Bunch decompression for laser-plasma driven free-electron laser demonstration schemes

T. Seggebrock,[1,*] A. R. Maier,[1,2,3] I. Dornmair,[1] and F. Grüner[1,2,3]
[1]*Department für Physik, Ludwig-Maximilians-Universität, 85748 Garching, Germany*
[2]*Center for Free-Electron Laser Science, Notkestrasse 85, 22607 Hamburg, Germany*
[3]*Institut für Experimentalphysik, Universität Hamburg, 22607 Hamburg, Germany*
(Received 13 November 2012; published 29 July 2013)

X-ray free-electron lasers (FELs) require a very high electron beam quality in terms of emittance and energy spread. Since 2004 high quality electrons produced by laser-wakefield accelerators have been demonstrated, but the electron quality up to now did not allow the operation of a compact x-ray FEL using these electrons. Maier *et al.* [Phys. Rev. X **2**, 031019 (2012)] suggested a concept for a proof-of-principle experiment allowing FEL operation in the vacuum ultraviolet range based on an optimized undulator and bunch decompression using electron bunches from a laser-plasma accelerator as currently available. In this paper we discuss in more detail how a chicane can be used as a bunch stretcher instead of a bunch compressor to allow the operation of a laser-wakefield accelerator driven FEL using currently available electrons. A scaling characterizing the impact of bunch decompression on the gain length is derived and the feasibility of the concept is tested numerically in a demanding scenario.

DOI: 10.1103/PhysRevSTAB.16.070703 PACS numbers: 41.60.Cr, 52.38.Kd

I. INTRODUCTION

X-ray free-electron lasers (FELs) are the latest generation of high brightness photon sources. However, they require high quality electron beams in terms of emittance and energy spread. Since the demonstration of quasimonoenergetic electron beams produced by laser-wakefield acceleration (LWFA) [1] in 2004 [2–4], there has been a growing interest in realizing a tabletop FEL using this acceleration technique [5–8].

Up to now the electron beams produced by LWFA reach charges on the order of tens of pC in an rms bunch length of 0.5 μm [9,10]. Energies up to 1 GeV have been demonstrated [11] as well as relative rms energy spreads on the order of 1% [12]. Recent emittance measurements showed a normalized emittance of $\epsilon_n = 0.2$ mm mrad [13].

This combination of charge and energy spread, however, is still not suitable for driving a compact x-ray FEL since it does not fulfill the requirement on the relative energy spread $\sigma_\gamma/\gamma < 0.5\rho_{\mathrm{FEL}}$ for FELs operating in the ultraviolet or x-ray range with typical Pierce parameters [14] on the order of $\rho_{\mathrm{FEL}} = 10^{-3}$–$10^{-4}$. Although relative energy spreads on the order of 1% have already been demonstrated it is not yet sure whether a reduction down to the range defined by typical Pierce parameters will be possible. An additional problem is the superradiant behavior [15] considering the bunch lengths of about 0.5 μm and less [9,10] in combination with a cooperation length on the same order of magnitude.

Different approaches to improve the FEL performance in the presence of large energy spreads have been suggested. One is to modulate the electron energy distribution using an inverse FEL process and a chicane [16]. However, this concept is not applicable for cooperation lengths on the order of the bunch length. Another approach is to disperse the bunch in the transverse direction and match the resulting position-energy correlation to a transverse gradient undulator [17]. This approach is not limited by the combination of a short bunch and long cooperation length, however, only the impact of the energy spread can be reduced in this setup. It is therefore especially suited for scenarios aiming at short radiation wavelengths and cooperation lengths significantly below the bunch length. We present an alternative approach to drive an FEL with LWFA beams, which is suited for the vacuum ultraviolet (VUV) wavelength range and allows for the operation of an FEL demonstration experiment using bunches currently available from LWFA, i.e., the setup is optimized for large energy spreads and bunch lengths on the order of the cooperation length.

In this paper we discuss in more detail how bunch decompression [8,18,19] can be used to reduce the gain length in high energy spread scenarios especially in combination with short electron bunches, to allow the operation of an x-ray FEL demonstration experiment with electrons close to that from recent LWFA experiments and a relative energy spread on the order of the Pierce parameter. We demonstrate the feasibility of this concept in a scenario expanding the case discussed in [18] towards shorter wavelengths, while still requiring electron parameters close to current experiments.

*thorben.seggebrock@physik.uni-muenchen.de

First we discuss the theoretical scaling of the gain length in the presence of an energy spread on the order of the Pierce parameter and how the gain can be optimized by stretching the bunch in a 1D model (Sec. II A). Then we discuss an approximation taking the effect of short bunches into account (Sec. II B) and derive a combined scaling (Sec. II C). This is followed by a discussion of the scaling of coherent spontaneous emission when decompressing the bunch (Sec. III) since this might be mistaken for an FEL signal. In Sec. IV we test the gain scaling using 1D and 3D simulations. Finally, we present a 3D simulation of a complete setup including degrading effects like coherent synchrotron radiation, chromaticity, and space charge using ELEGANT [20] and GENESIS [21] demonstrating the feasibility of the concept in a specific case (Sec. V).

II. THEORETICAL DESCRIPTION

In this section we will discuss how energy spread and bunch length affect the FEL gain process independently and derive a combined scaling taking both effects into account. In all cases the scaling of the gain length when using bunch decompression is discussed.

A. Energy spread

In general the evolution of the field amplitude in an FEL can be characterized by an exponential ansatz $E(z) = \sum_i A_i \exp(\alpha_i z)$. In order to describe the gain of an FEL in the 1D theory for arbitrary energy distributions the dispersion relation [22],

$$\alpha = (\mathrm{i}\Gamma^3 - k_p^2 \alpha) \int_{-\delta}^{+\delta} \frac{f_0(\eta)}{(\alpha + \mathrm{i}2k_u \eta)^2} \mathrm{d}\eta, \tag{1}$$

has to be solved for the three eigenvalues α_i. The parameters used are the gain parameter Γ, the plasma wave number k_p, the relative energy deviation $\eta = (\gamma - \gamma_r)/\gamma_r$ with $\gamma_r = \sqrt{\lambda_u(1 + K^2/2)/(2\lambda_l)}$ being the resonant energy, the radiation wavelength λ_l, the undulator wave number $k_u = 2\pi/\lambda_u$, the undulator parameter K, and the energy distribution $f_0(\eta)$. An analytical solution for the typical case of a Gaussian distribution

$$f_0(\eta) = \frac{1}{\sqrt{2\pi}\sigma_\eta} \exp\left[-\frac{1}{2}\left(\frac{\eta - \eta_0}{\sigma_\eta}\right)^2\right], \tag{2}$$

using the relative energy spread $\sigma_\eta = \sigma_\gamma/\gamma_0$ and the detuning with respect to the resonant energy $\eta_0 = (\gamma_0 - \gamma_r)/\gamma_r$, is not possible. However, asymptotic solutions for the real part of the largest eigenvalue characterizing the growth rate of the FEL power can be found [23]. In the case of a small normalized energy spread $\Delta^2 = \sigma_\gamma^2/(\gamma\rho_{\mathrm{FEL}})^2 \ll 1$ with ρ_{FEL} being the Pierce parameter the growth rate of the FEL power is given by [23]

$$\Re(\alpha_1) \simeq \frac{\sqrt{3}}{2}(1 - \Delta^2) 2k_u \rho_{\mathrm{FEL}}. \tag{3}$$

For the case of a large energy spread $\Delta^2 \gg 1$ the growth rate is given by [23]

$$\Re(\alpha_1) \simeq \frac{0.76}{\Delta^2} 2k_u \rho_{\mathrm{FEL}}. \tag{4}$$

The resulting normalized gain length as a function of the normalized energy spread can therefore be approximated for all cases by

$$\frac{L_g(\Delta)}{L_{g,1\mathrm{D}}} = \frac{1}{2\Re(\alpha_1)} \frac{1}{L_{g,1\mathrm{D}}} \approx 1 + \Delta^2, \tag{5}$$

with $L_{g,1\mathrm{D}}$ being the ideal 1D gain length in the case of no energy spread. This resembles the 1D limit of the well-known gain length scaling derived by Xie [24]. The approximated scaling as well as the two asymptotic cases are shown in Fig. 1.

In the case of an uncorrelated energy spread on the order of the Pierce parameter the gain length can be reduced by decompressing the bunch, e.g., in a chicane. We neglect the resulting energy chirp since it can be compensated by an equivalent taper of the undulator [25]. Stretching the bunch in the chicane increases the bunch length by a factor n, consequently the current is reduced by $1/n$. The ideal gain length scales as $L_{g,1\mathrm{D}} \propto \rho_{\mathrm{FEL}}^{-1} \propto I^{-1/3} \propto n^{1/3}$. The local energy spread σ_γ scales as $1/n$ and therefore the normalized energy spread as $\Delta \propto n^{-2/3}$. These different scalings already suggest that a reduction of the gain length by using bunch decompression is possible in energy spread dominated cases. The actual gain length in the case of a bunch stretched by the factor n with an initial normalized energy spread Δ scales according to

$$L_g(n, \Delta) = \left(1 + \frac{\Delta^2}{n^{4/3}}\right) n^{1/3} L_{g,1\mathrm{D}}. \tag{6}$$

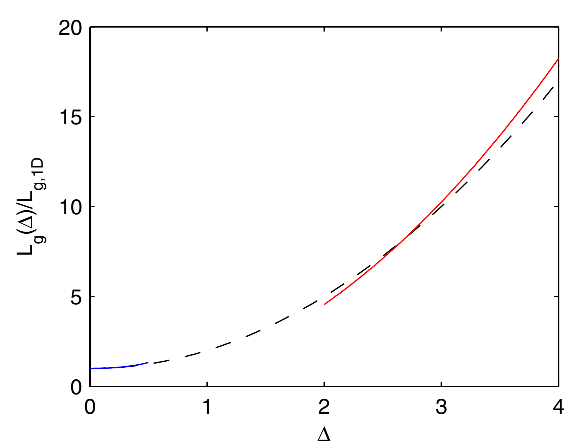

FIG. 1. Approximated normalized gain length $L_g(\Delta)/L_{g,1\mathrm{D}}$ as a function of the normalized energy spread $\Delta = \sigma_\gamma/(\gamma\rho_{\mathrm{FEL}})$ (dashed black). Asymptotic analytical solutions for $\Delta^2 \ll 1$ (blue) and $\Delta^2 \gg 1$ (red).

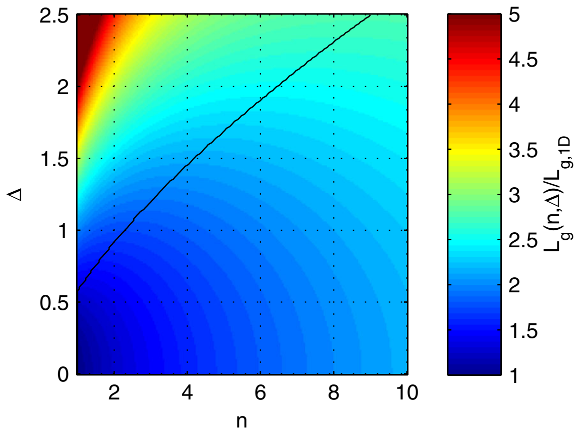

FIG. 2. Normalized gain length $L_g(n, \Delta)/L_{g,1D}$ as a function of the stretching factor n and the initial normalized energy spread Δ. The black line marks the ideal stretching factor resulting in the shortest gain length for each initial normalized energy spread. Dark red are regions with a normalized gain length of 5 and higher.

Figure 2 shows the resulting scaling of the gain length ratio $L_g(n, \Delta)/L_{g,1D}$. In general, a reduction of the gain length is possible for all normalized energy spreads higher than $\Delta \approx 0.6$; below this the well-known scheme of bunch compression is of advantage. The ideal stretching factor minimizing the gain length scales as

$$n_{\rm opt} = 3^{3/4}\Delta^{3/2}. \tag{7}$$

In the case of a normalized energy spread $\Delta = 1$, relation (6) has a minimum at a stretching factor of $n \approx 2.3$ and the gain length is reduced by 13% allowing a significant improvement of the resulting FEL performance when compared to the reference case with $n = 1$.

B. Bunch length

Besides the energy spread, the short bunch length of about 500 nm expected from LWFA electrons [9,10] can reduce the FEL gain in the case when the cooperation length, defined as the slippage length of the radiation over one gain length $L_c = \lambda_l L_g/\lambda_u$, is on the same order. This is caused by the reduced interaction length due to the radiation slippage. An analytical scaling for the power growth in this regime is discussed in [15,26]; however, it is only valid for flattop current profiles and therefore not suited for typical bunches expected from a LWFA. A fit for the scaling of the gain length in the case of a Gaussian current profile based on non-period-averaged 1D simulations has been obtained by Bajlekov [27],

$$L_g(\sigma_z) = (1 + \eta_z)L_{g,1D}, \tag{8}$$

using

$$\eta_z = b_1 \exp\left[b_2\left(\frac{\sigma_z}{L_{c,1D}}\right)^{b_3}\right], \tag{9}$$

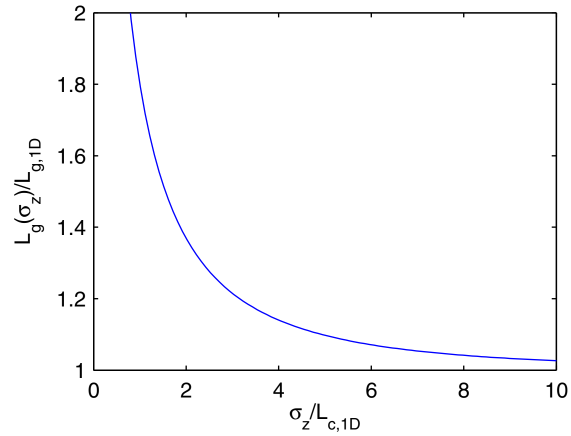

FIG. 3. Normalized gain length $L_g(\sigma_z)/L_{g,1D}$ as a function of the normalized bunch length $\sigma_z/L_{c,1D}$.

with the bunch length σ_z, the cooperation length $L_{c,1D} = \lambda_l L_{g,1D}/\lambda_u$, and the fit parameters

$$b_1 = 16.7512, \qquad b_2 = -3.0420, \qquad b_3 = 0.3267.$$

The resulting scaling of the normalized gain length as a function of the normalized bunch length is shown in Fig. 3. As in the energy spread discussion we find two competing scalings. On the one hand, the ideal 1D gain length increases as $n^{1/3}$; on the other the normalized bunch length increases as $\sigma_z/L_c \propto n^{2/3}$. This suggests again a possible reduction of the resulting gain length by stretching the bunch, but this is not the case. The gain length scales as

$$L_g(n, \sigma_z) = \left\{1 + b_1 \exp\left[b_2\left(\frac{\sigma_z}{L_{c,1D}} n^{2/3}\right)^{b_3}\right]\right\} n^{1/3} L_{g,1D}, \tag{10}$$

using the initial normalized bunch length $\sigma_z/L_{c,1D}$ and the stretching factor n. For all values of $\sigma_z > 0$ and $n \geq 1$ this is a monotonically increasing function of n. Consequently, a reduction of the gain length by increasing the normalized bunch length σ_z/L_c using bunch decompression is not possible as long as the energy spread is neglected.

C. Combined scaling

Since an FEL driven by a typical LWFA bunch is subject to both degrading effects discussed above, it is crucial to analyze the combined scaling taking energy spread and bunch length into account. This can be accomplished by applying the energy spread scaling first and using the resulting gain length for the correction due to the bunch length. The combined scaling reads

$$L_g(n, \Delta, \sigma_z) = \left\{1 + b_1 \exp\left[b_2\left(\frac{n\sigma_z}{L_c(n, \Delta)}\right)^{b_3}\right]\right\} \times \left(1 + \frac{\Delta^2}{n^{4/3}}\right) n^{1/3} L_{g,1D}, \tag{11}$$

using the cooperation length in the case of energy spread and stretching $L_c(n, \Delta) = \lambda_l L_g(n, \Delta)/\lambda_u$. In this combined scaling one can see that stretching short bunches with high energy spreads is even more useful than expected from the simple scalings above. The reduction of the gain length due to the reduced local energy spread after stretching results in a second reduction of the gain length due to the elongated bunch and the reduced cooperation length.

Figure 4 shows the combined scaling for the ideal normalized bunch lengths $\sigma_z/L_{c,1D} = 3$ and $\sigma_z/L_{c,1D} = 1$. One can see that in the case of a short bunch and a given energy spread Δ the stretching factor resulting in the minimum gain length shifts towards higher values of n when compared to the case without bunch length correction.

In the case of an initial normalized energy spread $\Delta = 1$ and an initial normalized bunch length of $\sigma_z/L_{c,1D} = 1$ the ideal stretching factor is increased to $n \approx 5.5$ and the gain length is reduced by 52%. This shows that in the case of short bunches and high energy spreads an even larger reduction of the gain length is possible by decompressing the bunch than expected by the simple energy spread scaling, although, the bunch length scaling alone allows no reduction of the gain length by decompression.

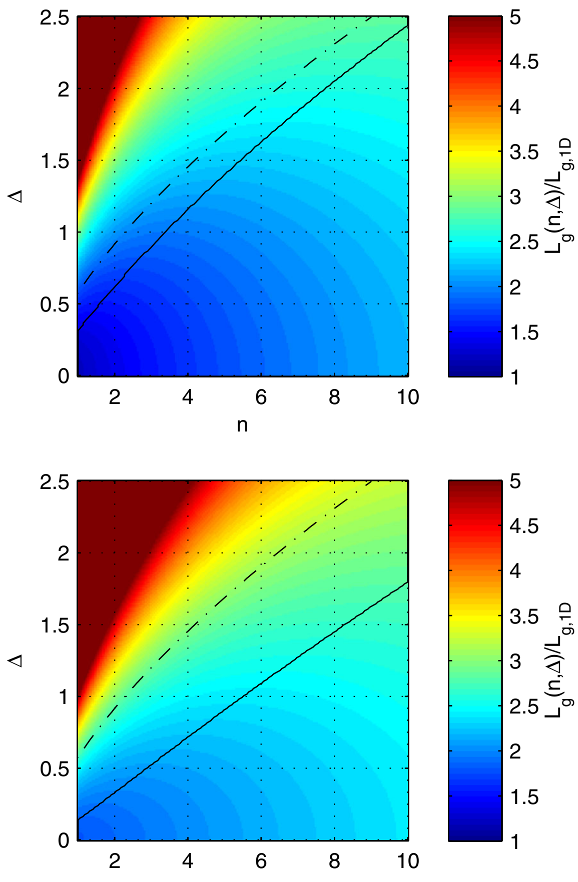

FIG. 4. Normalized gain length $L_g(n, \Delta)/L_{g,1D}$ as a function of the stretching factor n and the normalized energy spread Δ for an ideal, initial normalized bunch length $\sigma_z/L_{c,1D} = 3$ (top) and $\sigma_z/L_{c,1D} = 1$ (bottom). The solid black line marks the ideal stretching factor resulting in the shortest gain length for each initial normalized energy spread; the dashed line marks the ideal stretching factor expected without bunch length correction. Dark red are regions with a normalized gain length of 5 and higher.

III. COHERENT SPONTANEOUS EMISSION

In addition to the FEL performance also the power of the spontaneous undulator radiation can be influenced by the decompression concept. Because of the bunch length on the order of the resonant wavelength coherent spontaneous emission (CSE) [28,29] can become intense depending on the current profile. The power of the spontaneous radiation is given by the sum of the incoherent and coherent contribution [29],

$$P(k) = N_e P_1 + N_e^2 P_1 f(k), \tag{12}$$

with the number of electrons in the bunch N_e, the power emitted by a single electron P_1, and the longitudinal form factor of the bunch $f(k)$. The form factor is defined as [29]

$$f(k) = \left| \int S(z) \exp(\mathrm{i}kz) \mathrm{d}z \right|^2, \tag{13}$$

using the normalized longitudinal current profile $S(z)$ and the wave number $k = k_l - k_u$, with $k_l = 2\pi/\lambda_l$. The ratio of coherent to incoherent power is therefore given by

$$\frac{P_{\mathrm{coh}}}{P_{\mathrm{incoh}}} = N_e f(k). \tag{14}$$

This ratio can reach high values depending on the charge and the current profile. In addition to that it can show shot-to-shot fluctuations due to instabilities in the acceleration process. The so obtained power measurements could be mistaken for an FEL signature especially in first proof-of-principle experiments having a few gain lengths only [30]. This detection problem can be counteracted by the decompression concept. While the FEL performance can be significantly increased by decompressing the bunch, the coherent fraction of the spontaneous emission will drop.

We have analyzed the impact of three idealized current profiles (Gaussian, flattop, and parabola) for a typical proof-of-principle parameter set as shown in Table I. Since this effect will be most significant for long resonant wavelengths we used the parameters leading to lasing at 134 nm. In the case of a typical Gaussian bunch the coherent fraction of the spontaneous emission is on the order of $N_e f(k) \approx 10^{-100}$ and therefore completely negligible. Assuming fast rising bunch edges like in the case of a flattop or parabola shaped current profile with the same full width at half maximum as the Gaussian profile, however, leads to a significant coherent contribution. Both are compared in Fig. 5 assuming that the shape of the current profile is retained during decompression. For a flattop current profile the coherent spontaneous emission remains

TABLE I. Setup and electron parameters for long and short wavelength case used in 1D and 3D simulation.

Undulator		
λ_u [mm]	15	
K	3.3	
L [m]	3	
Electrons		
Q [pC]	15.0	20.0
γ	600	1000
σ_γ/γ [%]	1.0	
σ_z [μm]	0.5	
$\sigma_{x,y}$ [μm]	20.0	
ϵ_n [mm mrad]	0.2	
Derived parameters		
λ_l [nm]	134	48.3
ρ_{FEL}	1.75×10^{-2}	1.15×10^{-2}
$L_{g,1\mathrm{D}}$ [cm]	3.95	5.98
$L_{c,1\mathrm{D}}$ [nm]	354	193
Chicane		
R_{56} [μm]		141

intense even when decompressing the bunch. In the case of a parabola like bunch, however, the coherent fraction decreases fast when stretching the bunch and drops under the limit for an FEL signature of $P_{\mathrm{FEL}}/P_{\mathrm{incoh}} = 10$ as proposed in [18] even for a decompression factor of only $n \approx 2.5$.

In a more realistic model taking the evolution of the bunch shape due to decompression of a bunch with a Gaussian energy spread into account the scaling changes significantly. For $R_{56}\sigma_\gamma/\gamma \gtrsim l_b$, with l_b being the bunch

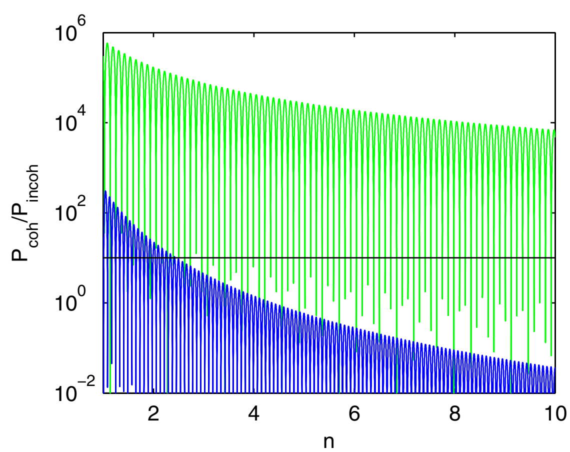

FIG. 5. Ratio of coherent to incoherent power as a function of the decompression factor for a flattop bunch (green) and a parabola shaped bunch (blue). The bunch parameters correspond to the long wavelength case shown in Table I. The detection threshold for an FEL signature of $P_{\mathrm{FEL}}/P_{\mathrm{incoh}} = 10$ as proposed in [18] is marked by the solid black line.

length, the bunch shape converges to a Gaussian with a width of $\sigma_z = R_{56}\sigma_\gamma/\gamma$ and the CSE signal drops exponentially independent of the initial bunch shape.

Tracking of actual electron bunches confirms the basic scaling of the analytic results. However, it shows that the noise in the random electron distribution leads to a minimum of $N_e f(k) \approx 10^0$ independent of the initial bunch profile. This is higher than expected by the idealized analytical scaling but still below the limit for an FEL signature.

In summary this shows that the decompression concept allows one to reduce the impact of CSE and that the power contribution for realistic bunch profiles can be reduced so that it cannot be mistaken for an FEL signal in a first proof-of-principle experiment.

IV. FEL SIMULATION

As a test of the combined scaling we performed time-dependent simulations with a period-averaged 1D code [31] based on the equations from [22]. In addition to that we used the 3D code GENESIS [21] as a further verification. The parameters are shown in Table I and correspond to a first proof-of-principle experiment operating at $\lambda_l \approx 134$ nm [18] and its extension towards shorter wavelengths at $\lambda_l \approx 48$ nm. This extension aims at a more interesting wavelength range for applications and should result in the reduction of the gain degradation due to slippage, although the energy spread impact will be increased due to the lower Pierce parameter. Both scenarios use the same undulator design and basic parameter set as discussed in [18]. Consequently, they are optimized for high energy spread acceptance by maximizing the Pierce parameter to allow for a first FEL demonstration with currently available electrons from LWFA. The electron parameters have either already been obtained in recent experiments or are at least very close to recent data [9,10,12,13]. The current profile is assumed to be Gaussian with $\sigma_z = 0.5$ μm rms length [9,10], containing a charge of $Q = 15$ pC in the long wavelength case and $Q = 20$ pC in the short wavelength case. In general the charge has been chosen to be as low as possible while still providing sufficient FEL gain after bunch decompression for the given undulator setup and electron energy. We use a normalized transverse emittance of $\epsilon_n = 0.2$ mm mrad [13] in combination with moderate normalized energies of $\gamma = 600$ in the long wavelength case and $\gamma = 1000$ in the short wavelength case. The relative energy spread is fixed to 1% in both cases and has already been demonstrated for a 150 MeV beam [12].

The stretching scenarios are modeled by using bunches with the same charge but different bunch length, slice energy spread, and chirp values according to

$$\sigma_z(n) = n\sigma_{z,0}, \tag{15}$$

$$\frac{\sigma_\gamma}{\gamma}(n) = \frac{1}{n}\frac{\sigma_{\gamma,0}}{\gamma}, \tag{16}$$

$$\frac{d\gamma}{cdt}(n) = \frac{\sigma_{\gamma,0}}{n\sigma_{z,0}}, \quad (17)$$

with $\sigma_{z,0}$ being the initial bunch length and $\sigma_{\gamma,0}/\gamma$ the initial normalized energy spread. The chirp has been compensated by tapering the undulator according to [25]

$$\frac{dK}{dz} = -\frac{\left(1+\frac{K_0^2}{2}\right)^2}{K_0\gamma^3}\frac{d\gamma}{cdt}, \quad (18)$$

with K_0 being the undulator parameter at the center of the undulator.

In both discussed cases the ideal cooperation length ($L_{c,1D,48\,\mathrm{nm}} \approx 193$ nm and $L_{c,1D,134\,\mathrm{nm}} \approx 354$ nm) is on the order of the bunch length, so a significant impact of the bunch length correction can be expected causing an additional increase of the gain length and expected stretching factor.

The resulting scaling of the gain length for the two cases is shown in Fig. 6 together with the derived scalings for the gain length with and without bunch length correction. The scaling obtained from the 1D simulation shows a slight deviation from the combined scaling for low stretching factors. This can be attributed to the fact that the fit characterizing the bunch length correction (9) was obtained using a non-period-averaged code [27]. In contrast to this the code used here is period averaged and could therefore underestimate the gain for short bunches [32]. This effect is especially noticeable in the long wavelength case where the normalized energy spread is lower and the gain degradation is dominated by the short normalized bunch length. In the short wavelength case the gain reduction due to slippage is significantly reduced as expected from the shorter wavelength. However, in both cases the need for the bunch length correction can be seen by comparing both derived scalings and the simulation data. Especially in the long wavelength case the bunch length correction is of importance, since the scaling depending only on the energy spread suggests no reduction of the gain length.

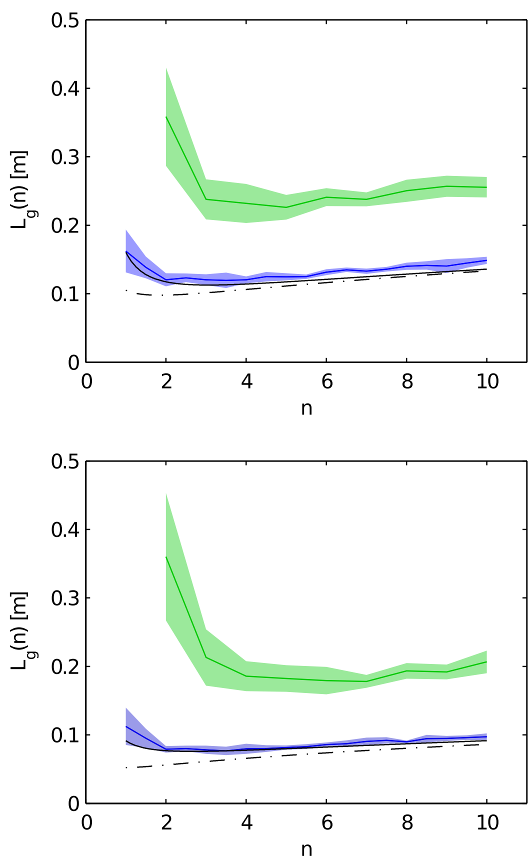

FIG. 6. Gain length $L_g(n)$ as a function of the stretching factor n for the short wavelength case (top) and long wavelength case (bottom) obtained from 1D simulation (blue), GENESIS (green), and analytical estimate with bunch length correction (solid black) and without (dash-dotted black). For each data point ten simulation runs with different shot noise seeds were averaged and the shaded areas indicate the standard deviation.

The high gain length values from the 3D simulation are caused by the inclusion of additional degrading effects like diffraction, space charge, and the evolution of the beam envelope in the undulator. For unstretched bunches $n = 1$ the GENESIS simulations showed a linear power growth resulting from spontaneous radiation and therefore no gain length could be estimated.

Despite the differences in the absolute values regarding the gain length, the combined scaling as well as the 1D and 3D simulations show that decompressing the bunch in these energy spread and bunch length dominated cases significantly improves the FEL performance or even is essential for allowing FEL operation at all. The ideal stretching factors are in good agreement with the analytical results and suggest an ideal bunch decompression with $n \approx 4$ in both cases.

In addition to the here presented cases, the combined scaling also allows one to estimate the stretching factor resulting in the shortest gain length for the case considered in [18]. There we discussed an FEL operating at 134 nm with a Pierce parameter of $\rho_{\mathrm{FEL}} \approx 1.8 \times 10^{-2}$, a relative energy chirp of $d\gamma/(\gamma c dt) = 1\%/0.5\ \mu$m, a relative slice energy spread of $\sigma_\gamma/\gamma = 0.5\%$, and an ideal cooperation length of $L_{c,1D} \approx 341$ nm. Since we did not use an appropriately tapered undulator to compensate the chirp in [18], the here mentioned scaling is not perfectly suited. We can, however, estimate an effective normalized energy spread by taking the slice energy spread and the additional energy spread accumulated over one gain length due to the uncompensated chirp into account. This results in an effective normalized energy spread of

$$\Delta_{\mathrm{eff}} = \frac{\sqrt{\sigma_\gamma^2 + [\frac{d\gamma}{cdt}L_c(\sigma_\gamma)]^2}}{\gamma\rho} \approx 0.55. \quad (19)$$

Using this effective normalized energy spread as a starting point for Xie's scaling [24] in combination with the bunch length scaling we obtain an ideal stretching factor of $n \approx 3.5$ matching the result of $n \approx 4$ obtained from GENESIS simulations in [18] very well.

V. COMPLETE SETUP

Having tested the combined scaling using idealized bunches, we now demonstrate the feasibility of the concept in a complete 3D simulation of the short wavelength case. ELEGANT [20] was used to track the electrons through the beam optics, i.e., a focusing system and a chicane, and GENESIS was used for the SASE FEL simulation. The simulation of the beam optics takes coherent synchrotron radiation (CSR) emitted in the chicane and the chromaticity of the focusing system into account. GENESIS has been used in the time-dependent mode to include slippage effects. In addition to that longitudinal space charge effects were enabled. The long wavelength case in a low charge version has already been discussed in [18]. In this paper we consider the short wavelength case, since it is of higher interest when it comes to first applications and allows the test of the stretching concept for a higher bunch charge and therefore a higher risk of bunch degradation due to CSR.

The layout of the setup is as follows: the electrons are focused by a permanent magnet quadrupole triplet with gradients of $g = 500$ T/m [33], with the focus being in the center of the undulator. The chicane is designed to stretch the bunch by a factor of 3 resulting in the $R_{56} \approx 141$ μm. The chicane length of about 1 m and the moderate decompression are a compromise between optimizing gain and limiting CSR emission while still being as compact and minimalistic as possible for the desired R_{56}. This leads to an emittance growth of ~10%. Since ELEGANT only uses a 1D CSR model this has been cross-checked with the fully 3D code CSRTRACK [34], confirming the low emittance growth. A further reduction of CSR effects is possible by switching to an asymmetric chicane layout [35], but this was not necessary in the discussed case.

Three different cases have been simulated: first, the unstretched case, i.e., only the focusing system without the chicane, as a reference; second, the stretched case, i.e., the focusing system and the chicane, without tapering; and third, the stretched case with the appropriate tapering according to Eq. (18) $dK/dz = 0.0839$ m^{-1}, which is technically feasible considering the short undulator length. The resulting power evolution along the undulator within 100% bandwidth around the resonant wavelength obtained from time-dependent GENESIS runs is shown in Fig. 7. The average power in the radiation pulse has been normalized to the average spontaneous power in the pulse.

With activated chicane and appropriate tapering the mean power at the end of the undulator was increased by more than 1 order of magnitude compared to the unstretched case. There the power rise is dominated by spontaneous emission and shows a nearly linear rise, except for a short boost at the center of the undulator where the current density reaches its maximum. Stretching the bunch and applying the tapering leads to an exponential power growth with a mean gain length of 34 cm. The gain length is not as good as expected from the scan discussed in the previous section; this is the result of the additional degrading effects introduced by the beam optics. However, this demonstrates the feasibility of the concept and shows that by bunch decompression the FEL performance can be significantly improved. The higher bunch charge and therefore more intense CSR did not pose a problem to the decompression concept.

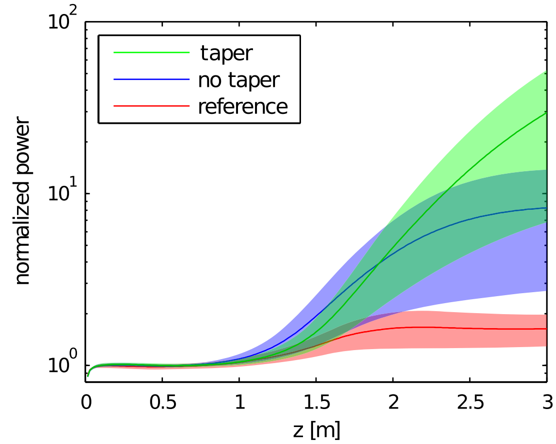

FIG. 7. Evolution of the average radiation power in the pulse normalized to the power of the spontaneous radiation simulated with GENESIS in the time-dependent mode for the unstretched bunch (red), the stretched bunch without tapering (blue), and the tapered case (green). All three cases have been averaged over ten independent runs using different shot noise seeds. The solid lines represent the mean, the shaded areas the standard deviation.

VI. CONCLUSION

In this paper we discussed how bunch decompression can be used to reduce the gain length in an FEL when using bunches with relative energy spreads on the order of the Pierce parameter and bunch lengths on the order of the cooperation length. This is of special interest when considering FEL experiments driven by currently available laser-plasma accelerators.

We analyzed the impact of the energy spread and the bunch length on the gain length independently when using bunch decompression and tested a scaling combining both effects, indicating the possibility for significant gain length reductions via bunch decompression. This scaling was shown to be in good agreement with 1D and 3D simulations when searching for an ideal stretching factor resulting in the shortest gain length and allows a better understanding of the impact of bunch decompression on the gain length in the discussed cases.

We considered two scenarios both aiming for a first FEL demonstration experiment using currently available electrons from LWFA to test the derived scaling and the decompression concept. Both cases were based on the same undulator design and basic parameter set [18] and only differed in electron energy and bunch charge. Bunch decompression lead to a significant reduction of the gain length in the two considered cases. The inclusion of the bunch length in the discussed scaling was shown to be crucial for correctly modeling the scaling of the gain length. The combined scaling could even be used to reproduce data obtained from an extensive parameter scan using GENESIS in [18], although the considered case did not use an appropriate undulator taper.

In addition to the scaling of the FEL performance we discussed the scaling of CSE under decompression. It was found that the decompression scheme can be used to significantly reduce the emitted CSE power so that it cannot be mistaken for an FEL signal in first proof-of-principle experiments having a few gain lengths only.

The feasibility of the concept was demonstrated for a case with a resonant wavelength as short as 48 nm using ELEGANT for the simulation of the beam optics including bunch degradation due to CSR and chromatic effects, and GENESIS in the time-dependent mode for the simulations of the FEL process including tapering, slippage, and space charge effects. This case is of special interest since it demonstrates that the decompression concept can still be used when reducing the wavelength towards more interesting ranges for applications and using the higher bunch charges required for this. The normalized power could be increased by more than 1 order of magnitude using the decompression concept, which was essential for enabling the FEL gain process.

ACKNOWLEDGMENTS

The authors would like to thank A. Meseck, C. B. Schroeder, and S. Reiche for fruitful discussions and acknowledge support by the DFG Excellence Cluster Munich-Centre for Advanced Photonics (MAP).

[1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. **81**, 1229 (2009).

[2] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, Nature (London) **431**, 541 (2004).

[3] C. G. R. Geddes, C. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, Nature (London) **431**, 538 (2004).

[4] S. Mangles, C. D. Murphy, Z. Najmudin, A. Thomas, J. L. Collier, A. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. Mori, P. Norreys, F. Tsung, R. Viskup, B. Walton, and K. Krushelnick, Nature (London) **431**, 535 (2004).

[5] F. Grüner, S. Becker, U. Schramm, T. Eichner, M. Fuchs, R. Weingartner, D. Habs, J. Meyer-ter Vehn, M. Geissler, M. Ferrario, L. Serafini, B. van der Geer, H. Backe, W. Lauth, and S. Reiche, Appl. Phys. B **86**, 431 (2007).

[6] C. B. Schroeder, W. M. Fawley, F. Grüner, M. Bakeman, K. Nakamura, K. E. Robinson, C. Toth, E. Esarey, and W. P. Leemans, AIP Conf. Proc. **1086**, 637 (2009).

[7] K. Nakajima, Nat. Phys. **4**, 92 (2008).

[8] C. B. Schroeder, C. Benedetti, E. Esarey, W. P. Leemans, J. V. Tilborg, Y. Ding, Z. Huang, F. Grüner, and A. R. Maier, in *Proceedings of the 34th International Free Electron Laser Conference* (Nara, Japan, 2012).

[9] A. Buck, M. Nicolai, K. Schmid, C. M. S. Sears, A. Sävert, J. M. Mikhailova, F. Krausz, M. C. Kaluza, and L. Veisz, Nat. Phys. **7**, 543 (2011).

[10] O. Lundh, J. Lim, C. Rechatin, L. Ammoura, A. Ben-Ismaïl, X. Davoine, G. Gallot, J.-P. Goddet, E. Lefebvre, V. Malka, and J. Faure, Nat. Phys. **7**, 219 (2011).

[11] W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Toth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, Nat. Phys. **2**, 696 (2006).

[12] S. M. Wiggins, R. C. Issac, G. H. Welsh, E. Brunetti, R. P. Shanks, M. P. Anania, S. Cipiccia, G. G. Manahan, C. Aniculaesei, B. Ersfeld, M. R. Islam, R. T. L. Burgess, G. Vieux, W. A. Gillespie, A. M. MacLeod, S. B. van der Geer, M. J. de Loos, and D. A. Jaroszynski, Plasma Phys. Controlled Fusion **52**, 124032 (2010).

[13] R. Weingartner, S. Raith, A. Popp, S. Chou, J. Wenz, K. Khrennikov, M. Heigoldt, A. R. Maier, N. Kajumba, M. Fuchs, B. Zeitler, F. Krausz, S. Karsch, and F. Grüner, Phys. Rev. ST Accel. Beams **15**, 111302 (2012).

[14] R. Bonifacio, C. Pellegrini, and L. Narducci, Opt. Commun. **50**, 373 (1984).

[15] R. Bonifacio, C. Maroli, and N. Piovella, Opt. Commun. **68**, 369 (1988).

[16] G. Stupakov, Y. Ding, and Z. Huang, in *Proceedings of the 31st International Free Electron Laser Conference* (STFC Daresbury Laboratory, Warrington, UK, 2009).

[17] Z. Huang, Y. Ding, and C. B. Schroeder, Phys. Rev. Lett. **109**, 204801 (2012).

[18] A. R. Maier, A. Meseck, S. Reiche, C. B. Schroeder, T. Seggebrock, and F. Grüner, Phys. Rev. X **2**, 031019 (2012).

[19] D. Xiang, Report No. SLAC-PUB-15196, 2012.

[20] M. Borland, Advanced Photon Source Technical Report No. LS-287, 2000.

[21] S. Reiche, Nucl. Instrum. Methods Phys. Res., Sect. A **429**, 243 (1999).

[22] P. Schmüser, M. Dohlus, and J. Rossbach, *Ultraviolet and Soft X-Ray Free-Electron Lasers*, Springer Tracts in Modern Physics Vol. 229 (Springer, Berlin Heidelberg, 2008).

[23] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, *The Physics of Free Electron Lasers* (Springer, Berlin, 2000).

[24] M. Xie, Nucl. Instrum. Methods Phys. Res., Sect. A **445**, 59 (2000).

[25] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Phys. Rev. ST Accel. Beams **9**, 050702 (2006).

[26] R. Bonifacio, L. De Salvo, P. Pierini, N. Piovella, and C. Pellegrini, Phys. Rev. Lett. **73**, 70 (1994).

[27] S. Bajlekov, Ph.D. thesis, University of Oxford, 2011.

[28] A. Doria, R. Bartolini, J. Feinstein, G. P. Gallerano, and R. H. Pantell, IEEE J. Quantum Electron. **29**, 1428 (1993).

[29] D. A. Jaroszynski, R. J. Bakker, A. F. G. van der Meer, D. Oepts, and P. W. van Amersfoort, Phys. Rev. Lett. **71**, 3798 (1993).
[30] R. Prazeres, J. M. Ortega, F. Glotin, and D. A. Jaroszynski, Nucl. Instrum. Methods Phys. Res., Sect. A **407**, 474 (1998).
[31] M. Dohlus (private communication).
[32] C. Maroli, V. Petrillo, and M. Ferrario, Phys. Rev. ST Accel. Beams **14**, 070703 (2011).
[33] S. Becker, M. Bussmann, S. Raith, M. Fuchs, R. Weingartner, P. Kunz, W. Lauth, U. Schramm, M. El Ghazaly, F. Grüner, H. Backe, and D. Habs, Phys. Rev. ST Accel. Beams **12**, 102801 (2009).
[34] M. Dohlus and T. Limberg, in *Proceedings of the 26th International Free Electron Laser Conference* (Comitato Conferenze Elettra, Trieste, Italy, 2004).
[35] F. Stulle, Ph.D. thesis, University of Hamburg, 2004.