Influence of Electron Beam Halos on the FEL performance

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Abstract

For single-pass free electron lasers (FEL), such as amplifiers and SASE device, saturation of the radiation power has to be reached within the length of the undulator. Therefore, detailed knowledge of electron beam parameters is crucial. So far, simulations have been performed with a given rms emittance and energy spread. At short radiation wavelengths, bunch compressors are used to compress the electron beam to achieve the desired high peak currents. In addition, external focusing along the entire undulator is used to maintain a constant small radius. The rotation of phase space due to compression might lead to a significant part of the bunch in tails that could increase the gain length. Furthermore, it is in general not possible to match both the beam core and the tail to the focusing structure. In this contribution, the influence of these tails, both transverse and in energy, on the FEL performance will be investigated. Simulations will be performed for beam parameters that have been assumed for the TESLA Test Facility (TTF) FEL at DESY.

1. Introduction

In many existing Free Electron Lasers, radiation power is amplified using a feedback system. In such a system, the most crucial constrain is that the gain exceeds the sum of all losses. As long as the number of passes needed to reach saturation is small compared to the total number of roundtrips of the field inside the cavity, the exact value of the single pass gain is of less importance. For a single pass device, more detailed knowledge of all parameters reducing the gain has to be obtained in order to determine the undulator length. In most studies thus far, the influence of beam emittance and energy spread has been investigated. In addition, a more exact estimate of the shotnoise power (in case of a SASE FEL [2]), the influence of magnetic errors and any misalignment [3] has been studied by several authors. In all these studies, however, the electron beam was assumed to be either Gaussian or parabolic. This is not neccesarily the case. First simulation studies of the bunch compressor of the TESLA Test Facility [1] have shown that the electron beam can have either tails or spatially separated distributions, both in any transverse plane and in energy. In this paper, the influence of two possible distributions on the FEL performance is studied. Two identical Gaussian distributions, spatially separated in the x-direction, are used. Only their distance and relative fraction is varied. Independently, two Gaussian distributions with the same central energy, but with

different rms-width provide the initial settings for the studies. The fraction of the two distribution has been change in the same manner as for the transverse displacement.

2. Results

Table 1. Undulator and optics parameters for the TTF FEL (Phase I at 230 MeV).

Electron beam	
Peak current	500 A
Normalized rms emittance	2π mmmrad
rms energy spread	500 keV
average beam size	$77\,\mu$m
ρ-parameter	$4 \cdot 10^{-3}$
undulator	
period length	27.3 mm
undulator peak field	0.497 T

Simulations with GENESIS 1.3 [4] have been performed for the TTF-FEL parameters. This is a fully 3 dimensional code, including time dependence. For these simulations, only the time-independent part has been used. Deviating from the TTF parameters the FODO-structure has been changed to get an almost constant β-function, with the average value equal to the value resulting from the real structure.
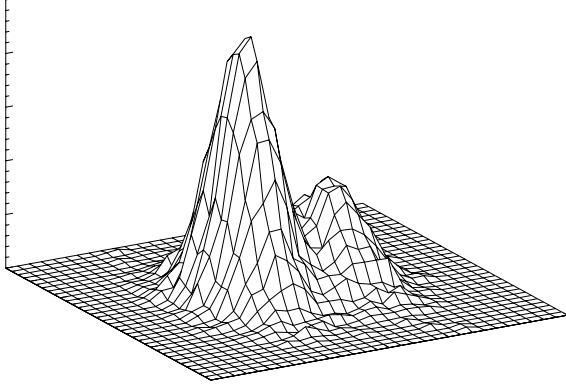
Fig. 1. *Example of a transverse electron beam distribution, in this case separated by 250 μm. The smaller Gaussian contains 30% of the charge.*

Fig. 2. *Saturation length (top figure) and power (bottom figure) versus normalized emittance for an electron beam consisting of two Gaussians separated in the x-direction in the range 50–250 μm. The fraction of electrons in one distribution varies from 10% to 50%, keeping the total charge constant. The points on the right indicate the saturaion length and power for a single Gaussian beam with a reduced current given by the indicated fraction.*

A first set of simulations has been performed assuming two identical Gaussian distributions, spatially separated by a certain amount in the x-direction. An example, with an offset of 250 μm and a charge of 70% in the large Gaussian and 30% in the smaller, is shown in Fig. 1. A similar displacement in y, or an initial kick in either x or y-direction would give similar results, the latter due to the FODO-structure, which makes the electron beam perform a betatron oscillation.

Results are shown in Fig. 2. The displacement in x varies from 50 to 250 μm, with the center of the total beam always on axis, e.g. $< x > = 0$. This means that, depending on the fraction in both distributions and on their relative offset, both are off-axis, performing a betatron oscillation. The rative fraction of the smaller Gaussian increases from 10% to 50% if saturation is reached within 17.5m. Especially for larger offsets saturation is only reached for smaller fractions. The normalized emittance given in the horizontal scale is calculated in the usual way, e.g. $e_x^2 = < \Delta x^2 >< \Delta x'^2 > - < (\Delta x \Delta x')^2 >$. As it can be seen, independent of the offset of the beams or their relative fraction, both power and saturation length seem to be related to the emittance calculated this way. One can also calculate the saturation power and length for an electron beam without halo, but with the same normalized emittance and the same mismatch of the initial conditions (resulting in the same beam envelope along the longitudinal axis). The results are within a few percent of the results shown in Fig. 2.

More important is, however, whether it is benificial to cut away part of the electron beam, place the remainder on axis and match it to the FODO-lattice. Resuts are shown to the right in Fig. 2. The reduction in current varies from 10% to 30%. As can be seen, within the parameter range studied, the saturation length for a given fraction in the halo tends towards the point where the current has been reduced
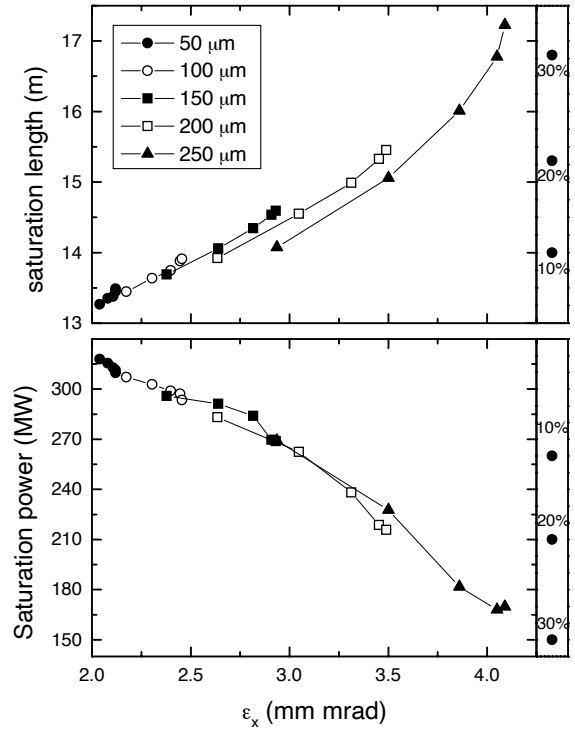
by the same amount. If one would not place the center of the beam on axis, but the largest fraction of the beam (90 to 50%), reducing the current gives similar results.

For a fraction of 20% in the halo, the offset has been extended to 500 μm. Results are shown in Fig. 3. In this case, two different positions of the beam are studied. In the top figure, the largest fraction of the beam is put on axis. For smaller offsets, this gives a slightly larger saturation length because of the large betatron oscillation performed by the off-axis part. For very large offsets, however, the 20% fraction no longer participates in the interaction and the saturation length and power are equal to the values obtained by cutting away this part of the current. In the bottom figure, the saturation length is slightly shorter for small offsets. As the offset increases, the saturation length increases beyond the value obtained for a 20% reduced current, because the large betatron oscillation of both parts of the beam reduce the interaction with the field. Therefore, the saturation length still increases (and the power decreases), but at a smaller rate than before.
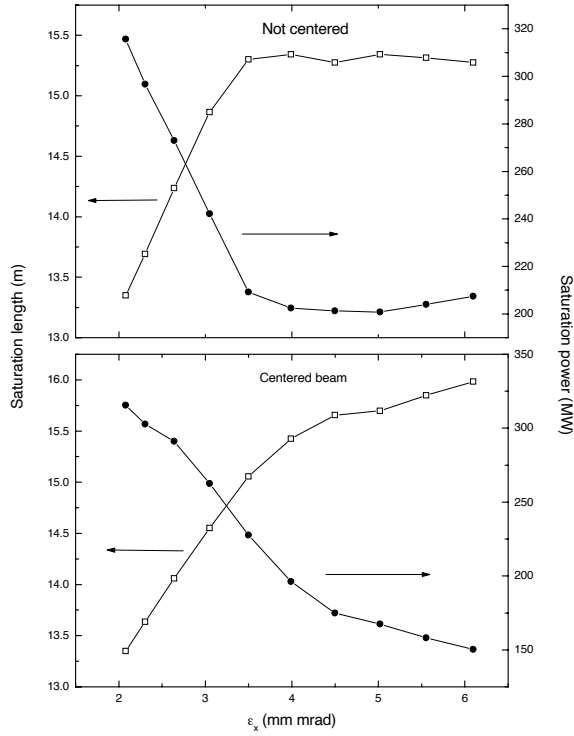
Fig. 3. *Saturation length versus normalized emittance for an electron beam consisting of two Gaussians separated in the x-direction in the range 50–500 µm. The fraction of electrons in one distribution is 20%. Either the largest fraction is put on axis (top figure) or the center of the entire beam, as before (bottom figure).*

Fig. 4. *Saturation length (top figure) and power (bottom figure) versus effective energy spread for an electron beam consisting of two Gaussians in energy. The core beam always has the same energy width, the halo has a width of up to 5 times the width of the core beam. The fraction in the two parts varies from 10% and 90% to 50% in both. The points on the right indicate the saturaion length and power for a single Gaussian beam with a reduced current given by the indicated fraction.*

The next set of simulations shows the influence of two overlapping Gaussians in energy. Fig. 4 shows saturation power and length for an energy width of the halo compared to the core of the beam from 2 to 5 times. In case the halo has a two times larger energy width up to 50% halo, saturation is still reached within the undulator length studied here. For a larger width this number decreases to 30%. The horizontal scale, the effective energy spread (given in MeV), is simply $< \gamma^2 > - < \gamma >^2$, with γ the Lorentz factor. There is no obvious relation between this parameter and the gain. Simulations of a single Gaussian energy distribution with this same width give different results. As can be seen, the levels are almost constant for an energy spread of the halo exceeding $2\sigma_\gamma$. In turn, these values are almost identical to the results with the current reduced by the same fraction as it was in the halo. This can be understood as follows. The energy spread of the normal beam without halo is about half of the ρ-parameter. The bucket in longitudinal phase space in which the electrons are captured have a height of no more than ρ, a value which is reached close to saturation. All electrons outside of this region will not interact with the electron beam. Therefore, for a given
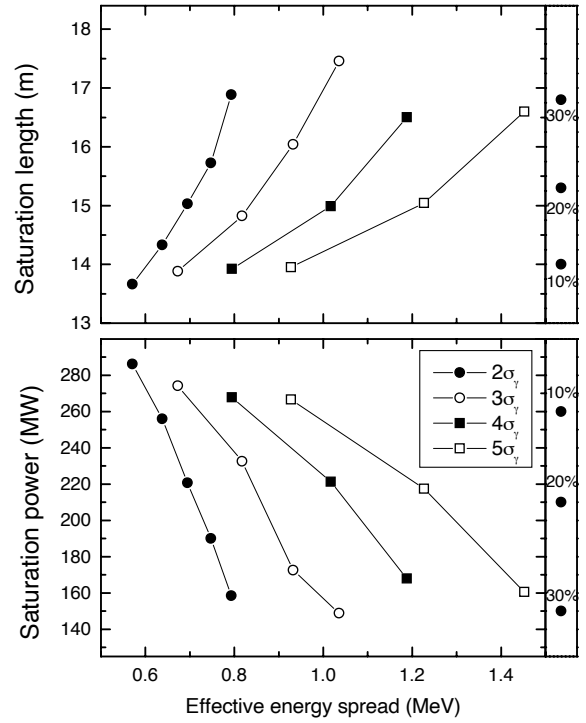
fraction in the halo, increasing the energy spread will not change saturation power or length if it exceeds ρ significantly. Changing the fraction will, however, reduce the gain, because of a reduced part that remains captured inside the bucket.

3. Conclusions

Simulations of halos have shown that they can strongly influence the performance of the FEL. For transverse distribution consisting of two (partly) separated but otherwise equal distributions, one benefits from re-aligning the electron beam to get the center on axis and to minimize the betatron oscillations for small offsets. For larger offsets, the large betatron oscillation reduces the gain if the center is placed on axis. For two overlapping Gaussians in energy, both with the same central energy but with different width, the saturation length and power cannot be changed significantly. Cutting away the halo, if this would be possible, and this reducing the current, does not give a better performance for the parameters studied here.

Acknowledgement

References

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