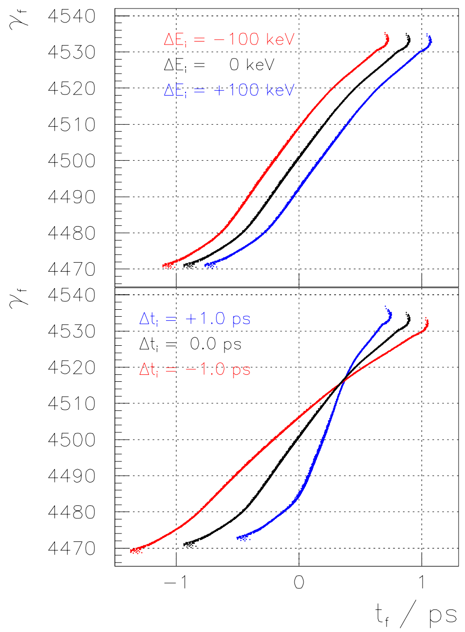


Figure 2: BESSY HGHG FEL: variations of the final longitudinal phase space (high energy beamline) due to energy (top) and timing (bottom) jitter from the injector.

seed for the final amplifier interacts with a lower current region on the bunch edges. In both cases the final radiation output might be significantly reduced.

A second problem is a variation of energy looking to a fixed longitudinal bunch position, just like the HGHG seeds do. It is caused by the the time jitter at the linac end in connection with the momentum chirp, which was required for the bunch compression. As every HGHG stage is optimized for a special energy this leads to a mismatch of the seeding and the insertion device resonant wavelength. The energy modulation and, later on, the bunching and the radiator output is reduced.

A time jitter from the injector not only leads to a time jitter at the linac end, with all the drawbacks just mentioned. It also strongly influences the bunch compression, by modifying the momentum chirp (lower graph in Figure 2), which can cause a significant output power degradation of a cascaded HGHG FEL.

To little compression results in a lower peak current with a longer flat top. The smaller peak current reduces the radiator output of the first HGHG stage, which acts as seed for the second one. Clearly the reduced seed power produces less momentum modulation in the second modulator. Thus the output power of the second radiator is not only reduced by the lower peak current but also by the smaller bunching.

Too much compression leads to a higher peak current with a shorter flat top. If the flat top becomes too short, again either the first or the last seed hits the edges of the flat top with less peak current. Even if this is not the case, too high peak currents can be disadvantageous: the increased output of the first radiator produces a stronger momentum modulation in the second modulator. Of course the strength of the dispersive section, converting the momentum into a current density modulation, is fixed, and one will end up with an over-compressed bunch. This reduces the output of the second radiator, but is counteracted to a certain degree by the higher peak current.

Finally, also in the case of an injector time jitter the sliced energy varies, leading again to a mismatch of seeding and resonant wavelength, as already described above.

## TOLERANCE BUDGET

Assumptions on the error sizes arise from experiences, made with PITZ at DESY/Zeuthen, the FZ Rossendorf and the Max Born Institute (MBI) and result from RF control simulations.

Two cases have been investigated: "case 1" with errors as they are presently already reached in the mentioned laboratories and "case 2" with decreased errors, as they are assumed to be in reach within the next few years. Listed in Table 1 are the considered (rms) errors of the longitudinal "shot-to-shot" tolerance budget.

The limited synchronization between the photo-cathode laser and the rf system determines the timing jitter. A 500 fs rms-jitter can be assumed today, with future state-of-the-art systems this value could be further reduced by 50% or

| | | case 1 | case 2 |
|---|---|---|---|
| cath. laser | jitter / ps | 0.5 | 0.25 |
| | bunch charge (rel.) | $1\times10^{-2}$ | |
| injector gun | phase / ° | 1.0 | 0.2 |
| | amplitude (rel.) | $5\times10^{-3}$ | $2\times10^{-3}$ |
| linac cav. | phase / ° | 0.1 | |
| | amplitude (rel.) | $3\times10^{-4}$ | |

Table 1: BESSY FEL: longitudinal tolerance budget.

more. For the integrated laser intensity stability, defining bunch charge fluctuations, an rms error of 1% was recently measured at PITZ [3].

Phase and amplitude errors have also been adopted from measurements at PITZ. A $1°$ phase error and a $3\times10^{-3}$ relative amplitude error has been deduced [4], limited by the thermal stability of the normal conducting cavity. With an extended cooling scheme and a direct measurement of the rf amplitude and phase in the gun, allowing for fast rf feedback, a further reduction to the values used for “case 2” seems to be feasible.

Values of $1\times10^{-4}$ and $0.1°$ for the relative stability of the rf amplitude and for the phase errors of the superconducting linac cavities are based on measurements at Rossendorf [5] and on rf feedback simulations [6].

## SIMULATION TECHNIQUES

Two codes have been used for the tolerance studies: `ASTRA` [7] for the injector and `ELEGANT` [8] for the linac part. To get a sufficient statistics, 100 runs were performed for each of the two cases. With `ASTRA` 25000 macro-particles were tracked, taking space charge forces into account. The output particle distribution in the 6D phase space is converted to the `ELEGANT` input format. With `ELEGANT` the particle distributions were tracked under the influence of wake and CSR fields. To reduce noise in the longitudinal density distribution, the number of particles was raised to 100 000, keeping the characteristic bunch parameters unchanged.

## SIMULATION RESULTS

**Injector:** in Figure 3 histograms of the `ASTRA` injector simulation results at the injector end ($E$ = 130 MeV) are shown.

For “case 1” the arrival time jitter is about 1.2 ps while the energy variation is 85 keV (rms). Comparing the rms time jitter with the “single error case”, even stronger modifications of the bunch compression have to be expected as presented in Figure 2. Also for the energy variation, the rms value is close to the assumptions for the “single error case” example. Thus disturbances of the longitudinal phase space have to be expected in an order as shown in Figure 2, which would represent a severe distortion of the electron bunch parameters.

There is one effect, that will reduce the arrival time variations at the linac end: in contrast to the simple examples in Figure 2, the real time and energy variations from the injector are correlated. This correlation is produced by the off crest passage trough the booster module, adjusted to produce the bunch compression chirp. For that reason the time jitter is compressed just like the bunches them self. In the frame of the simple examples, shown in Figure 2, the final arrival time variations caused by injector time and energy jitter have opposite signs and will cancel partially.

For “case 2” arrival time and energy variations reduce significantly to about 0.4 ps and 30 keV, respectively (rms). In this case much smaller disturbances of bunch timing and shape are expected.

**Main linac:** the results of the `ELEGANT` linac simulations are shown in Figure 4. Histograms of the central bunch arrival time and energy are plotted in Figure 4a and 4b. Compared to the injector values, the time variations are strongly reduced due to the correlation of the injector jitter. No significant difference between the two error cases occurs for the arrival time variation, which indicates a nearly full compression of the correlated injector time jitter. In contrast the rms value of the energy variation is strongly reduced for the “case 2” scenario, compared to the “case 1” value.

In Figure 4c and 4d histograms of the distribution of the horizontal emittance and energy spread are shown. Both values are averaged over all slices, weighted by the slice current. The variation of the horizontal emittance is less than 20% and 10% for “case 1” and “case 2”, respectively. For the energy spread, there is no big difference between the two error scenarios, most of the bunches have values around $1\times10^{-4}$.

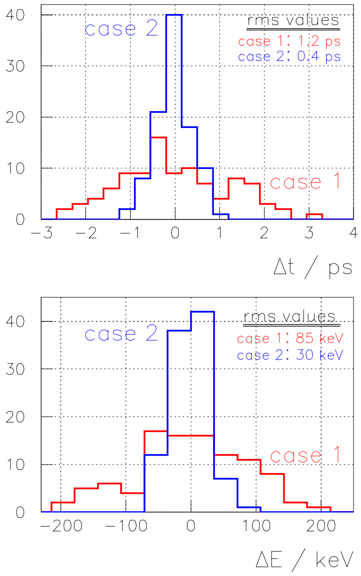


Figure 3: Injector simulation results: histograms of the central bunch arrival time (top) and energy (bottom) variation at the injector end (case 1: red, case 2: blue).

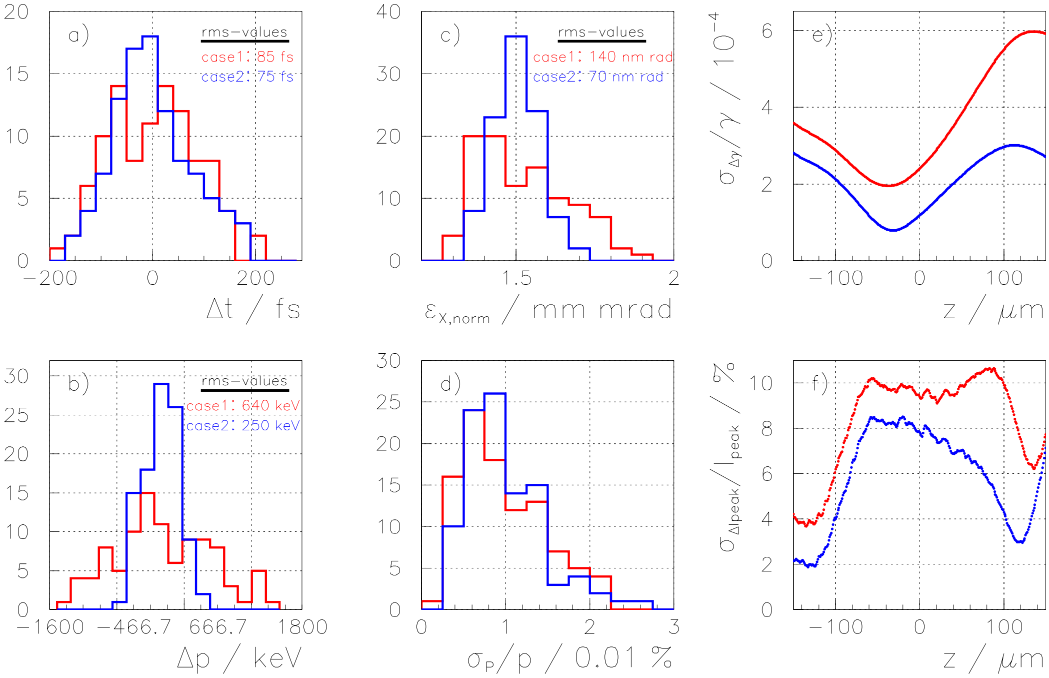

Figure 4: Linac simulation results: histograms of the variations of the central bunch arrival time (a), energy (b), the sliced horizontal emittance (c) and the sliced energy spread (d) at the linac end. The relative rms values of the momentum (e) and peak current (f) variations as function of the longitudinal position are drawn. (case 1: red, case 2: blue)

In Figure 4e and 4f the rms values for the sliced mean energy and peak current variations of all runs of each case are plotted versus the longitudinal position. This is of major importance for the HGHG process, as it describes the bunch parameter changes for every HGHG stage. The maximum energy variations occur in the head of the bunch and reach $6\times10^{-4}$ for "case 1" and $3\times10^{-4}$ for the second scenario. The momentum acceptance of the final amplifier of the most critical four stage HGHG is about $1\times10^{-3}$, which is about $2\sigma$ even with "case 1". The maximum peak current variations do not strongly differ for "case 1" and "case 2" and amount 11% and 8% respectively.

Simulations on the FEL radiation performance under the influence of single error sources (energy, current, emittance, energy spread) show relative output variations on the order of the assumed relative errors compared to the ideal case, but no drastic decrease [9].

## CONCLUSION

S2E simulations for the BESSY FEL injector and linac have been performed. Final distortions of the longitudinal phase space are dominated by error sources in the injector. Time and energy jitters at the injector end are transformed by the bunch compressors and yield tolerable values for both investigated error cases, where "case 2" with smaller error assumptions clearly delivers smaller final distortions.

A reliable proof of FEL power losses due to the estimated bunch distortions can only be done, using the simulated realistic bunches to perform S2E FEL simulations, where all variations of the sliced bunch parameters are taken into account.

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