

Two-color x-ray free-electron laser based on self-seeding configuration

Yixuan Liu^{1,2,*} Kai Hu,^{3,*} Chuan Yang^{1b,3,4,†} Tao Liu,¹ Dong Wang,¹ and Weiqing Zhang^{1b,5}

¹*Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China*

²*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

³*Institute of Advanced Light Source Facilities, Shenzhen, 518107, China*

⁴*Department of Physics, Southern University of Science and Technology, Shenzhen, Guangdong 518055, China*

⁵*State Key Laboratory of Chemical Reaction Dynamics, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China*



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Generating two-color x-ray pulses is crucial for the research of ultrafast dynamics. The development of x-ray free electron lasers (XFELs) has enabled the production of high-power ultrashort two-color x-ray pulses. In this work, we propose a two-color XFEL scheme based on a self-seeding configuration. A chirped x-ray pulse is first generated by a chirped electron beam in the first undulator. Then the chirped electron beam passes through a chicane, and the chirped x-ray pulse passes through a multilayer-based two-color filter to produce a two-color seed. Finally, this seed is amplified to saturation by the electron beam in the second undulator, yielding ultrashort two-color x-ray pulses with spectral-temporal separation. This scheme offers a novel approach for producing ultrashort two-color XFEL pulses.

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I. INTRODUCTION

Basic dynamical phenomena in the microscopic world occur on ultrafast timescales, with different physical processes occurring at distinct time intervals. For instance, atomic, molecular, and lattice dynamics take place on the femtosecond scale, while electronic dynamics occur on the attosecond scale [1]. The pump-probe experimental method is crucial for studying these ultrafast processes [2]. Extending this method to the x-ray regime is highly significant because x-rays can selectively excite inner-shell electrons, offering significant help in analyzing transient electronic dynamics. High-harmonic generation (HHG) light sources have produced two-color pulse pairs in the extreme ultraviolet (EUV) regime [3,4], enabling the implementation of EUV pump-probe experiments. However, extending HHG to the x-ray regime remains a significant challenge due to the low efficiency of high-harmonic conversion [5–7]. It is exhilarating to see that XFEL user facilities have made great progress [8–13], creating opportunities for generating two-color ultrashort x-ray pulses. As is well known, the wavelength λ_r of the

XFEL radiation is determined by the resonance condition:

$$\lambda_r = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right), \quad (1)$$

where λ_u , γ , and K are the undulator period, the mean Lorentz factor of the electron beam, and the undulator strength parameter, respectively. In XFEL user facilities, the undulator period is preset and cannot be altered, and the only adjustable parameters are K and γ . Therefore, two-color XFEL schemes can be generally classified into two groups. The first group adopts an electron beam passing through two undulators with different magnetic field strengths [14–28]. The second group uses electrons of different energies through the same undulator [29–37].

For the first group, several schemes have been proposed. Two-color FEL operation was initially demonstrated in the midinfrared region [14], followed by the generation of two-color FEL pulses in the ultraviolet [15] and x-ray regimes [16–18]. Based on the first-group configuration, several two-color XFEL schemes have been proposed and demonstrated for polarization control [25,26] and attosecond-level duration minimization [27,28]. However, the peak power of the two-color FEL pulses is limited because the same electron beam is employed in both undulators. The peak power can be enhanced by allowing only a part of the electron beam to lase in each undulator section. This target can be achieved through methods such as electron-beam-tilt-based fresh-slice XFEL [18–21] and slice-matching-based fresh-slice XFEL [22–24].

*These authors contributed equally to this work.

†Contact author: yangc@mail.iasf.ac.cn

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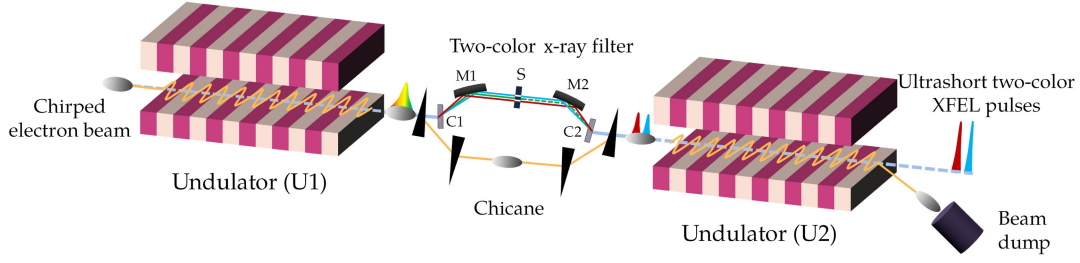


FIG. 1. Layout of the self-seeding two-color XFEL scheme.

For the second group, the initial demonstration employed twin electron bunches with different energies [29,30]. Compared to the first group, these schemes employ all undulator modules simultaneously, reducing the required undulator length. However, it is challenging to produce such twin pulses, and there are limitations on the adjustability of both the wavelength and the time delay of the pulses. Some evolved schemes have also been proposed, such as using different parts of a chirped electron beam to emit two-color XFEL pulses in the same undulator [31–37]. In these schemes, two-color XFEL pulses are generated by creating local current spikes or suppressing lasing in localized parts of the chirped electron beam. This is achieved using methods such as emittance spoiling [31,32], temporally shaped laser heating [33], sextupole magnet approaches [34], photocathode laser emittance spoiling [35], wakefield excitation [36], nonlinear compression [37], and activation within the FEL gain bandwidth [38]. In addition to the above two groups, there are other two-color FEL solutions that are not straightforward to categorize. These include the chirped seed scheme [39,40], the seeded FEL based on tilted beam lasing in a transverse-gradient undulator [41], the single-crystal self-seeded FEL with a chirped electron beam [42], the split-and-delay line based on multilayer Bragg mirrors [43], and the Laue x-ray compressor method [44]. Two seed pulses, temporally separated and of different colors, are sent with the same electron bunch through an undulator [45] or through undulator sections tuned to each color [46]. These technical solutions outline a promising future for generating two-color XFEL pulses, smoothing the path for ultrafast dynamics investigations and serving as a reference for novel two-color FEL schemes.

In this paper, we propose a novel scheme for generating two-color XFEL pulses based on a self-seeding configuration with a chirped electron beam. The scheme consists of two undulator sections, with a magnetic chicane and a two-color x-ray filter based on multilayers located between them. It can produce two-color XFEL pulses with separation in both time and spectrum, a peak power of gigawatts, and femtosecond pulse duration. The paper is organized as follows. First, the layout of the proposed self-seeding two-color XFEL scheme is introduced in Sec. II. Then, the principle of the two-color x-ray filter is briefly described in Sec. III. To verify the feasibility of the proposed self-seeding two-color XFEL scheme, numerical simulations

are performed in Sec. IV. Finally, the results and discussion are summarized in Sec. V.

II. LAYOUT OF THE SCHEME

The layout of the proposed self-seeding two-color XFEL scheme is presented in Fig. 1. In this scheme, a down-chirped x-ray SASE pulse is first produced when a down-chirped electron beam passes through the first undulator (U_1). Then, the down-chirped electron beam and the down-chirped x-ray SASE pulse pass through a magnetic chicane and a two-color x-ray filter, respectively. Here, “down-chirp” means that the higher-energy electrons (or photons) are located at the bunch head. The magnetic chicane serves as a bypass channel for the electron beam and can wash out the microbunching generated in the first undulator segment. The two-color x-ray filter, similar to a pulse compressor, consists of two dispersive elements ($C1$, $C2$), two concave mirrors ($M1$, $M2$), and a double slit S . The focal lengths of the two concave mirrors $M1$ and $M2$ are f_1 and f_2 , respectively. The distance between $M1$ and $M2$ is $f_1 + f_2$. The distance from the first dispersion device $C1$ to $M1$ is f_1 , while that of the second dispersion device $C2$ to $M2$ is f_2 . The chirped SASE pulse impinges horizontally on $C1$, and the x-ray pulse is deflected with concomitant angular dispersion. Then, the dispersed x-ray pulse is collimated by mirror $M1$, and the different frequency components become separated in the vertical dimension. The double slit, placed at distance f_1 from $M1$, selects two specific photon energy components from the dispersed x-ray pulse, generating a two-color x-ray seed. Subsequently, the selected two-color seed propagates through $M2$ and $C2$ and exits horizontally. Here, we adopt asymmetry-cut multilayers as hard x-ray dispersive elements. In the second undulator (U_2), the electron beam overlaps with the two-color x-ray seed and amplifies it to saturation, generating two-color XFEL pulses separated in both time and spectrum.

III. PRINCIPLE OF THE TWO-COLOR X-RAY FILTER

In this section, we introduce the principle of the two-color x-ray filter. As mentioned in Sec. II, the filter is similar to a typical x-ray pulse compressor [44,47]. In this work, we focus on the hard x-ray regime, so we adopt

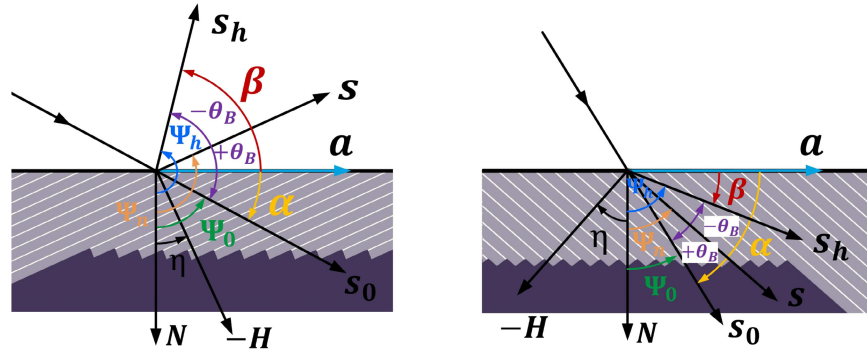


FIG. 2. Orientation of the angles in Bragg geometry and Laue geometry.

asymmetry-cut multilayers as the dispersive elements. To properly describe the principle of the two-color x-ray filter, we first need to define the parameters and angles that will be used in x-ray diffraction from a multilayer. As shown in Fig. 2, the vector $\mathbf{H}$ is the reciprocal lattice vector, and the unit vectors $\mathbf{s}$, $\mathbf{s}_0$, and $\mathbf{s}_h$ correspond to the directions of the lattice plane trace, incident beam, and diffracted beam, respectively. The crystal surface normal N points inward. The key angles are defined as: $\eta = (\mathbf{N}, -\mathbf{H})$ (asymmetry angle between surface and reflecting planes); $\Psi_0 = (\mathbf{N}, \mathbf{s}_0)$, $\Psi_h = (\mathbf{N}, \mathbf{s}_h)$, $\Psi_n = (\mathbf{N}, \mathbf{s})$ (angles between normal and incident, reflected, and trace vectors). The Bragg angle θ_B is defined as the included angle between the reflecting planes and the incident direction, with $(\mathbf{s}, \mathbf{s}_0) = +\theta_B$ and $(\mathbf{s}, \mathbf{s}_h) = -\theta_B$. Let $\mathbf{a}$ be the crystal surface vector. The parameters α and β denote the angles between $\mathbf{a}$ and $\mathbf{s}_0$ and between $\mathbf{a}$ and $\mathbf{s}_h$, respectively. Based on the definition, we have the following angular relationships:

$$\begin{aligned} \Psi_0 &= \Psi_n + \theta_B, & \Psi_h &= \Psi_n - \theta_B, & \Psi_n &= \eta - \pi/2, \\ \alpha &= \Psi_0 + \pi/2, & \beta &= \Psi_h + \pi/2. \end{aligned} \quad (2)$$

The asymmetry geometry of the asymmetry-cut multilayer can be described by the asymmetry ratio γ

$$\gamma = \frac{\cos \Psi_h}{\cos \Psi_0} = \frac{\cos(\Psi_n - \theta_B)}{\cos(\Psi_n + \theta_B)}. \quad (3)$$

For asymmetry-cut multilayers, the Bragg condition can be equivalently expressed as

$$D(\cos \alpha - \cos \beta) = m\lambda, \quad (4a)$$

$$2D \sin \eta \sin \theta_B = m\lambda, \quad (4b)$$

where λ and m are the wavelength and the diffraction order, respectively. $D = d/\sin |\eta|$, where d is the period of multilayers. We can find that Eq. (4a) is similar to the grating equation. The angular dispersion for asymmetric-cut crystals and multilayers is written as

$$\frac{\partial \beta}{\partial \lambda} = -\frac{1}{\lambda_B} \left(1 + \frac{1}{\gamma} \right) \tan \theta_B. \quad (5)$$

Equation (5) indicates that angular dispersion exists only in the asymmetry-cut geometry ($\gamma \neq -1$). This is why we adopt asymmetry-cut multilayers to generate dispersion and then utilize a double slit to select the two-color x-ray seed. In this work, we employ a two-color x-ray filter scheme with the same configuration as the mentioned x-ray pulse compressor. Therefore, the filter is capable of controlling the group delay dispersion (GDD), such as adjusting the temporal separation and the pulse duration of the two-color seed. The dispersion coefficients of the filter are expressed as

$$\mathcal{D}_1 = \left. \frac{\partial}{\partial \omega} \phi(\omega) \right|_{\omega_0} = -\frac{G[\cos(\alpha - \beta) - 1]}{c \sin \beta} \Big|_{\omega_0}, \quad (6a)$$

$$\mathcal{D}_2 = \left. \frac{\partial^2}{\partial \omega^2} \phi(\omega) \right|_{\omega_0} = -\frac{4\pi^2 m^2 c G}{\omega^3 D^2 \sin^3 \beta} \Big|_{\omega_0}, \quad (6b)$$

$$\mathcal{D}_3 = \left. \frac{\partial^3}{\partial \omega^3} \phi(\omega) \right|_{\omega_0} = -\frac{12\pi^2 m^2 c G}{\omega^4 D^2 \sin^3 \beta} \left(\frac{2\pi m c \cos \beta}{\omega D \sin^2 \beta} - 1 \right) \Big|_{\omega_0}, \quad (6c)$$

where $\mathcal{D}_1$, $\mathcal{D}_2$, and $\mathcal{D}_3$ are the group delay, GDD, and the third-order dispersion, respectively. c is the speed of light, ω_0 is the angular frequency corresponding to the central wavelength of the x-ray pulse. For the two-color filter scheme adopted in Fig. 1, the parameter $G = -(f_2 - f'_2) \sin \beta$. It is obvious that the sign of G can be tuned by adjusting the magnitudes of f_2 and f'_2 , thereby enabling precise and flexible control over the GDD value. Consequently, the sign of $\mathcal{D}_2$ is rigorously determined by the inequality between the value of f_2 and f'_2 : $\mathcal{D}_2$ is positive when f_2 exceeds f'_2 , is zero when f_2 is equal to f'_2 , and becomes negative once f_2 is less than f'_2 . In the following numerical validation, we set $\mathcal{D}_2 = 0$.

IV. NUMERICAL VALIDATION

In this section, we evaluate and validate the proposed scheme through numerical simulations. FEL simulations are performed using GENESIS 1.3 [48], while three-dimensional FEL pulse propagation through the two-color x-ray filter is simulated with FURION [49,50]. In the simulation, we use the parameters of Shanghai High repetition rate XFEL and Extreme light facility (SHINE). There are 11 undulator segments in the first undulator section and 14 undulator segments in the second undulator section. The simulation parameters are summarized in Table I.

In the design of the two-color x-ray filter, C1 and C2 are two identical asymmetry-cut multilayers, while M1 and M2 are two identical multilayer-coated curved mirrors, and the lengths f_1 , f_2 , and f'_2 are each set to 1 m. All the optics have the same period of 2 nm, with Mo and Si as the layer materials. Within each period, the thickness of the Mo layer is 0.5 nm and the thickness of the Si layer is 1.5 nm. C1 (C2) is oriented in the Laue diffraction geometry, and the reflectivity of C1 (C2) is strongly thickness-dependent, as shown in Fig. 3(a). The optimal thickness of C1 (C2) is 9.5 μm , and the corresponding reflectivity is shown as the black curve in Fig. 3(b), with a maximum of 77%. The thickness of the Mo-Si coating of M1 (M2) is 20 μm , while the reflectivity of M1 (M2) is plotted as the green curve in Fig. 3(b), and the peak reflectivity reaches 87%. Consequently, the overall efficiency (within the selected bandwidth) of the two-color x-ray filter in this scheme is approximately 27%. The relevant parameters of x-ray optics are given in Table I.

Numerical simulations of the scheme are performed with parameters of the SHINE user facility. The parameters of the electron bunch are listed in Table I. An ideal flattop electron bunch with a 20 fs duration is adopted, and the linear chirp of the electron bunch is 2.3 MeV/fs. Using

GENESIS 1.3, the chirped SASE pulse is produced in the first-stage undulator, and the Wigner phase-space distribution of the chirped SASE pulse is presented in Fig. 4(a). The corresponding spectral bandwidth is approximately 100 eV and the average output power is 20 MW. The transverse-longitudinal intensity distributions of the chirped SASE pulse before and after C1 are presented in Figs. 4(b) and 4(c), respectively. We can find that pulse front tilt is introduced after the pulse passing through C1. Before impinging on M1, the pulse is laterally expanded by angular-dispersion-induced divergence. After the pulse is collimated by mirror M1, the transverse-longitudinal intensity distributions of the pulse before and after the double slit are shown in Figs. 4(d) and 4(e), respectively. After the double-slit filtering, the transverse-longitudinal intensity distributions of the pulse before and after C2 are presented in Figs. 4(f) and 4(g), respectively. The Wigner phase space of the two-color seed is shown in Fig. 4(h). Figures 4(a)–4(h) provide a comprehensive visualization of the propagation characteristics of the SASE pulse in the two-color x-ray filter system. The peak power of the two-color seed is approximately 3 MW, with a bandwidth of 3 eV and a peak separation of 30 eV. Simulation results indicate that, after passing through the two-color x-ray filter optics, the power of the frequency components extracted from the chirped SASE pulse is reduced by roughly an order of magnitude.

As the chirped SASE pulse passes through the two-color x-ray filter, the electron beam passes through the chicane that washes out the microbunching generated in the first undulator. The electron beam then amplifies this two-color seed to saturation in the second undulator. Figure 5(a) presents the gain curve of pulse energy along the undulator, and the output power reaches 2 GW. Near the saturation point ($z = 100$ m), the Wigner phase space of the two-color x-ray FEL pulse is shown in Fig. 5(b), and the corresponding power and spectrum distributions are given in Figs. 5(c) and 5(d). In Fig. 5(c), the longitudinal power profiles from 100 simulation shots are presented, and the two-color peaks reach an average power of 0.4 GW, with FWHM durations of 1.5 fs for the left peak and 1.3 fs for the right peak. Figure 5(d) shows the spectrum distribution, and the bandwidth (FWHM) of the two peaks to be

TABLE I. The relevant parameters of numerical simulation.

Parameter	Value	Unit
Electron energy	8.0	GeV
Slice energy spread	0.8	MeV
Peak current	1500	A
Photon energy E_0	10	keV
Undulator period λ_u	2.6	cm
Electron beam length	6	μm
Undulator length in unit of λ_u	152	...
Drift length in unit of λ_u	40	...
Average beta function	23	m
Normalized emittance	0.4	mm mrad
Curvature radius of M1 (M2)	64.53	m
Period of multilayer	2.0	nm
Asymmetry angle of C1(C2)	80	deg
$ \alpha_1 $, $ \beta_1 $ of C1	8.224, 11.776	deg
$ \alpha_2 $, $ \beta_2 $ of C2	11.77, 8.224	deg

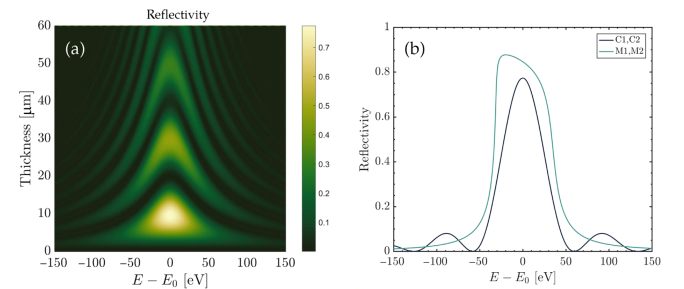


FIG. 3. (a) Thickness optimization of C1 and C2. (b) The reflectivity of C1, C2, M1, and M2.

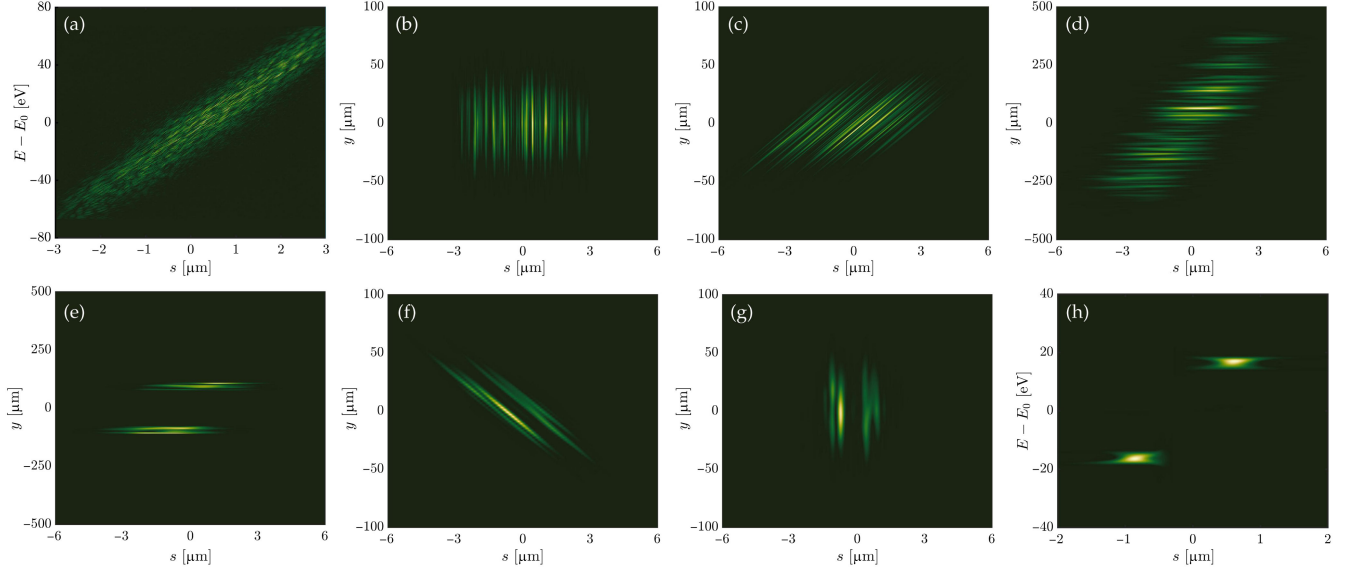


FIG. 4. (a) The Wigner phase space of the chirped SASE pulse at the exit of the first undulator. (b)–(g) The transverse-longitudinal intensity distributions of the x-ray pulse at different positions of the two-color x-ray filter: (b) before C1, (c) after C1, (d) before the double slits, (e) after the double slits, (f) before C2, (g) after C2. (h) The Wigner phase space of the two-color seed after the filter.

approximately 3.5 eV, slightly broader than the 3 eV set by the slits.

In our simulations, the power of the chirped SASE pulse before the two-color x-ray filter reaches ~ 10 MW.

Even after passing through the filter (which has a typical efficiency of $\sim 27\%$), the two-color seed power is reduced by less than an order of magnitude. The resulting seed power (~ 1 MW) remains significantly higher than the

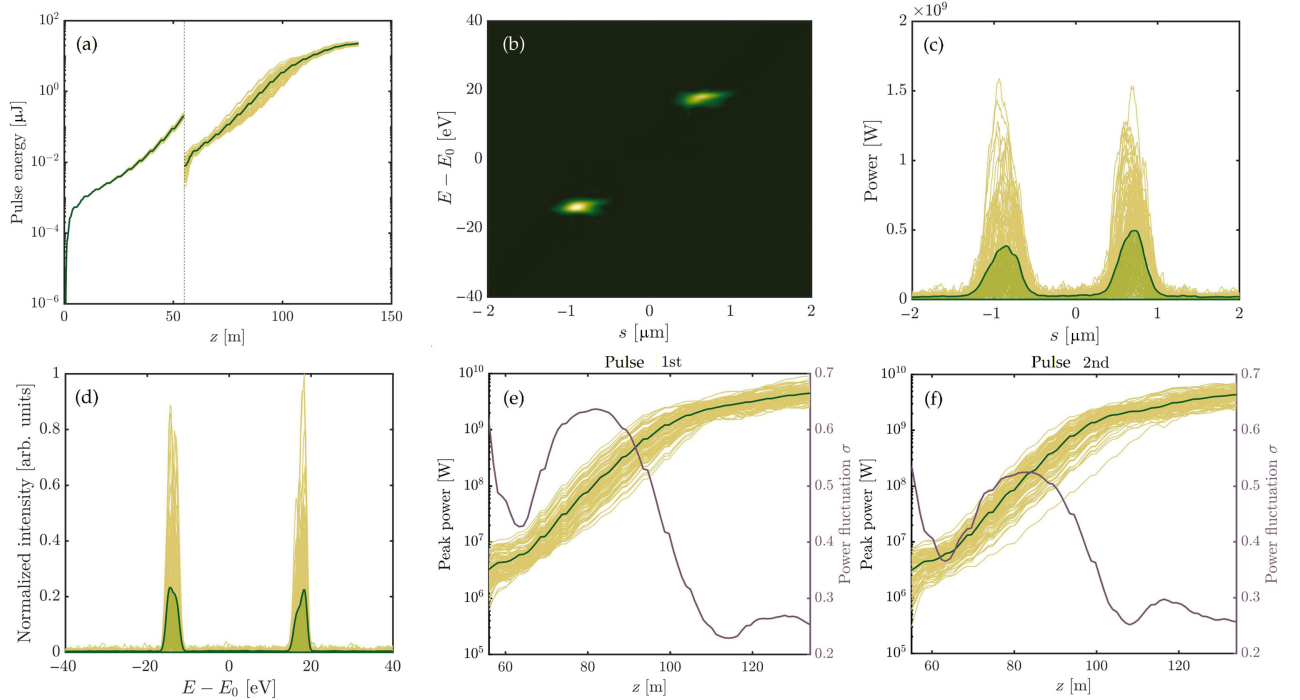


FIG. 5. (a) FEL gain process of the proposed scheme. (b) The Wigner phase space of the two-color FEL pulse around the saturation point. (c) The power distribution of the two-color FEL pulse around the saturation point. (c) The spectrum distribution of the two-color FEL pulse around the saturation point. The evolution of the peak power for the two-color pulses (pulse 1, pulse 2) is shown in panels (e) and (f), with the purple curves tracing their respective power fluctuations. The yellow curves in (a), (c), (d), (e), and (f) show 100 individual simulation shots, and the black curves show their average.

shot-noise power ($\sim$ kW) at the beginning of the second undulator stage, which effectively suppresses spontaneous emission and ensures efficient seeding. Although the power of the two-color seed reaches the MW level, it exhibits significant power fluctuations on the order of 50% to 60%, as shown in Figs. 5(e) and 5(f). However, as the two-color pulses are amplified, their power fluctuations (σ , standard deviation) decrease rapidly and saturate at nearly the same longitudinal position. The final power jitter of the pulses is reduced to about 20%–30%. This demonstrates that the high-gain FEL process effectively suppresses the initial shot-to-shot energy fluctuations, leading to stable and balanced two-color pulses at the output.

V. RESULTS AND DISCUSSION

This paper presents a scheme based on self-seeding configuration for generating ultrashort two-color XFEL pulses by means of an asymmetry-cut Laue multilayer-based two-color x-ray filter. This scheme essentially belongs to the second group of two-color XFEL schemes. This concept innovatively adapts the conventional monochromator, which combines a dispersive optical element with a slit, to a hard x-ray self-seeding FEL configuration, thereby producing ultrashort two-color x-ray pulses. This method is conceptually analogous to the slotted-foil technique that spoils the emittance of a chirped electron beam to generate two-color pulses [31,32], except that this scheme manipulates a chirped photon beam through a slit instead of an electron beam. Numerical simulations based on the baseline parameters of SHINE confirm the feasibility of the proposed scheme. At a photon energy of 10 keV, the scheme delivers two-color pulses with a separation of 5 fs, individual pulse durations down to 1.3 fs (FWHM), and an energy separation of 30 eV between the two pulses. By adjusting the electron-beam chirp and the slit spacing, both the spectral bandwidth and the temporal delay of the two-color radiation can be flexibly controlled. This work thus offers a promising solution for generating ultrashort two-color XFEL pulses.

In the simulation, the two-color x-ray filter introduces an optical delay of approximately 12.6 ps, which imposes a requirement for a large chicane for compensation. However, by optimizing the period of the Mo-Si multilayer, the Bragg angle can be reduced, thereby reducing the optical delay. For instance, with the multilayer period adjusted to 6 nm in the proposed scheme, the induced optical delay would be decreased to 1.3 ps. This value falls within the compensation range of the chicane used in the SHINE self-seeding scheme. While using a chicane to compensate for the delay, the R_{56} of the chicane causes a certain degree of decompression of the electron beam. Under the optimized condition of a 1.3 ps delay, the decompression reduces the peak current to approximately 0.66 times its initial value. Since the FEL gain length scales as $I^{-1/3}$, this reduction results in only a minor increase in

the gain length, implying a relatively small impact on the current operating point. However, if the target temporal delay is further increased, the required R_{56} grows, and the decompression effect rapidly worsens. The resulting severe drop in peak current and the alteration of the beam chirp would significantly degrade the FEL gain and heavily constrain the achievable operating points. Therefore, in practical experimental designs aiming for larger temporal delays, the impact of R_{56} on beam parameters must be carefully evaluated.

Compared to the schemes of the first group, such as the staged fresh bunch/slice technique [18–24], the proposed scheme exhibits superior temporal synchronization of the output pulses. This critical advantage derives from the generation of both two-color seeds from the same chirped SASE pulse, which ensures that the relative timing jitter is fundamentally determined by the two-color seeds, potentially reaching femtosecond or attosecond scales. This intrinsic synchronization is a significant benefit for pump-probe experiments and is inherently challenging to achieve in a staged fresh bunch/slice scheme, where the two colors are generated in separate undulator sections under different electron beam conditions.

Compared to the conventional two-color single-crystal self-seeding scheme [42], our approach offers several key advantages. First, it enables the generation of pulses with significantly shorter durations, potentially reaching the sub-femtosecond regime by controlling the GDD. In contrast, the conventional method is limited to femtosecond scales due to the intrinsic pulse stretching induced by the self-seeding crystal [51]. For diamond crystals, specifically common lattice planes such as C(111), C(220), C(311), and C(400), this stretching effect typically ranges from a few femtoseconds to hundreds of femtoseconds. Furthermore, our scheme provides greater flexibility in tuning the central wavelengths and energy separation of the two pulses. Additionally, it can be extended to generate multicolor pulses simply by increasing the number of slits. These capabilities represent a significant benefit for experiments requiring precisely tailored pulse properties.

It should be noted that in this scheme, the photon energy separation is constrained by two primary factors: the chirp rate of the electron bunch and the finite FEL gain bandwidth of the second undulator, which must simultaneously amplify both colors. For example, the FEL gain bandwidth is approximately 130 eV, which implies that the photon energy separation of the two-color pulses must be contained within this bandwidth. The pulse delay is primarily controlled by adjusting the R_{56} of the chicane and the GDD of the two-color x-ray filter. Therefore, this scheme offers considerable flexibility in adjusting both energy separation and pulse separation. The operating range of this scheme is therefore a balance between these interdependent parameters.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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