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Optimization of an X-ray SASE-FEL

C. Pellegrini[a], S. Reiche[a,*], J. Rosenzweig[a], C. Schroeder[a], A. Varfolomeev[b], S. Tolmachev[b], H.-D. Nuhn[c]

[a] *UCLA - Department of Physics & Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095-1444, USA*
[b] *Russian Research Center, Kurchatov Institute, Moscow 123128, Russia*
[c] *Stanford Linear Accelerator Laboratory, Stanford, CA 94309, USA*

Abstract

The most important characteristics of an X-ray SASE-FEL are determined by the electron beam energy, transverse and longitudinal emittance, and by choice of the undulator period, field, and gap. Among them are the gain and saturation length, the amount and spectral characteristics of the spontaneous radiation, the wake fields due to the vacuum pipe. The spontaneous radiation intensity is very large in all X-ray SASE-FELs now being designed, and it contributes to the final electron beam energy spread, thus affecting the gain. It also produces a large background for the beam and radiation diagnostics instrumentation. The wake fields due to the resistivity and roughness of the beam pipe through the undulator, also affects the beam 6-dimensional phase space volume, and thus the gain and the line width. In this paper, we discuss ways to optimize the FEL when considering all these effects. In particular we consider and discuss the use of a hybrid iron-permanent magnet helical undulator to minimize some of these effects, and thus optimize the FEL design. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

When moving towards shorter FEL wavelengths the demands on the electron beam parameters and undulator design becomes more severe. While the typical undulator length is longer, the tolerable emittance and energy spread are smaller. Therefore, the FEL performance is more sensitive to effects such as wake fields and spontaneous emission.

The emission of incoherent undulator radiation is the same for all electrons, and yields an energy loss, which can be compensated by tapering the undulator, and an increased energy spreads, which can reduce the gain. Wake fields effects change depending on the electron position within the bunch, and produce an energy loss from the entrance to the exit of the undulator which reduces the gain.

The wake fields effects can, however, be reduced by proper design of the vacuum chamber, increasing its diameter and reducing the resistivity and the roughness, and of the undulator, to reduce its length by maximizing the gain. The general

*Corresponding author. Tel.: +1-310-206-5584; fax: +1-310-825–8432.
E-mail address: reiche@stout.physics.ucla.edu (S. Reiche).

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strategy to reduce wake fields effects is to increase the vacuum chamber diameter and to shorten the undulator length. Therefore, in this discussion we compare the planar LCLS undulator, considered as a reference, with helical undulators, in particular a novel design by the Kurchatov Institute for a helical undulator with very high magnetic field. With this design a shorter length can be achieved compared to planar undulator.

2. Undulator and beam parameters models

Both planar and helical undulators, have been successfully used for FELs in the past. In the models, presented in this paper, we consider helical undulators with large gaps, except for the LCLS reference case, which uses a planar hybrid undulator. The choice of high field helical undulator is motivated by the fact that with a new design helical undulators can give a short gain length, while the gap can be as large as in the planar case. With a larger gap the vacuum chamber size can be increased, thus reducing the impact of wake fields (see Section 4).

For the discussion we consider 4 cases

- a high field helical undulator (case A);
- a low field helical undulator (case B);
- a low charge, high field helical undulator (case C);
- the reference LCLS case, as presented in the CDR [1].

The exceptionally high field helical undulator is a permanent magnet system designed by the Kurchatov group. This undulator can provide a large field or a large gap (see Fig. 1). The choice has to be determined by considerations of wake field effects in the undulator vacuum pipe, and total undulator length. For this discussion a gap width of 8.5 mm is used providing the resonant wavelength at almost the same energy as the LCLS undulator.

In case B a different, conventional design for a helical undulator is used, providing a lower magnetic field and larger period length. This requires a lower electron beam energy to obtain the same resonance wavelength. The benefit of the model is the rather simple design of the undulator. Beside combinations of permanent magnets and iron yokes the same field profile can be obtained by a double helix of current carrying copper embedded in an iron yoke. The required current does not exceed 2000 A, and the Ohmic losses can be cooled by liquid nitrogen.

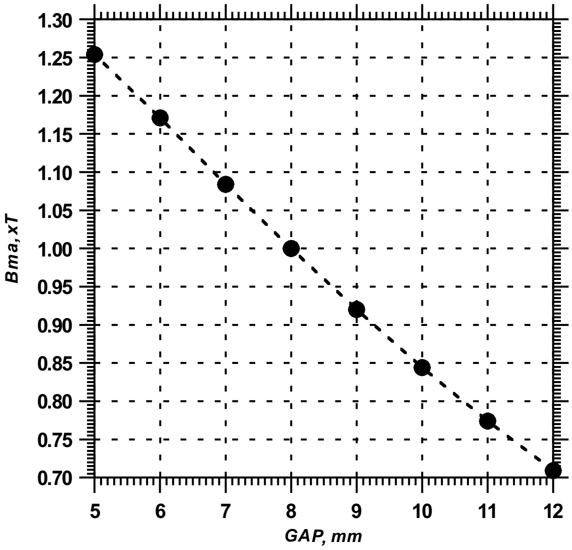

Fig. 1. On-axis field strength versus gap for the Kurchatov design of the helical undulator.

Model C is a modified version of Model A, where the bunch charge and, thus, the bunch length and beam emittance are smaller [2]. The reduced emittance effects and the use of stronger focusing result in a shorter undulator.

The undulator and electron beam parameters for the four cases are presented in Table 1.

For completeness a fifth model could have been considered, using a planar undulator with larger gap while providing the same on-axis peak field as the LCLS case. The construction of this undulator was suggested by Kurchatov group also. The physics would have been same as for the LCLS case except that the wake fields are reduced to the level of the helical models. This impact is covered by Section 4.

Table 1
Parameters for LCLS (planar undulator) and alternative models based on helical undulators (cases A–C)

	LCLS	A	B	C
Undulator period (cm)	3	3	4	3
Undulator field (T)	1.3	0.96	0.48	0.96
Undulator (K)	3.7	2.7	1.8	2.7
Undulator gap (mm)	6.0	8.5	8.0	8.5
Focusing beta function (m)	18.0	17.7	20.5	5.0
Beam energy (GeV)	14.4	14.7	10.65	14.7
Total synchrotron radiation (GW)	90	50	11.6	10
Normalized emittance, mm mrad	1.1	1.1	1.1	0.3
Charge (nC)	0.95	0.95	0.95	0.2
Peak current (kA)	3.4	3.4	3.4	1.17
Relative energy spread at undulator entrance (10^{-5})	6	6	8	6
Resonant wavelength (Å)	1.5	1.5	1.5	1.5
FEL parameter ($\rho \times 10^4$)	5	6	6	10
Gain length (m)	4.2	2.8	4.2	1.84

3. Power and saturation length

For the simulation we used the 3D time-dependent FEL code GENESIS 1.3 [3], which has been benchmarked to various other FEL codes in the steady-state regime of an FEL [4]. To reduce the CPU time and to exclude many independent runs to exclude the fluctuation due to the SASE process all models have been simulated as an FEL amplifier. The initial power level has been estimated by the 1D theory [5], which is applicable for X-ray FELs because they are not dominated by diffraction effects.

The general performance of the different models is given by the solid lines in Fig. 2 (Section 4 discusses the wake fields effect, also shown in this plot).

For all models the saturation level is almost identical at 10 GW while the saturation length varies. Model C shows the best performance with a saturation length of 37 m due to the reduced emittance and stronger focusing. But even with the same electron beam parameters the performance of the high field undulator (case A) exceeds that of the LCLS undulator. The low field helical undulator has the longest saturation length. This is caused by the emittance effects which are stronger for a lower beam energy while keeping the undulator parameter the same [6].

In the conceptional design study of LCLS the ability to tune the resonant wavelength between 1.5 and 15 Å is an important feature for a wider range of experiments with a high brilliant X-ray beams. All models are able to fulfill this requirement by changing only the electron beam energy. At 15 Å the saturation length is below 30 m for all cases. The benefits of a reduced bunch charge and emittance are not as significant as for the 1.5 Å case, because the FEL performance is less affected by emittance effects at lower beam energy.

4. Spontaneous emission

The difference between a planar and a helical undulator becomes obvious when the spontaneous radiation is taken into account. Typically a planar undulator radiates at a higher power lever with a richer content of higher harmonics than a helical undulator. Since the FEL is driven by a lower beam energy, case B has the lowest radiation level considered in this discussion. In addition, spontaneous radiation of a helical undulator is always emitted at an angle with respect to the undulator axis, which makes it easier to separate the FEL radiation from the spontaneous emission.

Another effect for X-ray FELs is the fluctuation in the number of emitted photons in the high frequency part of spectrum of the radiation spectrum. It yields an increased energy spread of the electron beam [7], which cannot be compensated by field tapering as it is the case for the average energy loss due to the spontaneous emission.

The growth rate of the energy spread scales with the electron beam energy. Therefore case B benefits from the lower beam energy and the FEL is hardly affected. For the other cases the initial energy spread grows about 100% before it is dominated by the saturation of the FEL (see Fig. 3). Because the FEL dynamic is rather affected by the electron beam emittance than the energy spread the overall effect of the quantum fluctuation in the spontaneous emission is small. Even for the worst case the power level at saturation is degraded by less than 10%.

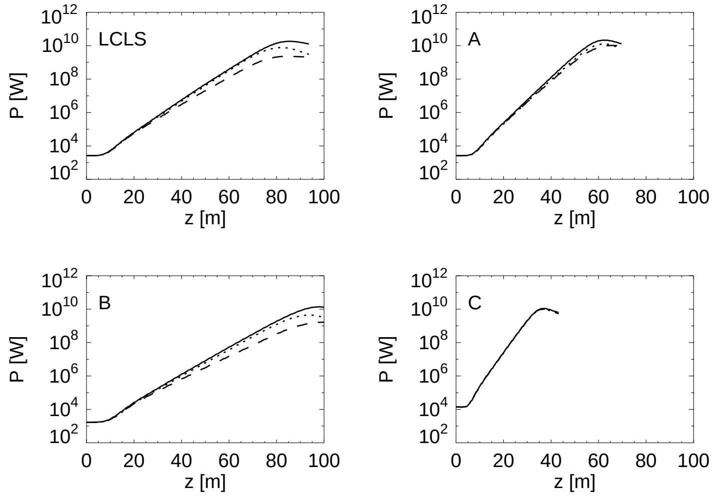

Fig. 2. Radiation power for the different cases including no wake fields, resistive wall wake fields and resistive wall + surface roughness wake fields (solid, dotted and dashed line, respectively).

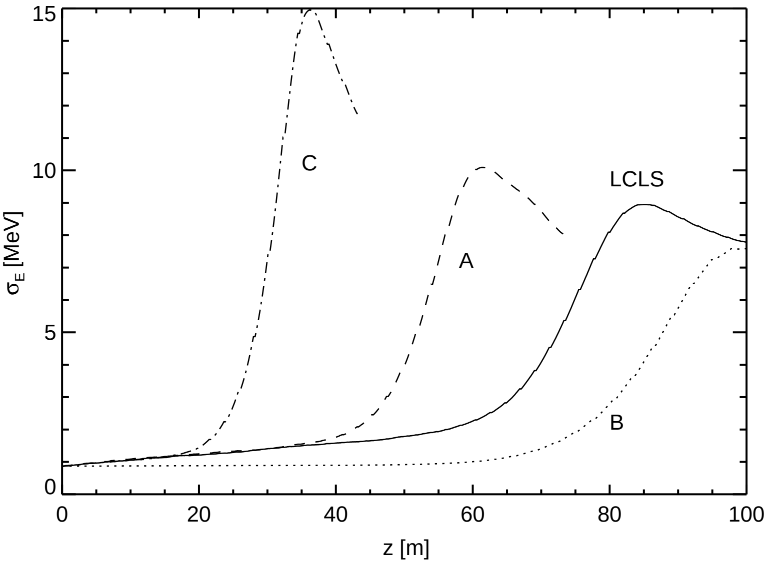

Fig. 3. Energy spread along the undulator including the effect due to the fluctuation of the emitted photons in the spectrum of the spontaneous emission.

5. Wake fields effects

Wake field effects within the undulator cannot be neglected due to the high peak current of the electron beam and the small diameter of the vacuum chamber, which enhance the wake field amplitude significantly. These effects have been the subject of much recent work [8–10]. The two main effects considered are those due to the resistivity and the imperfections of the vacuum pipe wall. A third source of wake field, produced by discontinuities in the vacuum chamber, is excluded in this discussion because an estimate of the wake field amplitude relies on an explicit design of the vacuum chamber including pumping ports, diagnostic sections and bellows.

Wake fields have longitudinal and transverse components. The latter are not taken into account because they are of higher order in the electron beam misplacement. Longitudinal wake fields cause a modulation of the electron beam energy along the bunch, and are commonly described by a wake potential.

For the resistive wall wake fields the wake potential [11] is

$$W_z(t) = -\frac{4ce^2 Z_0}{\pi R^2}\left[\frac{1}{3}e^{t/\tau}\cos(\sqrt{3}t/\tau) - \frac{\sqrt{2}}{\pi}\int_0^\infty dx \frac{x^2 e^{tx^2/\tau}}{x^6+8}\right] \quad (1)$$

where t is the longitudinal position of the test particle with respect to the particle generating the field, $\tau = [2R^2/Z_0\sigma c^3]^{1/3}$ is the characteristic scale of the wake potential, σ is the conductivity of the vacuum chamber, R is the chamber radius and $Z_0 \approx 377\ \Omega$ is the vacuum impedance.

For the effect of imperfection there are several models under consideration. A more conservative model [8] describes the surface roughness by a thin dielectric layer where the thickness δ is equivalent to the rms surface modulation.

The resulting wake potential is

$$W_z(t) = -\frac{ce^2 Z_0}{\pi R^2}\cos(k_0 t) \quad (2)$$

with $k_0 \approx \sqrt{4/R\delta}$.

If the longitudinal characteristic length of the surface imperfection is much larger than the depth, the wake field amplitude is strongly reduced [9] and negligible compared to the resistive wake field.

Fig. 4 shows the wake potential for the LCLS parameter using a beam pipe radius of 2.5 mm. For larger radii, as it is the case for all helical undulators (A–C), the amplitude is noticeable reduced and the FEL performance is less degraded (Fig. 2). The wake fields are further reduced by using a low charge beam (case C), where the resulting effects are almost negligible. The benefit of a larger beam pipe is partially removed by a longer saturation length for case B because the energy modulation is accumulated over a longer distance.

The FEL amplification is less influenced in regions of the electron bunch where the total wake potential is zero. The average temporal radiation profiles for the LCLS case and case A are shown in

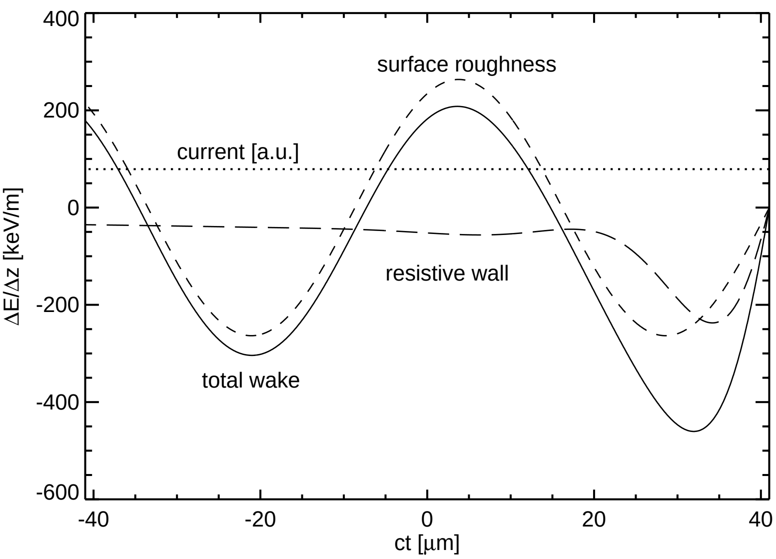

Fig. 4. Wake potentials for the LCLS undulator.

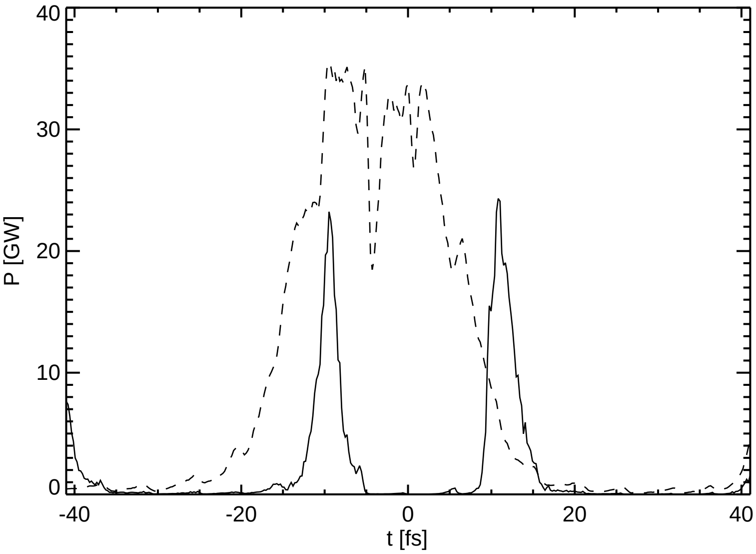

Fig. 5. Average radiation envelope for the LCLS case and case A (solid and dashed line, respectively) close to saturation.

Fig. 5. Again, the helical case exhibits superior performance regarding the effective length of the radiation pulse, which is approximately 40% for case A but 10% for LCLS, compared to the electron bunch length.

6. Conclusion

The impact of spontaneous emission and wake fields on the X-ray FELs gain has to be taken into account during the design and manufacturing phase of the undulator. To reduce the amplitude of wake fields a larger chamber size and a shorter undulator are desired. This can be fulfilled by a novel designs of helical undulators with a very high magnetic field, leading to a consideration of these undulator for an X-ray FEL, instead of planar undulators based on a more conventional design. An additional benefit of helical undulators is the easier separation between spontaneous emission and FEL radiation, thus facilitating the diagnostic for the system. This feature should not be underestimated during the commissioning phase of the FEL.

The energy loss by spontaneous emission can be compensated by field tapering and does not depend on the undulator type. Similarly, the increase of the energy spread is mainly determined by the beam energy, and puts a limit to the shortest wavelength obtainable for SASE-FELs.

In conclusion, our results show that the novel helical undulator design of the Kurchatov group, providing an unusual high magnetic field, has important advantages compared to planar undulators for an X-ray FEL.

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