DEVELOPMENT AND APPLICATION OF FIGURES OF MERIT TO EVALUATE THE OUTPUT OF HGHG FEL CASCADES*

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Abstract

In the design of Free Electron Lasers (FEL), parameters like the peak power and the spectral power were established as figures of merit to evaluate the FEL's output quality. However, spectra obtained with studies using bunches from start-to-end simulations including errors show that it is not sufficient to optimise these simple parameters. To establish a stable and reliable user facility, parameters like pulse reproducibility, stability of the source point or signal to background ratio have to be considered and optimised. This paper suggests different criteria and parameters to describe and compare the output of different FEL schemes with respect to a regular user operation. As these criteria are not readily available from common FEL codes a post processing IDL code has been written, that extracts the relevant information from a standard GENESIS output. The code is used to reevaluate start-to-end simulations for the BESSY low energy FEL [1].

INTRODUCTION

A growing number of proposals for FEL projects plan to use High Gain Harmonic Generation (HGHG) structures in order to exploit the advantages that arise from seeding the FEL process, at wavelengths much shorter than what is available today with conventional seed lasers [2]. As the efficiency in the generation of higher harmonics declines rapidly with the harmonic number, a multi step harmonic generation in cascaded structures can be used to extend the wavelength range of this concept down to a few nanometers. Cascaded structures require an overall bunch length of the electron beam in the order of some hundred femtoseconds, because for each stage an unspoiled part of the bunch must be used (fresh-bunch technique). These long bunches usually exhibit parameter profiles at the end of the linac that are far from being constant. For example, an energy chirp is needed for bunch compression, the current is not constant and the emittance and energy spread vary for different slices. As a result, the temporal and spectral power functions are not as smooth as known from theoretical studies. Fig. 1 shows the power spectra of three different simulations including errors of the BESSY low energy FEL. The spectra are not Gaussian anymore, and they vary considerably for each set of errors. Although the peak power varies by less than 20% the pulse energy differs significantly.

The result of start-to-end simulations including phase and amplitude errors in the gun and in the linac and charge and timing errors of the photo cathode laser, for the two stage low energy FEL line have been published in [3]. Those 24 cases are reevaluated in the current paper incorporating aspects that are relevant for the users of the FEL radiation.

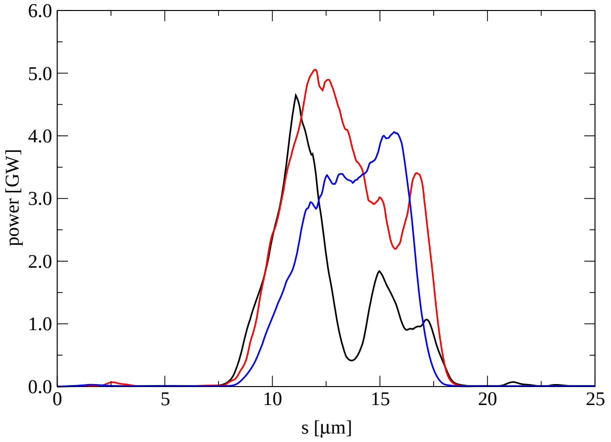

Figure 1: Power emitted by the final amplifier of the BESSY low energy FEL-line for three different sets of errors in the gun and the linac. The pulses are not Gaussian.

The BESSY soft X-ray FEL is designed as a user facility and hence the quality of the radiation will be judged at the position of the experiment. For the passage through the beam line, three radiation parameters are of major importance, namely the transverse and longitudinal position of the source point and its size. Vertical offsets give rise to energy fluctuations behind the monochromator. Horizontal offsets lead to intensity fluctuations behind horizontal slits. Both offsets should not exceed 20% of the radiation size. Variations in the size or the location of the source point degrade the energy resolution. Location fluctuations should not exceed one Rayleigh length. The signal to background ratio and the pulse energy within a selected bandwidth are further figures of great interest to the experimenters and beam line designers. Most of these criteria are indirectly supplied by FEL codes like GENESIS [5], but not easily accessible, especially when a larger number of runs are considered, as in tolerance studies. Therefore, a small evaluation program has been written using IDL [6] in combination with the original GENESIS output interpretation routines. The given figures of merit as well as the limits set for stability, result from discussions with the BESSY

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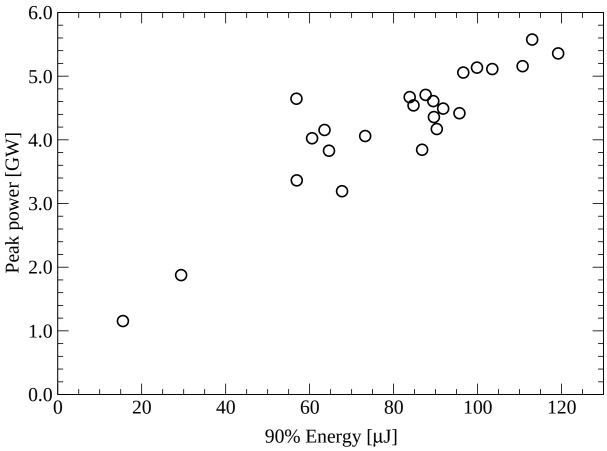

Figure 2: Peak power versus 90% energy for 24 pulses in the BESSY low energy FEL final amplifier. The spread in pulse energy can be considerable for similar peak power.

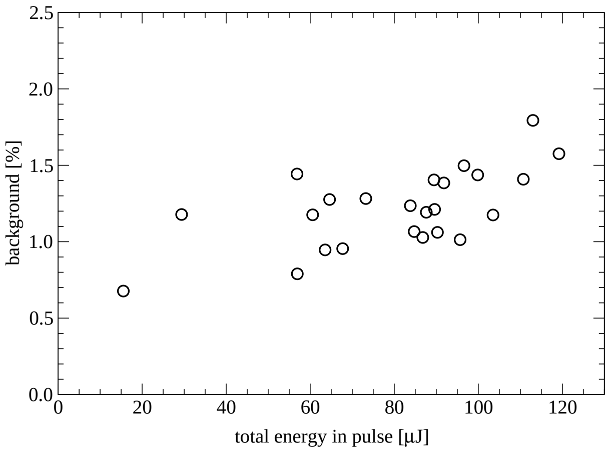

Figure 3: The background signal of the lasing part of the bunch in percent of the total pulse energy.

experimental group.

PULSE ENERGY AND BACKGROUND

In order to describe the FEL pulse, the FWHM of the pulse is determined as well as the width of the pulse at 10% of the peak power, called the 10%-width. For a Gaussian pulse, the ratio of the two is ≈ 1.8. 75% of the 24 investigated cases have a ratio around 1.2, indicating a pulse shape with steep flanks, only one case showed a wide profile with a ratio bigger than three.

The integral of the power inside the 10%-width is called the 90% pulse energy. Fig. 2 shows the peak power versus the 90% energy for the 24 runs. Especially around peak powers of 4 GW, where most pulses lie, the spread in pulse energy, which is the figure of interest for the experiment is considerable, due to the different pulse shapes. Therefore the peak power is not well suited as a figure of merit.

Any power outside the 10%-width is considered to be background. The signal to background ratio is important for the quality of the experiments. The background is computed in percent of the total pulse energy, see Fig. 3. It is below 2% in all cases.

It must be mentioned, that in order to reduce the computation time only short parts of the complete 700 fs bunch are simulated in the studies. The calculation of the background at this point includes power emitted outside the 10%-width of the 100 fs long bunch part tracked through the final amplifier. Contributions of the two parts seeded in upstream stages will approximately double the shown background, while the contribution of unseeded parts is negligible.

SOURCE POINT CHARACTERISATION

In seeded devices, the determination of the radiation size is not straightforward. At the beginning, the radiation is dominated by the seed. While the seeding radiation diverges, bunching builds up in the seeded part of the electron bunch and power is emitted, increasing exponentially. The radiation size calculated by FEL codes thus usually increases in the initial part of seeded FEL amplifiers due to the diverging seed and only later decreases due to the build up of coherent FEL radiation.

FEL codes usually calculate the radiation size for each slice of the bunch. For seeded devices though, averaging over all bunch slices will yield wrong results, as the radiation size at the location of the seed's interaction is much smaller than in the rest of the bunch, where the little power emitted is independent of the seeded process.

The radiation size and divergence of each slice provided by GENESIS has to be weighted with the power emitted by the slice. The result follows the behaviour described earlier. The radiation size has a maximum inside the final amplifier, where the divergence slightly decreases. In order to calculate the phase space volume, the radiation size and divergence at the end of the final amplifier are used. Note that from [7] it is known, that the beam waist, when calculated exactly by back tracking the radiation, lies a couple of meters upstream and is smaller than at the end of the device. Thus, the data plotted in Fig. 4 is an upper limit, and the phase space volume is expected to be up to 50% smaller. Still most points lie close to the line indicating twice the diffraction limit. As the waist location will jitter from shot to shot, this conservative estimate seems adequate.

SOURCE POINT STABILITY

Transverse Stability

As mentioned earlier, transverse jitter of the source point reduces the energy resolution of the beam line. It is desired to reduce the transverse fluctuations to less than 20% of the rms radiation size.

Rather than first locating the source point, and then com-

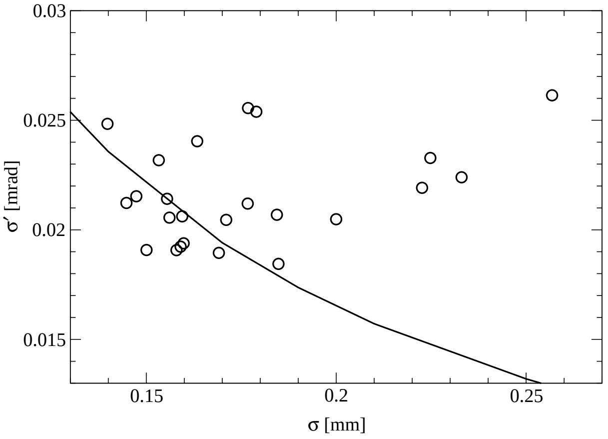

Figure 4: The size and divergence of the radiation field at the end of the final amplifier. The black line indicates twice the diffraction limit. The beam waist will in reality lie a few meters upstream the end of the undulator and will be up to 50% smaller, on the other hand jitter of the waist location has to be taken into account.

paring the beam offsets at this point to the radiation size, the ratio between the transverse offsets and the radiation size is computed at each point in final amplifier. The maximum of each of the resulting curves for the 24 runs is depicted in Fig. 5. These results only show shot-to-shot fluctuations, that are due to phase and amplitude errors in the gun and in the linac. The amplitudes at the beginning of the cascades amounted to $< 1\mu$m rms in the horizontal and $< 0.5\mu$m rms in the vertical plan.

The major source for beam steering, though, are quadrupole jitters, e.g. due to ground vibrations. All time independent beam offsets will be corrected by the steering magnets. Start-to-end calculations assuming a Gaussian rms quadrupole jitter of 300 nm, resulted in rms beam offsets at the beginning of the HGHG cascades as listed in Tab. 1.

Table 1: Transverse jitter (rms) at the end of the linac, due to random quadrupole vibrations with 300 nm offsets (rms).

	offset [μm]	angle [μrad]
horizontal	27.5	1.55
vertical	10.0	1.57

For an estimate of their effect, bunches where started on the phase space ellipse described in Tab. 1 and tracked through the final amplifier. The largest transverse offsets in the undulator where reached for large initial horizontal amplitudes, the maximum reached was 28μm. The minimal radiation size of all investigated cases is 140μm, Fig. 4, therefore the 20% criterion is fulfilled throughout the final amplifier for all runs. Alternative optics, taking the larger horizontal trajectory jitter into account, could even improve on the results.

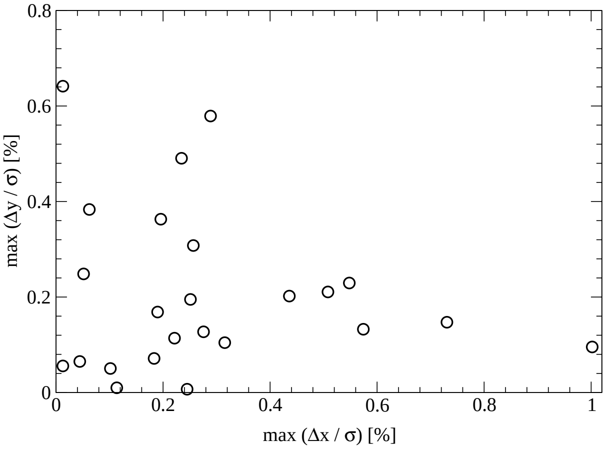

Figure 5: The maximum of the vertical and horizontal transverse offsets in the final amplifier in percent of the radiation size, when errors in the gun and the linac are included in the start-to-end calculations. To include effects of quadrupole offsets, the data can be linearly scaled.

Longitudinal Stability

The longitudinal location of the source point is difficult to determine. It does not coincide with the saturation point. Furthermore, in start-to-end calculations including errors, each bunch is populated differently and is seeded at varying locations due to timing jitter, so that the source point moves from shot to shot.

In [7], an exact, but time consuming procedure is introduced to locate the position and size of the radiation waist. It is pointed out that the waist lies over 5m upstream of the end of the undulator for the investigated cases. Furthermore, the horizontal and vertical waist position do not necessarily coincide.

A shot-to-shot jitter in the location of the source point or a variation in its size, leads to a degradation of the energy resolution. The criterion for longitudinal stability has been set to fluctuations in the beam radius of less than a factor of $\sqrt{2}$, which for Gaussian beams corresponds to variations of the source point location of less than one Rayleigh length.

It can be extracted from [7] that the distance, in which the beam radius increases by $\sqrt{2}$ is $>$ 5m and thus much larger than the theoretical Rayleigh length. With a total length of the final amplifier of 7.5 m, the longitudinal stability criteria is fulfilled as long as the beam waist location lies well inside the final amplifier.

SPECTRUM

Due to the energy chirp on the electron bunch and the jitter between the arrival time of the bunch and the seeding laser, the average energy of the electrons interacting with

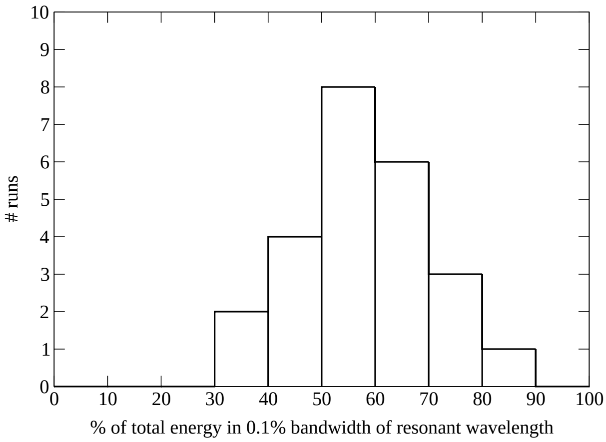

Figure 6: Histogram over the percent of total pulse energy in 0.1% bandwidth around the central frequency of each pulse. High temporal resolution experiments usually work without monochromator.

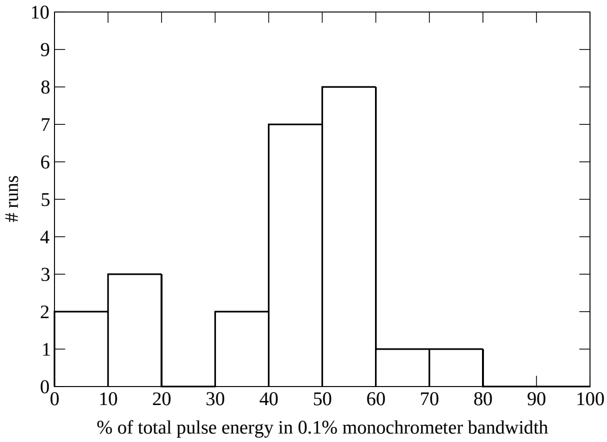

Figure 7: Histogram over the percent of total pulse energy in 0.1% bandwidth of a given (monochromator) frequency. The figure is important for high energy resolution experiments.

the seeding radiation varies, which results in a fluctuation of the central wavelength of the HGHG spectrum.

In order to evaluate spectral properties, the routines supplied by the post processing IDL-code XGENESIS are used on the Fairfield power on axis. The fraction of the energy in 0.1% bandwidth is calculated and compared to the total energy in the spectrum. The bandwidth can be either taken around a given frequency for all runs, or for the central frequency of the individual spectra.

Different experiments are interested in different spectral qualities. Experiments depending on high temporal resolution will usually work without monochromator and depend on the energy in a certain bandwidth around the resonant wavelength of each pulse. This case is depicted in Fig. 6, where 75% of the runs hold more than half and up to 90% of their power in 0.1% of the bandwidth of their resonant frequency, amounting to 50 μJ on average.

High energy resolution experiments need a large fraction of the total pulse energy close to the central frequency of the monochromator, Fig. 7. 70% of the runs would still deliver above 40% of their total pulse energy within the given bandwidth. These experiments usually average over many shots.

CONCLUSION

FEL codes deliver information about the development of the radiation inside the amplifying devices during the interaction between the electrons and the electro magnetic field. The quality of the produced radiation is judged much further down the beam line at the experimental station. Figures of merit have been proposed to evaluate the FEL output in view of the beam line and experimental demands. All quantities can be deduced from the output provided by, e.g. GENESIS. A post processing code for GENESIS has been introduced. It has been used to evaluate the results of 24 complete start-to-end runs including errors in the gun and the linac of the BESSY low energy FEL line. The given criteria for the radiation quality could be met. Despite the immense computing effort it would be desirable to improve on the statistics.

ACKNOWLEDGEMENT

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