Design considerations for a SASE X-ray FEL

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Abstract

The well developed theory of short wavelength SASE-FELs is now being used to design two X-ray lasers, LCLS and Tesla-FEL. However, the physics and technology of these projects present some unique challenges, related to the very high peak current of the electron beam, the very long undulator needed to reach saturation, and the importance of preserving the beam phase-space density even in the presence of large wake-field effects. In the first part of this paper, we review the basic elements of the theory, the scaling laws for an X-ray SASE-FEL, and the status of the experimental verification of the theory. We then discuss some of the most important issues for the design of these systems, including wake-field effects in the undulator, and the choice of undulator type and beam parameters. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Undulator radiation is particularly useful because of its small line width and high brightness, is being used in many, if not all, synchrotron radiation sources built around the world, and provides at present the brightest source of X-rays. For long undulators, the free-electron laser (FEL) collective instability gives the possibility of much larger X-ray intensity and brightness. The instability produces an exponential growth of the radiation intensity, together with a modulation of the electron density at the radiation wavelength. The radiation field necessary to start this instability is the spontaneous radiation field, or a combination of the spontaneous radiation field and an external field. In the first case, we call the FEL a Self Amplified Spontaneous Emission (SASE) FEL. If the external field is dominant we speak of an FEL amplifier.

The existence of an exponentially growing solution for the FEL has been studied in Refs. [1–13]. This work led to the first proposals [14–17] to operate a SASE-FEL at short wavelength, without using an optical cavity, difficult to build in the Soft X-ray or X-ray spectral region.

The analysis of a SASE-FEL in the one-dimensional (1-D) case has led to a simple theory of the free-electron laser collective instability, describing all of the free-electron laser physics with one single quantity, the FEL parameter $\rho$ [6],

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a function of the electron beam density and energy, and of the undulator period and magnetic field. The extension of the FEL theory to three dimension, including diffraction effects [18–22] has been another important step toward a full understanding of the physics of this system. From the collective instability theory, we can obtain a scaling law [23] of a SASE-FEL with wavelength, showing a weak dependence of the gain on wavelength, and pointing to the possibility of using this system to reach the X-ray spectral region. This analysis shows that to reach short wavelengths one needs a large electron beam six-dimensional phase-space density, a condition until recently difficult to satisfy.

The development of radio frequency photocathode electron guns [24], and the emittance compensation method [25,26] has changed this situation. At the same time, the work on linear colliders has opened the possibility to accelerate and time compress electron beams without spoiling their brightness [27–30]. At a Workshop on IV Generation Light Sources held at SSRL in 1992 it was shown [31] that these new developments make possible to build an X-ray SASE-FEL. This work led to further studies [32,33], and to two major proposals, one at SLAC [34], the other at DESY [35], for X-ray SASE-FELs in the 1 Å region, with peak power of the order of tens of GW, pulse length of about 100 fs or shorter, full transverse coherence, peak brightness about ten orders of magnitude larger than that of III generation synchrotron radiation sources.

While the theory of the SASE-FEL has been developed starting from the 1980s, a comparison with experimental data has become possible only during the last few years, initially in the infrared to visible region of the spectrum [36–46]. These experimental data agree with our theoretical model, in particular the predicted exponential growth, the dependence of the gain length on electron beam parameters, and the intensity fluctuations. A recent experiment at DESY [47] has demonstrated gain of about 1000 at the shortest wavelength ever reached by an FEL, 80 nm. These results give us confidence that we can use the present theory to design an X-ray SASE-FEL.

2. Free-electron laser physics

The physical process on which a FEL is based is the emission of radiation from one relativistic electron propagating through an undulator. We consider for simplicity only the case of a helical undulator, and refer the reader to other books or papers, for instance Refs. [48,49], for a more complete discussion.

Let us consider the emission of coherent radiation from \( N_e \) electrons, that is the radiation at the wavelength

\[
\lambda = \frac{\lambda_u}{2\pi}(1 + a_u^2) \quad (1)
\]

within the coherent solid angle

\[
\pi \theta_c^2 = \frac{2\pi \lambda}{\lambda_u N_u} \quad (2)
\]

and line width

\[
\Delta \omega / \omega = \frac{1}{N_u}. \quad (3)
\]

In Eq. (1) \( E_{\text{beam}} = \gamma mc^2 \) is the beam energy, and \( a_u = eB_u\lambda_u/2\pi mc^2 \) is the undulator parameter.

When there is no correlation between the field generated by each electron, as in the case of spontaneous radiation, the total number of coherent photons emitted is

\[
N_{\text{ph}} = \pi x N_e a_u^2 / (1 + a_u^2),
\]

where \( x \) is the fine structure constant. Hence, the number of coherent photons is about 1% of the number of electrons. If all electrons were within a radiation wavelength, the number of photons would increase by a factor \( N_e \). Even when this is not the case, and the electron distribution on the scale of \( \lambda \) is initially random, the number of photons per electron can be increased by the FEL collective in-stability [6].

The instability produces an exponential growth of the field intensity and of the bunching parameter

\[
B = \frac{1}{N_e} \sum_{k=1}^{N_e} \exp(2\pi i z_k / \lambda)
\]

where \( z_k \) is the longitudinal position of electron \( k \). The growth saturates when the bunching parameter is of the order of one. For a
long undulator the intensity is approximately given by
\[ I \approx \frac{I_0}{9} \exp(z/L_G) \]  
where \( L_G \) is the exponential growth rate, called the gain length, and \( I_0 \) is the spontaneous coherent undulator radiation intensity for an undulator with a length \( L_G \), and is proportional to the square of the initial value of the bunching factor, \( |B_0|^2 \).

The instability growth rate, or gain length, is given, in a simple 1-D model by
\[ L_G \approx \frac{\lambda_u}{4\sqrt{3\pi\rho}} \]  
where \( \rho \) is the free-electron laser parameter \([6]\),
\[ \rho = \left( \frac{a_u \Omega_p}{4\gamma \omega_u} \right)^{2/3} \]
\( \omega_u = 2\pi c/\lambda_u \) is the frequency associated to the undulator periodicity, and \( \Omega_p = (4\pi c^2 n_e/\gamma)^{1/2} \), is the beam plasma frequency, \( n_e \) is the electron density, and \( r_e \) is the classical electron radius.

A similar exponential growth, with a different coefficient, occurs if there is an initial input field, and no noise in the beam (uniform beam, \( B_0 = 0 \)), i.e. amplified stimulated emission. In the SASE case, saturation occurs after about 20 gain lengths, and the radiated energy at saturation is about \( \rho N_e E_{\text{beam}} \). In a case of interest to us, an X-ray FEL with \( E_{\text{ph}} \approx 10^4 \text{eV} \), \( E \approx 15 \text{GeV} \), \( \rho \approx 10^{-3} \), we obtain \( N_{\text{ph}} \approx 10^3 \), i.e. an increase of almost 5 orders of magnitude in the number of photons produced per electron.

The instability can develop only if the undulator length is larger than the gain length, and some other conditions are satisfied:

(a) Beam emittance smaller than the wavelength:
\[ \varepsilon < \frac{\lambda}{4\pi} \]  
(b) Beam energy spread smaller than the free-electron laser parameter:
\[ \sigma_E < \rho \]  
(c) Gain length shorter than the radiation Raleigh range:
\[ L_G < L_R \]  
where the Raleigh range is defined in terms of the radiation beam radius, \( \omega_0 \) by \( \pi \omega_0^2 = \lambda L_R \).

Condition (a) says that for the instability to occur, the electron beam must match the transverse phase-space characteristics of the radiation. Condition (b) limits the beam energy spread. Condition (c) requires that more radiation is produced by the beam than what is lost through diffraction.

Conditions (a) and (c) depend on the beam radius and the radiation wavelength, and are not independent. If they are satisfied, we can use with good approximation the 1-D model. If they are not satisfied and the gain length deviates from the one-dimensional value (5)—as in the LCLS case where the emittance is about 3 times larger than \( \lambda/4\pi \)—it is convenient to introduce an effective FEL parameter, defined as
\[ \rho_{\text{eff}} = \frac{\lambda_u}{4\sqrt{3\pi L_{G3D}}} \]  
where \( L_{G3D} \) is the three-dimensional gain length obtained from numerical simulations, including the effects of diffraction, energy spread, and emittance. This quantity is a measure of the three-dimensional effects present in the FEL, and can be used to obtain more realistic information on the system.

2.1. Scaling laws

Analyzing Eqs. (6)–(8), one obtains the scaling law for a SASE-FEL at a given wavelength. We assume that the beam is focused by the undulator and an additional focusing structure, to provide a focusing function \( \beta_F \) of the order of the gain length. We use the emittance \( \varepsilon = \sigma_\gamma^2 / \beta_F \) and the longitudinal brightness \( B_L = ecN_e/2\pi\sigma_L \gamma \sigma_\gamma \), where \( \sigma_L \) and \( \gamma \sigma_\gamma \) are the bunch length and the bunch absolute energy spread, to describe the bunch density and energy spread. The result is that the FEL \( \rho \) parameter scales like the beam longitudinal
where we have assumed \( \sigma_E = a \rho, \varepsilon = b \lambda / 4 \pi, \) and \( I_A = \varepsilon c / r_c \) to be of the order of 0.001. Since this discussion does not consider explicitly gain losses due to diffraction, undulator errors and beam misalignment, we need in practice a larger value of \( B_L \).

To obtain an emittance which satisfies condition (7) at about 0.1 nm, using a photo-cathode gun and a linac, we need a large beam energy, of the order of several GeVs, to reduce the emittance by adiabatic damping. The beam longitudinal brightness is determined by the electron source. Wakefields in the linac can, however, reduce it considerably. For LCLS the photo-cathode gun gives a slice emittance \( \varepsilon = 6 \times 10^{-8} \) m rad, slice longitudinal brightness \( B_L = 8000 \) A at 10 MeV. Acceleration and compression in the SLAC linac then gives \( \varepsilon = 4 \times 10^{-11} \) m rad, \( B_L = 1500 \) A at 15 GeV, good enough to produce lasing, even considering the gain losses due to diffraction, imperfections and misalignment.

2.2. Slippage, fluctuations and time structure

When propagating in vacuum, the radiation field is faster than the electron beam, and it moves forward, “slips”, by one wavelength \( \lambda \) for each undulator period. The slippage in one gain length defines the “cooperation length” [55],

\[
L_c = \frac{\lambda}{\lambda_u} L_G.
\]  

For the SASE case the radiation field is proportional to \( I(\omega) \), the Fourier component at \( \omega = 2 \pi c / \lambda \) of the initial bunching factor \( B_0 \), and the intensity to \( |I(\omega)|^2 \). If the bunch length, \( L_B \) is such that \( L_B \gg \lambda \), and the beam is generated from a thermionic cathode or photo-cathode, the initial bunching and its Fourier component \( I(\omega) \) are random quantities. The initial value of \( B_0 \) is different for each beam section of length \( \lambda \), and has a random distribution. The average values are \( \langle I(\omega) \rangle \sim \langle B_0 \rangle = 0 \), and \( \langle |I(\omega)|^2 \rangle \sim \langle |B_0|^2 \rangle \sim N_c \).

As the beam and the radiation propagate through the undulator, the FEL interaction introduces a correlation on the scale length of \( L_c \), producing spikes in the radiation pulse, with a length of the order of \( L_c \), and a random intensity distribution. The number of spikes is [55,56] \( M = L_B / 4 \pi L_c \). The total intensity distribution is a Gamma distribution function

\[
P(I) = M^M \frac{I^{M-1}}{\langle I \rangle^M} \exp(-MI / \langle I \rangle)
\]  

where \( \langle I \rangle \) is the average intensity. The standard deviation of this distribution is \( 1 / \sqrt{M} \). The line width is approximately the same as for the spontaneous radiation, \( \Delta \omega / \omega \approx 1 / N_a \).

3. Experimental results on SASE-FELs

A SASE-FEL is characterized by \( L_G \) and the intensity fluctuations, the distribution of \( |B_0|^2 \). Very large gain in the SASE mode has so far been observed in the centimeter [36–38] to millimeter wavelength. Gain between about 1000% and 100% has been observed at Orsay [39] and UCLA [40] in the infrared, and at Brookhaven [43] in the visible. Larger gain in the infrared has also been observed at Los Alamos [41], and gain as large as \( 3 \times 10^7 \) at 12 \( \mu \)m has been measured by a UCLA-LANL-RRIK collaboration [42]. The intensity distribution function has been previously measured for spontaneous undulator radiation [57], with no amplification, and long bunches, and more recently for amplified radiation, and a short bunch length [40,42].

A BNL group [44], has demonstrated high gain harmonic generation seeding the FEL with a 10.6 \( \mu \)m external laser and producing a 5.3 \( \mu \)m FEL output, with intensity \( 2 \times 10^7 \) larger than spontaneous radiation. The VISA group is commissioning a 0.8–0.6 \( \mu \)m experiment, using a 4 m long undulator with distributed strong focusing quadrupoles. Initial results have shown a gain of about 100 [45]. An experiment at Argonne uses the APS injector, with an energy of 220–444 MeV, wavelength 500–20 nm, and an 18 m
long undulator. SASE amplification as a function of undulator length has been demonstrated recently at 530 nm [46]. A DESY group is using the TESLA Test Facility superconducting linac. In Phase 1 the electron beam energy can reach up to 390 MeV, and a wavelength of 42 nm. Phase 2 will reach 1000 MeV, and 6 nm, with an undulator length of 30 m. Initial results have shown a gain of about $10^3$ over a wavelength range from 180 to 80 nm, the shortest wavelength ever obtained in an FEL [47]. Similar experimental programs on SASE-FELs are being prepared also in Japan, at Spring 8 and other laboratories, and in China.

The main results of the UCLA-LANL-RRIK-SSRL experiment are shown in Figs. 1 and 2. Fig. 1 shows an increase in output intensity by more than $10^4$, when changing the electron charge by a factor of seven. The bunch radius, energy spread, and length change with the charge, making impossible to have a simple analytical model to evaluate the intensity. The experimental data and the theory have been compared using the simulation code Ginger [58], and the measured values of all bunch parameters. The results are plotted in Fig. 1, and, within experimental errors, agree with the data. The intensity measured at a charge of 2.2 nC corresponds to a gain of $3 \times 10^5$, the largest measured until now in the infrared. The measured intensity fluctuations, shown in Fig. 2 are well described by a Gamma function with the M parameter evaluated from the experimental data, and is in agreement with the theory.

4. LCLS: an X-ray SASE-FEL

The first proposal for an X-ray SASE-FEL was made in 1992 [31], it was then developed by a study group until 1996 and by a design group that has prepared the LCLS design report [34]. The LCLS parameters are given in Table 1. The average brightness, $\langle B \rangle$, and peak brightness $B_p$, are measured in photons/s/mm$^2$/mrad$^2$/0.1% bandwidth.

The LCLS experimental setup is shown in Fig. 3. The electron beam is produced in a photo-cathode gun, developed by a BNL-SLAC-UCLA collaboration [50], and producing a bunch with a charge of 1 nC/bunch, normalized emittance, rms, 1 mm mrad; pulse length, rms, 3.3 ps [51]. The beam is then accelerated to 14.3 GeV and compressed to a peak current of 3400 A in the SLAC linac. During acceleration and compression the transverse and longitudinal phase-space densities are increased by space charge, longitudinal and transverse wake-fields, RF-curvature, coherent synchrotron radiation effects. The acceleration and compression system has been designed to minimize all these effects simultaneously, and it
limits the transverse emittance dilution to about 10% or less.

The planar hybrid LCLS undulator has vanadium permendur poles, Nd–FeB magnets, and $K=3.7$ [52]. It is built in sections about 3 m long, separated by 23.5 cm straight sections [53]. Since the natural undulator focusing is weak at the LCLS energy, additional focusing is provided by permanent magnet quadrupoles located in the straight sections. Optimum gain is obtained for a horizontal and vertical beta function of 18 m, giving a transverse beam radius of 30 $\mu$m, radiation Raleigh range of 20 m, twice the field gain length, making diffraction effects small. The FEL gain is sensitive to errors in the undulator magnetic field, and to deviation in the beam trajectory. Simulations of these effects, including beam position monitors and steering magnets along the undulator to correct the trajectory, show that the field error tolerance is 0.1%, and the beam trajectory error tolerance is about 2 $\mu$m [54].

LCLS generates coherent radiation at $\lambda \approx 1.5$ nm and its harmonics [59]. It also generates incoherent radiation, which, at 14.3 GeV, has a spectrum extending to about 500 keV, and a peak power density on axis of $10^{13}$ W/cm$^2$. The power density of the coherent first harmonic is about $2 \times 10^{14}$ W/cm$^2$, and the peak electric field is about $4 \times 10^{10}$ V/m. Filtering and focusing the radiation and transporting it to the experimental areas is a challenge. A normal incidence mirror at 100 m would see an energy flux of about 1 J/cm$^2$, about 1 eV/atom, large enough to damage exposed materials. The LCLS large power density will push the optical elements and instrumentation into a new strong field regime, but offers also new opportunities for scientific research.

### Table 1

LCLS electron beam, undulator, and FEL parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy, GeV</td>
<td>14.3</td>
</tr>
<tr>
<td>Peak current, kA</td>
<td>3.4</td>
</tr>
<tr>
<td>Normalized emittance, mm mrad</td>
<td>1.5</td>
</tr>
<tr>
<td>Energy spread, %, at undulator entrance</td>
<td>0.006</td>
</tr>
<tr>
<td>Bunch length, fs</td>
<td>67</td>
</tr>
<tr>
<td>Undulator period, cm</td>
<td>3</td>
</tr>
<tr>
<td>Undulator length, m</td>
<td>100</td>
</tr>
<tr>
<td>Undulator field, T</td>
<td>1.32</td>
</tr>
<tr>
<td>Undulator K</td>
<td>3.7</td>
</tr>
<tr>
<td>Undulator gap, mm</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength, nm</td>
<td>0.15</td>
</tr>
<tr>
<td>FEL parameter, $\rho$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Field gain length, m</td>
<td>11.7</td>
</tr>
<tr>
<td>Effective FEL parameter, $\rho_{\text{eff}}$</td>
<td>$2.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pulses/s</td>
<td>120</td>
</tr>
<tr>
<td>Peak coherent power, GW</td>
<td>9</td>
</tr>
<tr>
<td>Peak brightness</td>
<td>$10^{33}$</td>
</tr>
<tr>
<td>Average brightness</td>
<td>$4 \times 10^{22}$</td>
</tr>
<tr>
<td>Cooperation length, nm</td>
<td>51</td>
</tr>
<tr>
<td>Intensity fluctuation, %</td>
<td>8</td>
</tr>
<tr>
<td>Linewidth</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Total synchrotron radiation energy loss, GW</td>
<td>90</td>
</tr>
<tr>
<td>Energy spread due to synchrotron radiation emission</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Fig. 3. LCLS experimental setup.
5. Effects of undulator wake-fields and spontaneous radiation

The emission of spontaneous radiation by the electrons in the undulator has two main effects, a decrease of the electron energy, $W_{eR}$, and an increase of energy spread, $\sigma_{eR}$. Both effects can reduce the gain if the conditions $W_{eR}/E \leq \rho_{\text{eff}}$, $\sigma_{eR} \leq \rho_{\text{eff}}$, are not satisfied. The two quantities $W_{eR}$, $\sigma_{eR}$, have been evaluated in Ref. [60]. For the LCLS case we have $W_{eR}/E_{\text{beam}} \approx 1.8 \times 10^{-3} > \rho_{\text{eff}}$, $\sigma_{eR} \approx 1.5 \times 10^{-4} \approx \rho_{\text{eff}}$, and both effects have to be considered, even if the effect on the gain is not large. The average energy loss can be compensated by tapering the wiggler. The energy spread could be reduced using a shorter undulator.

For an X-ray FEL, with a large peak current, and a long undulator, the wake-fields in the undulator vacuum pipe can have an important effect on the lasing process, and can reduce the output power and change the temporal structure of the X-ray pulse. To evaluate these effects, we use a model which considers the effects of the vacuum pipe resistivity and roughness. The resistive longitudinal wake-field is [61]

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

(14)

where $t$ measures the longitudinal position of the test particle respect to the particle generating the field, $Z_0$ is the vacuum impedance, $\tau = (2R^2/Z_0\sigma)^{1/3}/c$, $\sigma$ is the conductivity of the material, and $R$ the pipe radius.

The effect of the pipe roughness has been evaluated by several authors. The first models of roughness impedance, based on a random distribution of surface bumps, were developed by Bane, Ng and Chao [62–64], and confirmed by Stupakov [66]. They give an inductive impedance proportional to $1/R$, depending on the ratio of bumps height to length. If this ratio is about one, and the field wavelength is larger than the bump height and width, then the rough surface can support the propagation of a wave synchronous with the beam. In this case the wake-field is rather strong, and the tolerance for LCLS is a bump height of about 40 nm. For a bump length much larger than the height, a different model, due to Stupakov, applies and the effect is much weaker. Electron microscope observations of the surface of a metal similar to that a vacuum pipe, reported in this paper [65], support this case.

In another model [67,68] the roughness is considered equivalent to a thin dielectric layer on the surface of the pipe, and the pipe can support a wave synchronous with the beam, giving a wake-field

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

(15)

where $\delta$ is the thickness of the layer, $Z_0$ the vacuum impedance, $k_0 = \sqrt{2e/(R\delta(\varepsilon - 1))}$, and it is assumed $\varepsilon \approx 2$.

To have no gain reduction from the wake-fields, we must satisfy the condition that the variation in energy that they induce be small compared to the gain bandwidth, $(\Delta E/E)_{\text{wake}} < \rho_{\text{eff}}$. In the LCLS case this gives the condition $W_z < 30$ KV/m.

6. Options for the choice of undulator and beam characteristics

The LCLS design shows the feasibility of an X-ray FEL. It is, however, possible to optimize the system by reducing the undulator saturation length; reducing in the ratio of total spontaneous synchrotron radiation to amplified coherent radiation; choosing electron beam parameters to reduce wake-field effects; controlling the X-ray pulse output power, pulse length, line-width.

The undulator saturation length is controlled by the FEL parameter $\rho$ (6) (5), by the ratio $e/\lambda$ (7), and by the electron energy spread (8). A reduction of the beam charge and emittance, keeping their ratio constant, leaves the 1-D gain length unchanged, and reduces the ratio $e/\lambda$. For systems, such as LCLS, where this ratio is larger than 1, this reduces the 3-D gain length. Reducing the charge can also reduce the FEL intensity, giving a way to control the output power [69], and reduces wake-field effects in the linac [70] and undulator.
An optimization of a SASE-FEL has been done in Ref. [71], where the five cases shown in Table 2 are discussed. One case is the LCLS. Cases A, B, D, use permanent magnet helical undulators with large gap and large field. For A, we use additional FODO focusing, while B uses only the natural undulator focusing; case D uses a lower beam charge, emittance and peak current. The beam parameter for this case have been obtained using the photo-cathode gun scaling laws [72], and discussed later in this sections. Case C uses a lower field helical undulator. The FEL power growth along the undulator for the 5 case has been evaluated using the numerical simulation code Genesis, and including the effect of synchrotron radiation emission, and of the resistive (14) and roughness wake-fields (15) in the undulator vacuum pipe. The total wake-field for the LCLS case is shown in Fig. 4. The wake-field violates the condition \( W_z < 30 \text{ KV/m} \) by almost a factor of ten. Even if we consider only the resistive wake-field this condition is violated in part of the bunch.

### Table 2

Parameters for helical undulator and low charge cases

<table>
<thead>
<tr>
<th></th>
<th>LCLS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy, GeV</td>
<td>14.3</td>
<td>14.7</td>
<td>14.7</td>
<td>12</td>
<td>14.7</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Normalized emittance, mm mrad</td>
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<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Peak current, kA</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>1.17</td>
</tr>
<tr>
<td>Energy spread, rms, %</td>
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<td>0.006</td>
<td>0.006</td>
<td>0.008</td>
<td>0.006</td>
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<tr>
<td>Undulator type</td>
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<td>Helical</td>
<td>Helical</td>
<td>Helical</td>
<td>3</td>
</tr>
<tr>
<td>Undulator period, cm</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Undulator parameter, K</td>
<td>3.7</td>
<td>2.7</td>
<td>2.7</td>
<td>1.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Undulator gap, mm</td>
<td>6</td>
<td>8.5</td>
<td>8.5</td>
<td>7.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Focusing beta function in undulator</td>
<td>18</td>
<td>17.7</td>
<td>73</td>
<td>20.5</td>
<td>5</td>
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<td>Total synchrotron radiation loss, GW</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td>11.6</td>
<td>10</td>
</tr>
<tr>
<td>Gain length, m</td>
<td>4.2</td>
<td>2.8</td>
<td>3.4</td>
<td>4.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Fig. 4.** Resistive and roughness wake-field along the electron bunch for LCLS [71].
The results from Genesis show that the undulator wake-fields produce an order of magnitude reduction in output power for the LCLS case, Fig. 5, and a smaller reduction in cases A, B, D. The reason for this reduction can be seen clearly in Fig. 6: only the electrons that have a small energy loss in traversing the undulator show gain, and these electrons are in a position in the bunch where the wake-field is near zero.

The power loss is less in case B, because of the larger undulator gap and of the smaller
undulator length. Wake-field effects are negligible in case C, Fig. 7, with a small peak current and undulator length. Due to the larger value of $\rho$, we have in case C the same output power as in the standard LCLS case, about 10 GWatt, while the spontaneous synchrotron radiation power is reduced from 90 to about 10 GWatt.

Two methods can be considered to reduce the charge and the emittance. One controls the laser intensity, spot size and phase on photocathode gun to minimize the emittance as a function of charge [72,73]. The scaling laws, neglecting the effect of thermal emittance, are

$$\varepsilon_N = 1.45 \times (0.38Q^{4/3} + 0.095Q^{8/3})^{1/2},$$

mm mrad, $Q$ in nC, \hfill (16)

$$\sigma_L = 6.3 \times 10^{-4} Q^{1/3}, \text{ m, } Q \text{ in nC}.$$ \hfill (17)

Another approach [74] is to produce a 1 nC bunch and then reduce the emittance and charge by collimation. As an example, with a collimator to beam rms radius ratio of 1.5, one can reduce the charge by a factor of 2.5 and the emittance by a factor of 5. The effect of the collimator wake-field on the emittance has also been studied and found to be small.

7. Conclusions

The possibility of large amplification of the spontaneous undulator radiation has been demonstrated in the recent SASE-FELs experiments in the infrared, visible, and UV spectral regions. The experimental results on the gain length and the intensity fluctuation distribution are in good agreement with the FEL collective instability theory. Gain as large as $3 \times 10^5$ have been observed in the infrared, bringing us near the saturation level, and large gain has been measured at a wavelength of 80 nm. Experiments over a range of wavelengths will continue, to study saturation, and the spectral, temporal, and angular properties of the SASE radiation, and completely characterize the FEL. These results, and the continued progress in the production, acceleration, measurements, and wake-field control of high brightness electron beams, together with the construction of high quality planar and helical undulators, will lead to a successfully operation of X-ray SASE-FEL in the next few years.
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