EFFECTS OF TAPERED BETAFUNCTION IN THE LCLS UNDULATOR

K. Goldammer*, BESSY, Berlin, Germany
P. Emma, Z. Huang, SLAC, Stanford, CA 94309, USA

Abstract

The Linac Coherent Light Source (LCLS) is an X-ray free-electron laser (FEL) project based on the SLAC linac [1]. With its nominal set of electron beam, focusing and undulator parameters, it is designed to achieve SASE saturation at an undulator length of about 100 m with an average power of 10 GW. In order to keep the electron beam focused in the undulators, a FODO lattice is integrated along the entire length of the undulators. Nominally, the quadrupole strengths are chosen to produce nearly constant betafunction and beam size along the undulator, optimized for the FEL interaction in the exponential growth regime. Since these quadrupoles are electromagnetic, it is possible to adjust the individual quadrupole strength to vary the betafunction and the beam size along the undulator, tailoring the FEL interaction in the start-up and the saturation regimes. In this paper, we present simulation studies of the tapered betafunction in the LCLS undulator and discuss the generated X-ray properties.

INTRODUCTION

In FEL theory and simulations, there is a clear optimal betafunction for the minimum gain length and for maximal saturation power. It can be estimated by a fitting formula [2] that takes into account various 3D effects.

The power gain length is one of the essential FEL performance parameters. In 1D theory, where emittance, diffraction and slippage is neglected, the gain length is inversely proportional to the Pierce parameter ρ. The quantity ρ is also refered to as the FEL parameter because it determines such important properties as the FEL saturation length, output power and spectral bandwidth. Since ρ scales with the electron beam size $\sigma_x = \sqrt{\beta\varepsilon}$ according to $\rho \sim \beta^{-1/3}$, focusing the beam to smaller beam sizes helps to shorten the FEL gain length. However, as the electron beam has a finite emittance ε, the electron beam angular divergence $\sigma'_x = \varepsilon/\sigma_x$ rises for smaller beam sizes. In 3D theory, this so called emittance effect can be shown to introduce a spread in the resonant wavelength of the FEL [3] which acts similar to an energy spread and degrades FEL performance. In combination with other effects, this yields one particular electron beam size that provides for the lowest gain length.

Fig. 1 illustrates these 3D effects. According to Fig. 1, top, the optimal betafunction for the shortest LCLS gain length is in the range of β=18 m. The maximum saturation power is reached for β=30 m. With regard to stable operation and a wide practical tolerance range, the current LCLS design considers an average β=30 m along the undulators. This requires strong focusing which is foreseen by electromagnetic quadrupoles integrated along the entire length of the undulator section. They are placed in the drifts between the undulators so that a FODO lattice can be established with any desired betafunction. With β=30 m and the set of nominal parameters [1], LCLS saturates a little after 100 m with about 10 GW of power while the average betafunction is kept constant along the undulators.

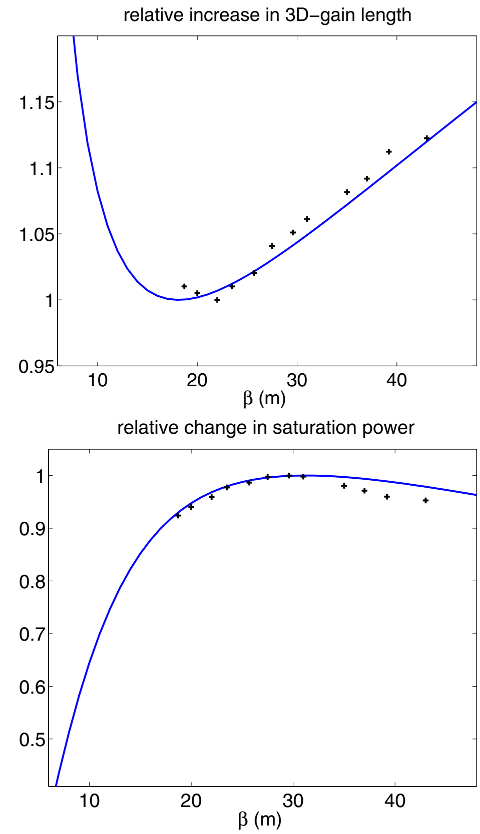

Figure 1: LCLS gain length and saturation power relative to their optimum values when varying betafunction. Solid lines calculated with M. Xie's formula, dots are results of numerical simulations using GENESIS.

Due to the emittance effect as explained above, lowering β would help to decrease the gain length so that saturation would occur earlier, but the FEL would saturate with lower power. However, it can be shown that in the start-up regime of LCLS, small betafunctions are of advantage, see Fig. 2. They lead to an increase in the diffraction angle $\Theta_d = \lambda_r^2/2\pi\sigma_x^2$, where λ_r is the FEL resonant wavelength and Θ_d is the two-dimensional diffraction angle in x and y. As the diffraction angle denotes the amount of sponta-

* goldammer@bessy.de

neous radition power in the forward direction, increasing Θ_d yields a larger amount of radiation power participating in FEL interaction.

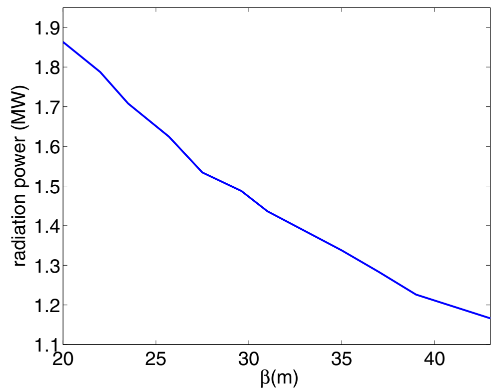

Figure 2: Radiation power at representative point in the FEL start-up regime when varying electron beam size.

If the electron beam size is then released in the course of the FEL process, the benefits from an initial increase in radiation can be exploited despite the emittance effect. One way to gradually change the electron beam size along the undulators is to individually adjust the quadrupole strengths in a linear taper. In this paper, we summarize the results of simulation studies on different types of beta tapers and report on their influence on radiation power and radiation mode properties. All simulations were done with the 3D-code GENESIS [4].

TAPERED BETAFUNCTION

In order to determine the impact of the betafunction at different regimes of the FEL, two kinds of tapers were conceived. The first type begins right in the start-up regime of the FEL where β is lowered to 15 m and then increases linearly. This aims at encouraging lots of spontaneous emission while later overcoming the emittance effect. For the second type of taper, the betafunction is set to its nominal value of 30 m until well into the exponential growth regime. From there, the quadrupole strength is changed linearly so that only the saturation regime is affected by the beta variation.

Full Linear Beta Tapers

In order to investigate the effects of full tapers of the betafunction, β was assumed to be 15 m at the first undulator, corresponding to twice the nominal quadrupole focusing strength k. The electron beam size was then released with different slopes, see Fig. 3, top, for one example, so that at the FEL exit, β ranges from 24 m to 44 m. The generated set of betafunctions is displayed in Fig. 3, bottom.

Fig. 4 displays the LCLS output power at a representative point in the saturation regime (z=100 m). Radiation power is slightly higher than in case of a constant betafunction of 30 m. This can be explained by the small initial β common to all tapers yielding higher levels of initial spontaneous radiation and starting the SASE process more effectively. It can also be observed that the radiation power around saturation scales proportional to β. This illustrates the influence of the emittance, suggesting that the emittance effect can be mitigated most effectively by a fast increase of β in the course of the FEL process.

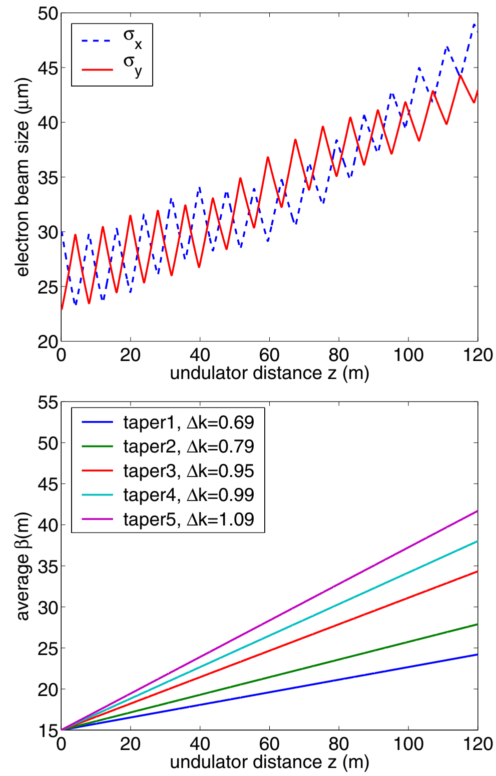

Figure 3: Evolution of transverse electron beamsize σ_x, σ_y, top, when gradually releasing the quadrupole strength k along the undulators. Bottom: evolution of average beta-function for different slopes Δk.

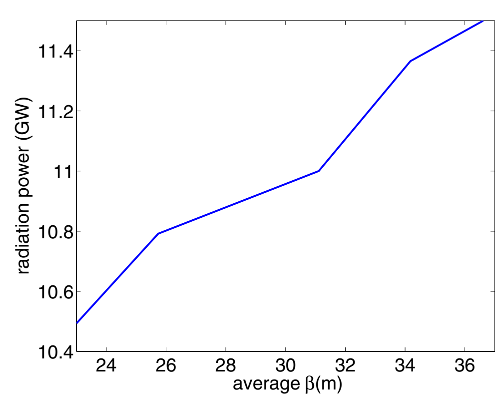

Figure 4: Power at 100 m into the undulators when beta-function is tapered linearly along FEL. In start-up regime, β is 15 m and increases with different slopes leading to average βs at 100 m as shown on abscissa.

Tapering Beta in the Saturation Regime

In order to determine the influence of β in the saturation regime, the second type of beta taper was applied. Until 80 m into the undulators, the average betafunction is constant at the nominal value of 30 m. Starting at that point, the quadrupoles are adjusted to produce linear beta tapers that only affect the saturation regime. With a change in effective quadrupole strength of k$\pm 0.6/\mathrm{m}^2$, the betafunction at the last undulator module can be varied from half to about twice its nominal value. At a representative point within the saturation regime (z=100 m), this yields the betafunctions and radiation powers that are given in Fig. 5, top. The saturation power again scales with β in such a way that releasing the electron beam size increases saturation power. This shows that the emittance effect is still critical and a fast increase of β is useful. Hence, even if applied in the late part of the FEL process, beta tapering helps to mitigate the emittance effect and improves FEL performance.

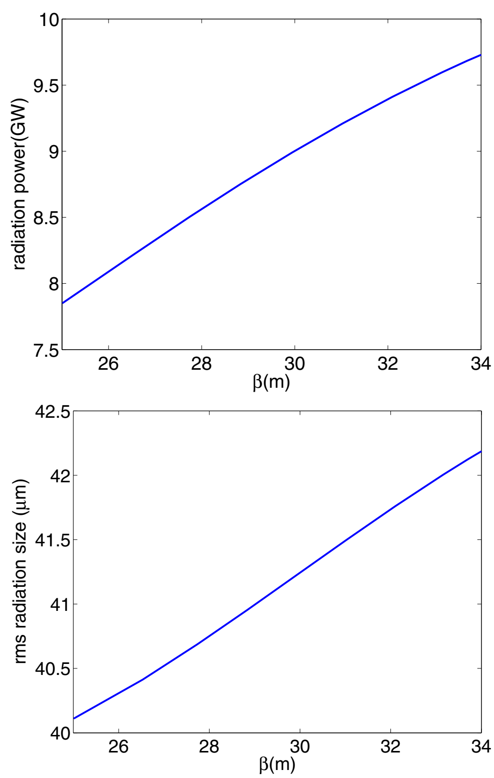

Figure 5: Output power, top, and rms radiation mode size, bottom, at 100 m into the undulators when β starts out constant and is varied around saturation. Abscissa: average β at 100 m as result of slope of taper.

A change in electron beam size also affects the radiation mode size. Due to gain guiding, the radiation size is expected to scale proportionally to the electron beam size. This could be verified, see Fig. 5, bottom, although the variation of radiation size is only in the order of a few percent.

COMPARISON OF RESULTS

Figure 6 displays the build-up of radiation power in LCLS comparing three cases: nominal case with an average betafunction of 30 m, one example where β is tapered only around saturation and one full beta taper. Compared to the nominal case, the saturation power can be increased by about 10% when tapering β around saturation and by 20% when using the full taper with strong initial focusing. Note that in Fig. 6, the full taper has the same average betafunction[1] as the nominal case where β is constant. Still, the saturation power is much higher. In addition, saturation clearly occurs earlier than in the two other cases as a result of the increase in initial start-up noise.

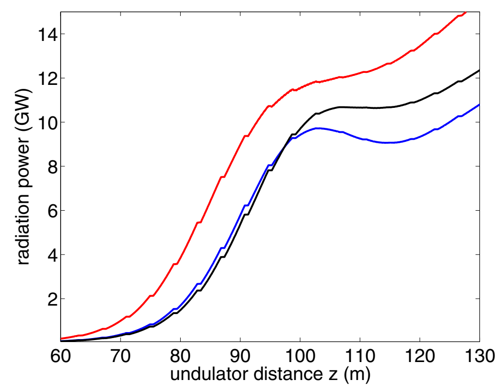

Figure 6: Evolution of average radiation power when using beta tapers in LCLS compared to nominal case, blue. Red: full linear taper, β is 15 m in start-up regime and 44 m at last undulator. Black: β constant in first 80 m of undulators, then linearly increased to 50 m.

CONCLUSION

Simulation studies of LCLS showed that varying the electron beamsize influences both the properties of output power and radiation mode size. The radiation size around saturation showed to scale proportionally to β but varies only marginally. The output power can be increased when enhancing spontaneous emission in the start-up regime of the FEL. This can be done effectively with a beta taper that provides for very strong initial focusing and then releases the electron beam size in the course of the FEL process.

REFERENCES

[1] LCLS CDR, SLAC-R-593,2002

[2] M. Xie, LBL Preprint No-36038, 1995

[3] K. Kim, Z. Huang, USPAS lecture note

[4] S. Reiche, Nucl. Instr. and Meth. A 429 (1999) 243

[1] Average here meaning that the betafunction is averaged over the length of all undulators.