Experimental demonstration of enhanced self-amplified spontaneous emission by photocathode temporal shaping and self-compression in a magnetic wiggler

Zhen Zhang, Joseph Duris, James P MacArthur, Alexander Zholents, Zhirong Huang and Agostino Marinelli

1 SLAC National Accelerator Laboratory, Menlo Park, California 94025, United States of America
2 Argonne National Laboratory, Lemont, IL, 60439, United States of America

E-mail: zzhang@slac.stanford.edu and marinelli@slac.stanford.edu

Keywords: free-electron laser, attosecond pulse, coherent synchrotron radiation, magnetic wiggler, electron beam shaping

Abstract

In this paper we demonstrate experimentally the generation of attosecond soft x-ray free-electron laser (XFEL) pulses based on a novel approach to enhanced self-amplified spontaneous emission. Instead of utilizing an external laser, we shape the electron beam at the cathode by laser pulse stacking. We enhance the high-current spike in the beam profile through a self-compression process which uses short-range coherent synchrotron radiation in a wiggler and a downstream magnetic chicane. The undulator taper is then matched with the energy chirp along the beam for attosecond XFEL generation. Start-to-end simulations are performed to demonstrate the proposed method. The measured spectra suggest that a $\sim 250$ as pulse duration is achieved at $\sim 940$ eV in the experiment.

1. Introduction

Valence electronic excitations in solids and molecules have an energy range in the few eV scale. From the time-energy uncertainty relationship it follows that the temporal evolution of valence electronic states is in the sub-fs range. The field of attosecond science is therefore generally concerned with the study of electron dynamics [1]. Ultrfast electron motion can be encountered in many quantum systems [2], and attosecond science now encompasses a broad range of fields from chemical sciences [3, 4] to condensed matter physics [5]. The specific case of valence charge migration in molecules and its potential role in chemical dynamics has generated considerable attention. The description of valence electron dynamics in molecules involves the complex interplay between electronic and nuclear motion [6], which is not supported by well-established theoretical models [3, 4]. Therefore a full understanding of attosecond dynamics and its relevance to chemical processes requires high-fidelity time-resolved pump–probe experiments.

The advent of attosecond light sources and attosecond metrology has greatly advanced the understanding of electron motion in atoms and molecules [7–9]. The most used method for the generation of attosecond radiation employs a process called high harmonic generation (HHG) [10–15], where a high-power infrared laser interacts with an atomic gas target to generate high-order harmonics of the drive field. Attosecond HHG sources are now capable of delivering pulses in the soft x-ray region, defined by photon energies above the carbon K-edge (280 eV). X-ray spectroscopy provides information on the electronic structure of quantum systems that is localized to specific atomic sites, and it is therefore a more powerful tool than its counterparts at lower photon energies. However the efficiency of HHG rapidly decreases at x-ray wavelengths with pulse energies in the pJ range, which is largely insufficient for multi-photon processes. We note that time-resolved pump/probe experiments are inherently non-linear and require pulses with sufficient intensity to interact with the sample with high probability. Furthermore, many techniques for creating and probing coherent electronic wave-packets on attosecond timescales rely on multi-photon processes for pumping and/or probing [16]. Therefore the study of electronic dynamics with
atomic site specificity requires new methods capable of generating attosecond x-ray pulses with much higher intensity.

X-ray free-electron lasers (XFELs) [17, 18] have a much larger conversion efficiency in the x-ray region compared to table-top sources with pulse energies that are six or more orders of magnitude higher than HHG in gas. Typical XFELs operate in the self-amplified spontaneous emission (SASE) mode and generate pulses with femtosecond durations [19–22]. In order to control the pulse duration of XFELs down to the attosecond regime, various bunch shaping methods have been proposed (e.g. [23–25]) with the idea of selectively shortening the lasing part of the electron beam by spoiling the electron beam properties in a time-dependent fashion. The shortest pulse achievable with these methods is given by the cooperation length

$$l_c = \lambda_r \times \frac{L_g}{\lambda_w},$$

where $\lambda_r$ and $\lambda_w$ are the radiation wavelength and the undulator period respectively, while $L_g$ is the FEL field amplitude gain length. $l_c$ represents the path-length difference (slippage) between the radiation and the electrons accrued in a gain length, and it is typically a monotonically decreasing function of the photon energy. For example, with the baseline beam parameters of the Linac coherent light source (LCLS) [19], the cooperation length is typically below 1 fs at hard x-rays while larger than 1 fs for soft x-rays ($\sim E < 1$ keV).

Due to the large cooperation length, the methods adopted to produce attosecond hard x-ray pulses at LCLS [23–25] are not applicable in the soft x-ray range.

Recently, a scheme based on the combination of the self-modulation of an electron beam in a wiggler [26] and enhanced SASE (ESASE) [27] was successfully adopted to generate attosecond soft x-ray FEL pulses at LCLS [28]. In this paper, we propose and experimentally demonstrate a different method that utilizes electron beam shaping at the photo-cathode to generate a short current spike in the electron beam. The spike is further amplified using the short-range wake of a magnetic wiggler and used for attosecond pulse generation in the FEL undulator. The paper is organized as follows. Section 2 describes the proposed self-compression scheme. Section 3 is devoted to develop a theoretical analysis of the amplification and shortening of the density perturbation by the self-compression. Start-to-end simulations with the experimental parameters are given in section 4. The measurement of the modulated electron beam and the generation of attosecond XFEL pulses are presented in section 5. Lastly, a short conclusion is given in section 6.

2. Self-compression scheme

The proposed scheme is named self-compression and illustrated in figure 1. A high brightness electron bunch has a current distribution composed of a smooth profile plus a density perturbation. As the bunch travels through a magnetic wiggler, the CSR field emitted by the density perturbation generates an energy modulation which is subsequently used to generate a high current spike with a duration of order 1 fs. In our experiment the initial current perturbation is generated by temporally shaping the photo-injector laser and introducing a small notch in the initial current profile. Unlike the self-modulation method demonstrated previously [26], in this article we employ the short-range CSR wake rather than the resonant interaction of the beam with a coherent wave emitted by the tail of the charge distribution. The advantage of this method is that the short-range CSR wake is considerably stronger than the resonant wake and enables the generation of a much larger chirp at the core of the electron bunch. Furthermore this scheme does not require the generation of a high current horn at the tail of the electron bunch, which considerably simplifies the beam transport and the tuning of the FEL performance.
3. Theoretical analysis of self-compression

The amplification and shortening of the density perturbation by the self-compression scheme can be analyzed with a simplified time-domain theory. When the beam's transverse size is much smaller than the oscillation amplitude in the wiggler, a line-charge model \([29–31]\) accurately describes the CSR-induced energy change. Assuming the bunch line electron density \(\lambda(s)\) as a function of the position \(s\) of an electron in the bunch, we introduce the time-dependent energy change \(\Delta \gamma(s)\) of the bunch after it passes an \(N_w\)-period wiggler

\[
\Delta \gamma(s) = 2\pi N_w e \int_{-\infty}^{s} ds' G(s-s') \frac{d\lambda(s')}{ds'},
\]

where \(e\) is the classical electron radius. The detailed expression of function \(G(s)\) is given in reference \([31]\). The positive values of \(\Delta \gamma\) correspond to an energy gain and the negative values imply an energy loss. In the short-range limit, which is expressed as \(\zeta = \gamma^2 k w / K^2 < 1\) where \(\gamma\) is the Lorentz factor, \(k_w = 2\pi / \lambda_w\) is the wiggler wave number and \(K\) is the wiggler normalized vector potential amplitude, the function \(G(s)\) is approximated as \(G(s) \approx -\left(\frac{2 \gamma^2}{\lambda^2}\right)^{1/3}\) \([31]\). For simplicity we will model the initial perturbation as a Gaussian distribution in the longitudinal coordinate with a Gaussian energy spread. The electron beam distribution as a function of the beam coordinate \(s\) and relative energy deviation \(\delta\) can be written as

\[ f_0(s, \delta) = \frac{1}{\sqrt{2 \pi c \sigma_s \sigma_\delta}} \exp \left( -\frac{\delta^2}{2 \sigma_\delta^2} - \frac{s^2}{2 \sigma_s^2} \right) \]

with peak current \(I_0\), root mean square (rms) bunch length \(\sigma_s\), and relative energy spread \(\sigma_\delta\). Here, \(c\) is the speed of light and \(e\) is the elementary charge. The line electron density \(\lambda(s)\) can be calculated by integrating \(f_0(s, \delta)\) over \(\delta\). The CSR-induced energy change along the beam becomes \(\Delta \gamma(s) / \gamma = A \sigma_s F(s / \sigma_s)\) with normalized amplitude

\[ A = \frac{\pi r_e K N_w I_0}{\sqrt{2 \pi e^2 c^3 \sigma_s (K k_w)^2}} \left(\frac{\gamma}{\sqrt{\gamma}}\right)^{1/3}, \]

and the form function

\[ F(x) = 2^{5/6} \Gamma \left(\frac{4}{3}\right) F_1 \left[\frac{7}{6}, \frac{3}{2}, \frac{x^2}{2}\right] - 2^{4/3} \Gamma \left[\frac{5}{6}, \frac{1}{2}, \frac{x^2}{2}\right] \]

Here, \(F_1\) is the generalized hypergeometric function. The form function is shown in figure 2 with the assumed Gaussian profile. The CSR-induced energy change along the beam produces two energy chirps with opposite slopes, which are separated by the two extreme points at \(s = s / \sigma_s \approx -0.38\) and 2.10. The modified distribution function with the CSR-induced energy chirp is expressed as

\[ f_1(s, \delta) = \frac{1}{\sqrt{2 \pi c \sigma_s \sigma_\delta}} \exp \left( -\frac{\delta^2}{2 \sigma_\delta^2} - \frac{(s - \gamma^2 \Delta \gamma(s) / K^2)^2}{2 \sigma_s^2} \right) \]

Either one of these two energy-chirped regions can be used for amplifying and shortening the current profile through the downstream magnetic chicane.

A magnetic chicane is used to compress the electron beam by introducing an energy-dependent path-length difference which is referred as \(R_{cs} = \partial \delta / \partial \delta\) in beam transport. For a given \(R_{cs}\), the linear density of the beam after compression is \(\lambda_2(s) = \int f_1(s - R_{cs} \delta, \delta) d\delta\). With an optimal \(R_{cs}\), we can obtain a high-current spike in the beam whose pulse width is much shorter than the initial one. In figure 3(b), we present the current profiles for different values of \(R_{cs} = R_{cs} \sigma_s / \sigma_t\) at \(A = 5\). This normalized amplitude is
Figure 3. (a): the FWHM of the spike versus the $R_{56}$ with $\hat{A} = 5$; (b): current profiles for different $R_{56}$ with $\hat{A} = 5$; (c) three current profiles for comparison; (d) the maximum peak current amplification factor versus the normalized energy modulation amplitude when $R_{56} > 0$ and $R_{56} < 0$ respectively. The current profiles are calculated from the analytical model.

similar to the CSR-induced energy loss from the wigglers in the following simulation and in the experiment. All the current profiles are normalized by the initial peak current. There are two groups of $R_{56}$ (I and III) producing high peak currents, which correspond to the optimal compression of the two chirped regions of the bunch. To compress the energy chirp $h_1$ in figure 2, we need a positive $R_{56}$, which can be provided by the common four-dipole chicane. For a chirp of the opposite sign $h_2$, a special chicane with negative $R_{56}$ is required. The current profiles for three different $R_{56}$ are presented in figure 3(c) for comparison. The full width at half maximum (FWHM) of the current spike is shown in figure 3(a). The amplification and shortening of the density bump depends on the energy modulation amplitude. When $\hat{A} = 5$, at the two optimal $R_{56}$ settings, the FWHM is decreased by a factor of 8 and 13 respectively while the peak current is amplified by 2.7 and 6 times. In figure 3(d), we present the amplification factor of the peak current as the normalized amplitude $\hat{A}$ is varied. When $R_{56} < 0$, the maximum amplification factor can be estimated by a linear fit $I_m/I_0 \sim 0.93\hat{A} + 1$ over the range of $\hat{A}$ shown in the figure. For $R_{56} > 0$, the fit formula of the maximum amplification factor is $I_m/I_0 \sim 0.35\hat{A} + 1$.

Note that the theoretical model above only includes a Gaussian density distribution. In the experimental implementation presented in this paper a density background is superimposed with the perturbation in the beam. This case can be modeled by a Gaussian distribution superimposed with a constant current. Since the CSR-induced energy change in equation (2) is determined by the derivative of the linear electron density with respect to the longitudinal coordinate, the inclusion of a uniform density background will not alter the energy change. However the final peak current will be larger since the same energy chirp is now applied to more electrons. For example, if we add a constant current background equal to the peak of the Gaussian distribution (the peak current becomes $2I_0$) and keep the same slice energy spread, under the same CSR-induced energy chirp $\hat{A} = 5$ and the optimal $R_{56}$, the maximum peak current can reach up to $14I_0$ with the peak current amplification factor about 7.

4. Start-to-end simulation

There are various methods to generate a density perturbation in the core part of the electron beam. In this paper, we adopt the method of laser shaping at the cathode by the pulse stacking technique [32–34]. Figure 4 shows a start-to-end simulation of this method. In the typical LCLS operation mode two laser pulses with Gaussian temporal profile and an rms duration of $\sim 0.9$ ps are usually stacked to produce a quasi-flattop profile for emittance compensation. In this experiment we increase the delay from $\sim 2$ ps to $\sim 3.2$ ps. This change is not detrimental to either the slice emittance of the perturbed region or the projected emittance. The increased delay results in a density notch in the beam after the injector, which is shown in figure 4(a). During the downstream acceleration, the density notch leads to a different local energy chirp in the beam due to the accelerator wakefields and longitudinal space charge [35], which in turn converts the density notch to a density bump during the beam compression process. The conversion between notch and bump happens once in each stage of acceleration and compression. This is due to the repulsive nature of the space-charge field which generates an energy modulation in opposition to the
existing bunching. In a typical free-electron laser facility, such as the LCLS [19], there are usually three stages of density conversion, which are labeled as beam compressor 1 (BC1), beam compressor 2 (BC2) and dogleg (DL) in figure 4. Numerical simulations are performed with Elegant [36] to verify the beam dynamics. A collimator in the middle of BC1 is implemented to cut the current horns at the two ends of beam [37]. From the longitudinal phase space in figures 4(a)–(d), we can observe the beam density evolution: a density bump with 6.5 kA peak current is produced at the core part of beam at the end of the DL (the value of the DL $R_{56}$ is $-100 \, \mu$m, which optimizes the current bump formation). In the area between DL and undulator, a 6-period wiggler (WG) and a magnetic chicane (CH) are used to amplify and shorten the density bump before the beam enters the undulator, as shown in figure 4(e). The wiggler period is 35 cm, and the gap is chosen for resonant interaction at 2.8 $\mu$m. The CSR-induced energy change increases the energy chirp in the density bump, which is converted into a high-current spike by the following chicane. The longitudinal phase space of the beam after the chicane ($R_{56} = 470 \, \mu$m) is shown in figure 4(e) with more than 14 kA peak current. For comparison, the peak current after the chicane is $\sim 7.4$ kA without this additional energy chirp from the wiggler. The energy chirp within the high-current spike is further increased by the longitudinal space charge in the downstream undulators [38] as shown in figure 4(f).

Matching the undulator taper to the beam energy chirp, we can obtain ultra-short XFEL pulses from the high-current spike [27, 28, 39]. The time-dependent FEL simulations are performed by the fully 3D code Genesis 1.3 [40] with the beam in figure 4(f). The undulator taper is optimized to obtain a single-spike power profile, which is shown in figure 5. Figures 6(a) and (b) present 30 typical shots of FEL power and spectral profiles respectively. The statistics of 150 shots with different initial shot noise are given in figures 6(c) and (d), including full width at half maximum (FWHM) of power and spectral profiles. Based on the simulation results, the average peak power is $193 \pm 46$ GW and the pulse energy is $101.4 \pm 13.5 \, \mu$J. The FWHM of the power profiles is $425 \pm 80$ as, and the FWHM of the corresponding spectral profiles is $7.36 \pm 2.23$ eV.

5. Experimental measurement and attosecond XFEL generation

The experimental demonstration of the proposed method was conducted at the LCLS. The time delay of the laser pulse stacking was increased to 3.2 ps to produce the density notch. The two-stage beam compression is optimized to form a density bump at the core part of the beam before the undulator. Figure 7 presents the longitudinal phase-space measured at the end of the undulator with an X-band deflector [41] in different experimental conditions. The phase space with the wiggler in and chicane on in figure 7(c) closely reproduces the simulation in figure 4(f). The FWHMs of the current spikes in the simulation and the experiment are close after considering the temporal resolution. We can also observe a similar rotation of the beam tail and the beam current profile. Note that the temporal resolution of the measurement limits the

![Figure 4](image-url)
shortest pulse width that can be resolved, leading to an underestimate of the peak current. Since the space-charge field is proportional to the derivative of the current profile, the space-charge induced energy spread of the electrons within the spike can be used to diagnose the current enhancement through the wiggler and the chicane. As shown in figures 4(e) and (f), the high peak current of the spike leads to an increase of beam energy spread within it through the longitudinal space charge force in the downstream drift and undulator. The larger energy spread in the spike indicates higher peak current. Figure 7 also shows the histograms of local energy spread within the spike of the three measured cases. When the wiggler gap is open and the chicane is off, a density bump is observed at the bunch center with $\sim 7$ MeV energy spread. When the wiggler gap is closed for resonant interaction at 2.8 $\mu$m for the 4.56 GeV beam and the chicane is turned on, the energy spread of the electrons within the spike reaches up to $\sim 12$ MeV, indicating the amplification and shortening the density bump by the self-compression scheme. For comparison, when only the chicane is turned on, the local energy spread within the spike is $\sim 8$ MeV, which is a little larger than the case of chicane off but still smaller than the case with wiggler in.

The high-current spike is used to generate ultra-short XFEL pulses in the last 10 undulator sections. Lasing in the first 22 undulator sections is suppressed with a large oscillation in the beam trajectory. Keeping these undulators inserted while suppressing lasing further delays the beam, increasing the space-charge induced energy chirp. This additional chirp further increases the FEL bandwidth and suppresses the formation of side-pulses via the chirp–tapered FEL principle [39, 42]. Making full use of the available range of the undulator strength, we adopt an inverse taper in the undulator to match the energy chirp within the spike, which is able to produce single-spike attosecond XFEL pulses [43]. The beam trajectories and the undulator taper are both shown in figure 8(a). The median pulse energy of the XFEL pulses measured by the gas detector is $\sim 30 \mu$J with a maximum value of more than 100 $\mu$J. The histogram
Figure 7. Measured longitudinal phase space under different cases. (a) Wiggler out and chicane off; (b) wiggler out and chicane on; (c) wiggler in and chicane on; (d) the energy spread of the electrons within the spike for the three cases. The beam’s head lies to the right.

Figure 8. Measured spectra of the FEL pulses. (a) The beam trajectories in the undulator and the undulator taper of the last 10 undulator sections; (b) beam energy distribution and average spectral intensity of 5913 shots as a function of electron beam energy and photon energy; (c) 20 typical shots of the measured spectra within the beam energy range shown by the dashed lines; (d) histogram of the XFEL pulse energies; (e) histogram of the FWHM of the XFEL spectral profiles.

of the measured pulse energy is given in figure 8(d). The fluctuation level of the pulse energy is consistent with the physics of single-spike SASE XFELs at saturation.

The spectra of the XFEL pulses are measured to estimate the attosecond pulse duration. The average spectral intensity of 5913 shots as a function of electron beam energy and photon energy is presented in figure 8(b). The center of the spectra is $\sim 940$ eV. The correlation between photon energy and the inherent electron beam energy jitter of the LCLS can be observed clearly, which is a feature of SASE. Figure 8(c) shows 20 typical shots of the measured spectra within the beam energy range shown by the dashed lines in figure 8(b). The histogram of the spectral FWHM bandwidth of the total 5913 shots is shown in figure 8(e) with an average value $7.84 \pm 2.60$ eV, which is much larger than the nominal bandwidth of SASE. The ripple of the spectra around $-3$ eV is due to a bad pixel in the spectrometer.

In this experiment, the XFEL pulse duration was not directly measured. However all the available observables (gain-length, bandwidth and undulator taper) are consistent with the measurements by the attosecond angular streaking reported in [28] at a similar photon energy, where the pulse duration is approximately 280 as. Therefore we estimate the pulse duration to be on the order of 250 as FWHM. The frequency chirp of the x-rays can be estimated from the undulator taper using the chirp/taper matching...
condition [42] and the method described in [28]. The estimated frequency chirp is roughly 12 eV fs⁻¹, which is consistent with the estimated pulse duration and the measured bandwidth (i.e. a Gaussian pulse with a 250 as duration and a 12 eV fs⁻¹ chirp would have a ∼7.8 eV bandwidth FWHM). The estimated value of pulse duration is within a factor of 2 of the simulation. The longer simulated pulse duration is consistent with the slightly narrower simulated bandwidth. This small discrepancy is likely due to the influence of numerical noise on the microbunching instability gain (the simulation used 10 million macroparticles while the real beam has 1.56 billion particles), which results in larger slice energy of the beam in the simulation.

6. Conclusion

In conclusion, we proposed and demonstrated a novel method to generate attosecond XFEL pulses by the amplification and shortening of a density bump in the beam through the self-compression process. The density bump is generated from an initial density notch imposed by shaping the photoinjector laser. As the beam passes through a wiggler, the short-range CSR wake modulates the beam energy, resulting in large energy chirp within the density bump, which makes it possible to enhance the peak current and shorten the spike width by a downstream chicane. The measured longitudinal phase space of the beam confirms the generation of a high-current spike. The experimental observables (bandwidth, taper and gain-length) are consistent with the values reported during the temporal streaking experiments in reference [28], which suggests that shorter than a half of fs pulse duration is achieved at a photon energy of ∼940 eV in this experiment. This conclusion is supported by start-to-end numerical simulations. We also demonstrated that it is possible to seed a well defined and pre-calculated feature on a beam at the head of an FEL facility such that it migrates into a desirable structure at the end for advanced user applications.

Acknowledgments

We would like to thank J Cryan and A Lutman for useful discussions and help in the experiments. This work was supported by U.S. Department of Energy Contracts No. DE-AC02-76SF00515, DOE-BES Accelerator and detector research program Field Work Proposal 100317 and Department of Energy, Laboratory Directed Research and Development Program at SLAC National Accelerator Laboratory, under contract DE-AC02-76SF00515.

ORCID iDs

Zhen Zhang https://orcid.org/0000-0002-9139-2497

References

[1] Krausz F and Ivanov M 2009 Attosecond physics Rev. Mod. Phys. 81 163
[2] Krausz F and Stockman M I 2014 Attosecond metrology: from electron capture to future signal processing Nat. Photon. 8 205
[3] Lépine F, Ivanov M Y and Vrakking M J 2014 Attosecond molecular dynamics: fact or fiction? Nat. Photon. 8 195
[4] Nisoli M, Decleva P, Calegari F, Palacios A and Martín F 2017 Attosecond electron dynamics in molecules Chem. Rev. 117 10760–825
[5] Seifert L et al 2017 Attosecond chronocopy of electron scattering in dielectric nanoparticles Nat. Phys. 13 766–70
[6] Lünemann S, Kuleff A I and Cederbaum L S 2008 Charge migration following ionization in systems with chromophore-donor and amine-acceptor sites J. Chem. Phys. 129 104305
[7] Corkum P B and Krausz F 2007 Attosecond science Nat. Phys. 3 381
[8] Chang Z and Corkum P 2010 Attosecond photon sources: the first decade and beyond J. Opt. Soc. Am. B 27 B9–B17
[9] Ciappina M F et al 2017 Attosecond physics at the nanoscale Rep. Prog. Phys. 80 054401
[10] Hentschel M et al 2001 Attosecond metrology Nature 414 509
[11] Sekikawa T, Kosuge A, Kanai T and Watanabe S 2004 Nonlinear optics in the extreme ultraviolet Nature 432 605
[12] Sansone G et al 2006 Isolated single-cycle attosecond pulses Science 314 443–6
[13] Goulielmakis E et al 2008 Single-cycle nonlinear optics Science 320 1614–7
[14] Feng X, Gilbertson S, Mashiho H, Wang H, Khan S D, Chini M, Wu Y, Zhao K and Chang Z 2009 Generation of isolated attosecond pulses with 20 to 28 femtosecond lasers Phys. Rev. Lett. 103 183901
[15] Ferrari F, Calegari F, Lucchini M, Vozzi C, Stagira S, Sansone G and Nisoli M 2010 High-energy isolated attosecond pulses generated by above-saturation few-cycle fields Nat. Photon. 4 875
[16] Mukamel S, Healion D, Zhang Y and Biggs J D 2013 Multidimensional attosecond resonant x-ray spectroscopy of molecules: lessons from the optical regime Annu. Rev. Phys. Chem. 64 101–27
[17] Huang Z and Kim K-J 2007 Review of x-ray free-electron laser theory Phys. Rev. Spec. Top. Accel. Beams 10 034801
[18] Pellegrini C, Marinelli A and Reiche S 2016 The physics of x-ray free-electron lasers Rev. Mod. Phys. 88 015006
[19] Emma P et al 2010 First lasing and operation of an Angstrom-wavelength free-electron laser Nat. Photon. 4 641–7
[20] Ishikawa T et al 2012 A compact x-ray free-electron laser emitting in the sub-angstrom region Nat. Photon. 6 540–4
[21] Kang H-S et al 2017 Hard x-ray free-electron laser with femtosecond-scale timing jitter Nat. Photon. 11 708
[22] Milne C et al 2017 Swissfei: the swiss x-ray free electron laser Appl. Sci. 7 720
[23] Emma P, Bane K, Cornacchia M, Huang Z, Schlarb H, Stupakov G and Walz D 2004 Femtosecond and subfemtosecond x-ray pulses from a self-amplified spontaneous-emission–based free-electron laser Phys. Rev. Lett. 92 074801
[24] Huang S et al 2017 Generating single-spike hard x-ray pulses with nonlinear bunch compression in free-electron lasers Phys. Rev. Lett. 119 154801
[25] Marinelli A, MacArthur J, Emma P, Guetg M, Field C, Kharakh D, Lutman A A, Ding Y and Huang Z 2017 Experimental demonstration of a single-spoke hard-x-ray free-electron laser starting from noise Appl. Phys. Lett. 111 151101
[26] MacArthur J P, Joseph D, Zhang Z, Lutman A, Alexander Z, Xu X, Huang Z and Marinelli A 2019 Phase-stable self-modulation of an electron beam in a magnetic wiggler Phys. Rev. Lett. 123 214801
[27] Zholents A A 2005 Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers Phys. Rev. Spec. Top. Accel. Beams 8 040701
[28] Joseph D et al 2020 Tunable isolated attosecond x-ray pulses with gigawatt peak power from a free-electron laser Nat. Photon. 14 30–6
[29] Saldin E L, Schneidmiller E A and Yurkov M V 1997 On the coherent radiation of an electron bunch moving in an arc of a circle Nucl. Instrum. Methods Phys. Res. A 398 373–94
[30] Saldin E L, Schneidmiller E A and Yurkov M V 1998 Radiative interaction of electrons in a bunch moving in an undulator Nucl. Instrum. Methods Phys. Res. A 417 158–68
[31] Wu J, Rubenheimer T O and Stupakov G V 2003 Calculation of the coherent synchrotron radiation impedance from a wiggler Phys. Rev. Spec. Top. Accel. Beams 6 040701
[32] Ferrario M et al 2011 Laser comb with velocity bunching: preliminary results at sparce Nucl. Instrum. Methods Phys. Res. A 637 543–6
[33] Petrillo V et al 2013 Observation of time-domain modulation of free-electron-laser pulses by multipeaked electron-energy spectrum Phys. Rev. Lett. 111 114802
[34] Marinelli A et al 2015 High-intensity double-pulse x-ray free-electron laser Nat. Commun. 6 6369
[35] Zhang Z, Ding Y, Marinelli A and Huang Z 2015 Longitudinal dynamics of twin electron bunches in the Linac coherent light source Phys. Rev. Spec. Top. Accel. Beams 18 030702
[36] Borland M 2003 Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation Advanced Photon Source LS-287
[37] Ding Y et al 2016 Beam shaping to improve the free-electron laser performance at the Linac coherent light source Phys. Rev. Accel. Beams 19 100703
[38] Geloni G, Saldin E, Schneidmiller E and Yurkov M 2007 Longitudinal impedance and wake from XFEL undulators. Impact on current-enhanced SASE schemes Nucl. Instrum. Methods Phys. Res. A 583 228–47
[39] Baxevanis P, Joseph D, Huang Z and Marinelli A 2018 Time-domain analysis of attosecond pulse generation in an x-ray free-electron laser Phys. Rev. Accel. Beams 21 110702
[40] Reiche S 1999 Genesis 1.3: a fully 3D time-dependent fe1 simulation code Nucl. Instrum. Methods Phys. Res. A 429 243–8
[41] Behrens C et al 2014 Few-femtosecond time-resolved measurements of x-ray free-electron lasers Nat. Commun. 5 3762
[42] Saldin E L, Schneidmiller E A and Yurkov M V 2006 Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses Phys. Rev. Spec. Top. Accel. Beams 9 050702
[43] Zhang Z, Joseph D, MacArthur J P, Huang Z and Marinelli A 2019 Double chirp-taper x-ray free-electron laser for attosecond pump–probe experiments Phys. Rev. Accel. Beams 22 050701