

Enhanced generation of single-spike hard x-ray free-electron laser pulses with lower charge and shorter electron beams in the injector

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Standard x-ray free-electron lasers (FELs) produce pulses with total durations of tens of femtoseconds and with time and spectral profiles consisting of multiple randomly distributed spikes. Strongly compressing an electron beam is a typical approach to produce shorter and coherent FEL pulses. We have advanced this method by starting at the injector of the FEL facility with electron beams with lower charges and shorter durations than in standard configurations. This leads to shorter electron beams with reduced energy spread after full compression and, consequently, to shorter and higher-quality FEL pulses. By operating with electron beams at the injector with charges of a few pC and rms durations of 360 fs, we show the generation of hard x-ray FEL radiation with practically all pulses having a single spike and a duration estimated from spectral measurements of about 300 as (full-width-at-half-maximum values). The demonstration was conducted at SwissFEL, the FEL at the Paul Scherrer Institute in Switzerland. Our work represents a simple way to enhance the production of single-spike events in x-ray FEL facilities, paving the way to achieve fully coherent hard x-ray FEL pulses with unprecedented durations.

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x-ray free-electron lasers (FELs) are state-of-the-art scientific tools to study matter with spatial and time resolution at the scale of atomic processes [1–10]. The x-ray FEL radiation is generated by a high-brightness and multi-GeV electron beam traveling through an undulator. x-ray FELs typically generate pulses with powers of tens of gigawatts and durations of tens of femtoseconds. Standard x-ray FEL facilities are based on the self-amplified spontaneous emission (SASE) process [11,12], which starts from the shot noise of the electron beam. The SASE process produces radiation with excellent transverse coherence but limited longitudinal (or temporal) coherence, with time and spectral profiles consisting of multiple randomly distributed spikes or modes.

There are two important research directions in x-ray FELs. First, extensive efforts are directed toward enhancing the longitudinal coherence of the produced pulses, for instance, with seeding [13–17] and slippage-enhancement approaches [18–20]. Second, researchers aim to produce shorter pulses to the femtosecond level and below. If a pulse is too short to contain multiple modes or spikes, it is also fully coherent. The FEL pulse duration is essentially defined by the duration of the electron beam that is of sufficient quality to produce FEL radiation. Its limit is given by the spike or coherence duration. The

coherence duration can be related to the cooperation duration $t_c = \lambda / (4\pi c \rho)$, where λ is the radiation wavelength, c is the speed of light, and ρ is the Pierce parameter [12]. A higher ρ corresponds to better FEL performance, i.e., higher power, shorter saturation length, and shorter coherence duration. The parameter ρ depends on the electron beam quality: Smaller emittances and higher peak currents correspond to higher ρ values. In the hard x-ray regime, values for ρ are typically in the range 10^{-4} to 10^{-3} , corresponding to coherence durations of a few hundreds of attoseconds or shorter.

In FEL facilities, radiofrequency (RF) photoinjectors [21] are normally used to generate high-brightness electron beams with relatively low energies (on the order of 10 MeV) and durations of a few picoseconds. These electron beams need to be accelerated to GeV energies and compressed to at most a few tens of femtoseconds before the undulator. This is achieved in the linac part of the FEL facility, which contains RF accelerating sections and bunch compressors consisting of magnetic chicanes.

Short FEL pulses can be achieved by producing a very short electron beam [22], usually with low charge and shorter duration at the injector, or by limiting the lasing part of the electron beam to a short fraction, for instance, with a slotted foil [23] or by transversely tilting the electron beam [24]. If the electron bunch duration that lases is comparable to the coherence duration, the FEL pulse will consist mostly of a single spike, whereas multiple spikes will appear for electron bunches longer than the coherence duration. The ultimate goal is to have very short electron beams (or lasing parts) and matching coherence durations to produce single-spike FELs with very short pulse durations.

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Subfemtosecond SASE-FEL pulses with a large majority of single spikes in the spectral domain, indicating also a single mode in the time domain, have been obtained in the soft x-ray regime by strongly compressing the electron beam [25–28]. Achieving single-spike operation is more difficult for hard x-rays due to the shorter coherence duration. At linac coherent light source (LCLS), a 65% single-spike fraction with estimated full-width-at-half-maximum (FWHM) pulse durations of 400 as were achieved for a photon energy of 5.6 keV using a slotted foil to limit the lasing part of the beam to a very small duration [29]. Also at LCLS, strong compression of a low-charge (20 pC) electron beam resulted in FEL pulses with a single-spike ratio of 0.5 and estimated FWHM pulse durations of 200 as for photon energies of 5.6 and 9 keV [30]. More recently, a scheme to achieve strong compression for a standard-charge (250 pC) electron beam at the European XFEL delivered radiation with 30% single spikes for 9 keV photon energies, with an estimated FWHM pulse duration of 200 as [31]. At SwissFEL, some of us reported the generation of FEL pulses with 30% single-spike fraction and estimated FWHM pulse durations of about 300 as by strongly compressing a low-charge (10 pC) beam [32].

In this Letter, we suggest to enhance the generation of short and coherent FEL pulses with strong compression by starting with a lower-charge and shorter-duration electron beam at the RF photoinjector. This, as we will explain in more detail later, helps to achieve shorter electron beams with better quality (i.e., reduced energy spread) at the undulator entrance. While standard low-charge operation in x-ray FEL facilities starts with electron beams with rms durations longer than 1 ps (e.g., FWHM values of 2.8 ps at LCLS [30] or rms durations of 1.4 ps at SwissFEL [32]); here, we employ initial electron beams with an rms duration of only 0.36 ps. We also operate with lower charges than usual (20 pC at LCLS [30] or 10 pC at SwissFEL [32]), down to 3–4 pC. In the following, we present experimental and simulation results at SwissFEL [10], which demonstrate the validity of the approach. Specifically, we show the generation of hard x-ray FEL radiation with an unprecedented single-spike ratio of 0.9 and estimated FWHM pulse durations from measured spectral bandwidths of around 300 as.

To first order, the compression factor in a bunch compressor can be expressed as $(1 + R_{56}h)^{-1}$, where R_{56} is the longitudinal dispersion of the magnetic chicane and h is the energy chirp of the electron beam. The energy chirp can be expressed as $h = d\delta/ds$, with $\delta(s) = \Delta E(s)/E$ the relative energy deviation along the bunch.

A fully compressed beam corresponds to $1 + R_{56}h = 0$. In this case, the minimum electron bunch length can be expressed, again to first order, as (see, e.g., Ref. [33]) $\sigma_{s2} = R_{56}\sigma_{\delta1}$, where $\sigma_{\delta1}$ is the relative intrinsic (or uncorrelated) energy spread of the electron beam before the compression stage. Considering that the uncorrelated energy spread is increased by the compression factor and that the relative energy spread σ_{δ} is reduced with the energy increase during acceleration (the absolute energy spread ΔE stays constant with acceleration), we can write (see, e.g., Ref. [32])

$$\sigma_{s2} = R_{56}\sigma_{\delta1} = R_{56}\sigma_{\delta0}C\frac{E_0}{E_2}, \quad (1)$$

where $\sigma_{\delta0}$ is the initial energy spread before compression, C is the intermediate compression factor between the injector and before the last compression stage ($C = 1$ means that there is no intermediate compression between the injector and the final compression stage), E_0 is the electron beam energy after the injector, and E_2 is the energy at the last compression stage.

The longitudinal emittance of the electron beam can be expressed, assuming no significant impact of the energy chirp, as the product of the bunch length and the uncorrelated energy spread: $\varepsilon_l = \sigma_s\sigma_E$. Assuming that the longitudinal emittance is preserved from the injector to the fully compressed state, we have $\sigma_{s0}\sigma_{E0} = \sigma_{s2}\sigma_{E2}$. If we now consider Eq. (1), we can write the following expression for the final relative energy spread after full compression:

$$\sigma_{\delta2} = \frac{\sigma_{s0}}{R_{56}C}. \quad (2)$$

The previous discussion and Eqs. (1) and (2) suggest two ways to enhance the production of fully compressed electron bunches: First, we may produce shorter electron beams by operating with lower charges, which corresponds to a reduced initial energy spread of the electron beam $\sigma_{\delta0}$ [see Eq. (1)]. This is because the energy spread of the electrons is increased by intrabeam scattering (IBS) effects, which scale with the square root of the peak current or beam charge for a given pulse duration [34], as has been experimentally verified at SwissFEL [35,36]. Measurements at other facilities have indicated or demonstrated the impact of IBS on the energy spread of the electron beam [37–39]. We note that there might be other significant contributions to the energy spread of the electron beam also increasing with the peak current, namely, space charge and microbunching instability, as observed in some FEL facilities (e.g. [35,37,40]).

Second, we suggest using a shorter laser pulse at the RF photoinjector, resulting in a shorter electron beam σ_{s0} and improved longitudinal emittance. This corresponds, for the same bunch length before the last compression stage, to a reduced C and thus to final shorter pulses [see Eq. (1)]. This also translates [see Eq. (2)], for given values of R_{56} and C , to a reduced final energy spread of the electron beam and thus to a better FEL performance. In any case, the relative energy spread of the electron beam must be smaller than the Pierce parameter [12], with values between 10^{-4} and 10^{-3} for x-ray FELs. Beyond this limit, better energy spread generally corresponds to better FEL performance (higher FEL power and shorter saturation length). Reducing the injector laser pulse duration corresponds to an increase of the electron beam peak current for a given bunch charge; thus, optimizing the balance between the bunch charge and the laser pulse duration is required for best performance. If the reduction in pulse duration is larger than the reduction in charge, the transverse size of electron beam at the photocathode must be increased (by increasing the transverse size of the laser) to compensate for stronger longitudinal space-charge forces, which would otherwise elongate the electron beam. This would correspond to an increase of the transverse emittance and, thus, to a reduction of the IBS effects on the energy spread [34].

Figure 1 shows a schematic of the SwissFEL hard x-ray beamline, called “Aramis.” The electron beam is produced in an RF photoinjector consisting of an S-band (3 GHz) RF gun. The electron beam energy is about 7 MeV after the gun and



FIG. 1. Schematic of the SwissFEL hard x-ray line “Aramis” (not to scale).

300 MeV after acceleration with the *S*-band RF cavities of the injector. Linacs 1–3 accelerate the electron beam at *C*-band frequency (5.7 GHz) to the final energy, up to a maximum of 6.2 GeV. In standard operation, the electron beam is compressed in two magnetic chicanes or bunch compressors (BC): BC1 at 300 MeV energy and BC2 at 2.2 GeV. A third chicane, BC3, normally operates in isochronous mode ($R_{56} = 0$) and acts as an energy collimator, but can be used in dispersive mode for further compression (see below). The undulator consists of 13 modules, each with a period of 15 mm, a total length of 4 m, and a maximum K value of 1.8.

The electron beam duration in the injector is defined by the pulse duration of the photocathode laser. At SwissFEL, the rms laser pulse duration for the standard 200 pC operation is around 3 ps, and 1.4 ps for standard low-charge operation of 10 pC. Here, we reduce the rms laser pulse duration to about 0.3 ps (minimum given by the laser system) and we operate with bunch charges of about 4 pC for best performance (lasing with highest proportion of single spikes). Space-charge effects are stronger in this case than in standard low-charge operation, since the reduction in laser pulse duration (about a factor of 5) is greater than the reduction in bunch charge (a factor of 2.5). To compensate for this, we operate with a larger transverse size of the laser: while we work with 80 μm for standard low-charge mode, here we increase the laser transverse size to 180 μm . The penalty for operating with larger iris is a larger emittance. The measured normalized slice emittance after compression in BC1 is between 100 and 150 nm at the core of the electron beam, which is quite low, but higher than the 80 nm obtained for optimum conditions in standard low-charge operation [41]. A larger transverse emittance has the advantage of reducing the IBS effects on the energy spread. In the mode presented here, final compression is achieved in BC3, which operates in dispersive mode with $R_{56} = -3.4$ mm, as in standard low-charge operation. With this R_{56} , we need a chirp of 294 m^{-1} to realize full compression after BC3.

We employ two transverse-deflecting structures (TDS) to measure the time-resolved properties of the electron beam. The first TDS is placed after BC1, works with *S*-band frequency (3 GHz) and has a resolution of about 10 fs. The second TDS is located between BC2 and BC3, operates at *C*-band frequency (5.7 GHz), and is capable of measuring the electron beam with subfemtosecond resolution [42]. After BC3, we do not have a TDS to measure the final time-resolved properties of the electron beam. SwissFEL is equipped with bunch compression monitors (BCMs) after each bunch compressor. The BCM after BC3 features two independent detectors (pyrodetector and optical fiber spectrometer), which allows an absolute measurement of the electron beam duration before the undulator [43]. Direct photon pulse duration measurements are currently unavailable at SwissFEL. Instead, we estimate the FEL pulse duration from the analysis of single-shot spectra [44], obtained from a photon spectrometer [45].

For the results presented here, we operated with a bunch charge of 4 pC, a final electron beam energy of 4.92 GeV, and produced FEL pulses at a central photon energy of 6.1 keV. We adjusted the injector and linac phases to have the required chirp for full compression after BC3. The bunch charge was optimized to provide significant lasing with the maximum ratio of single spikes. For all charges, we slightly tuned the compression phases for best performance.

Single-shot current profile measurements of the electron beam after the injector (BC1) with and without compression, as well as after BC2 are presented in Fig. 2. The beam image obtained after BC2 shows the electrons streaked in time by the TDS and resolved in energy by dispersion and is therefore a representation of the longitudinal phase space (LPS) of the electrons before BC3. The LPS is clearly linear in time, indicating that nonlinear effects do not significantly alter the current distribution in this case. Simulation shows that the same holds true after full compression in BC3. This is because we work with shorter electron beams in the injector. The rms electron beam duration is 359 ± 1 fs after the injector, 103 ± 2 fs after BC1, and 8.9 ± 0.2 fs before BC3 (the error bars reflect statistical fluctuations between measurements), corresponding to a total compression factor C of 40 in the first two compression stages. The LPS measurement indicates a relative energy spread of $7.85 \pm 0.06 \times 10^{-4}$ (rms), which corresponds to an energy chirp of $294 \pm 7 \text{ m}^{-1}$, in accordance with the expected value to achieve full compression after BC3.

We recorded and analyzed 500 spectra each for slightly different compression configurations. We determine the number of spikes from standard algorithms considering a minimum spike height and a prominence of 10% of the maximum intensity. For the best configurations, our analysis yields between 80% and 90% of single-spike spectra with a bandwidth of $5.5 \pm 1.2 \text{ eV}$ (FWHM). Assuming transform-limited pulses, we estimate, from the measured spectral bandwidths, average FEL pulse durations of 330 as (FWHM). Figure 3 shows 20 consecutive single-shot spectra, each consisting of a single spike. For comparison, Fig. 4 shows six selected single-shot spectra, each consisting of two spikes. The pulse energies were measured to be about 4 μJ . Comparable FEL output was obtained in later measurement shifts with similar electron beam parameters.

Equation (1) allows an estimate of the electron bunch duration. The LPS measurement does not have sufficient resolution to accurately determine the uncorrelated energy spread before BC3, but we know or can estimate the parameters of the right-hand side of the second equation in Eq. (1): $R_{56} = -3.4$ mm, the intermediate compression factor $C = 40$, and the electron beam energies $E_2 = 4.92$ GeV and $E_0 = 300$ MeV are well known. Our greatest uncertainty is due to the initial uncorrelated energy spread σ_{80} . Here, we may rely on previous measurements: During a different shift, working with similar parameters, we measured the initial uncorrelated energy

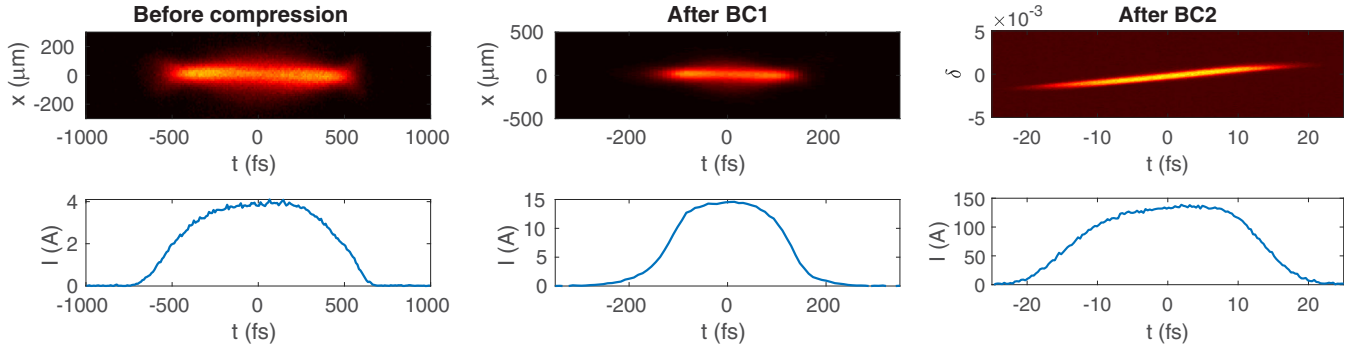


FIG. 2. Time-resolved measurements of the electron beam for a charge of 4 pC. Single-shot images of the streaked electron beam (top plots) and corresponding current profiles (bottom plots) before compression (left), after BC1 (center) and after BC2 (right). The measurement before compression is done with the TDS after BC1 by removing any chirp before BC1, so that BC1 is not compressing. For the streaked-beam image after BC2, the vertical axis corresponds to energy. See text for more details.

spread of the electron beam to be about 3.0 keV. This value is roughly in accordance with the measurements presented in Ref. [35], when properly scaled to account for IBS effects (square-root dependence of the increase in energy spread with distance), that would give 2.7 keV. Substituting these numbers into Eq. (1), taking an energy spread of 2.85 keV, we obtain an electron bunch length of $0.08 \pm 0.01 \mu\text{m}$, or a bunch duration of 0.26 ± 0.03 fs, where we have assigned a 10% error to the dominant uncertainty due to the intrinsic energy spread. The absolute bunch duration measurement enabled by the BC3 compression monitor gave a value of 0.33 ± 0.13 fs, in excellent agreement with the estimate based on Eq. (1). The estimated energy spread after full compression obtained from

Eq. (2) is approximately 8×10^{-4} , consistent with the LPS measurements shown in Fig. 2, corresponding to an absolute value of about 4 MeV.

RF jitter is a critical aspect when strongly compressing the electron beam, as it directly affects the stability of the electron bunch duration and peak current, and thus the stability of the FEL performance. For our set up, we found that the short-term stability of the final electron bunch duration, as measured relatively by the pyrodetector after BC3, is about 15%. On the FEL side, the ratio of the single spike spectra remains stable at 80%–90% in the short term, and pulse energy fluctuations derived from spectral measurements are within 30%–40%. The long-term performance can be stabilized by implementing feedback loops that control the phases of the RF systems before each bunch compressor (injector, linac 1, and linac 2/3) based on signals from the compression monitors.

We have simulated the generation of FEL pulses with these electron beams. To this end, we use elegant [46] to simulate compression in BC3 and transport to the undulator, and apply the code Genesis 1.3 [47] for FEL generation, including space-charge effects as well as wakefield effects in the undulator. As input for the simulations, we adopt the measured or assumed values mentioned before. To improve FEL performance, we move slightly away from full compression to achieve some energy chirp along the beam, which is later compensated by space charge and wakefield effects. Figure 5 shows five simulated single-shot spectral and power profiles. Most of the simulated pulses exhibit a single spike at saturation, with pulse energies of a few microjoules, average spectral bandwidths of 5.3 eV (FWHM) and pulse durations

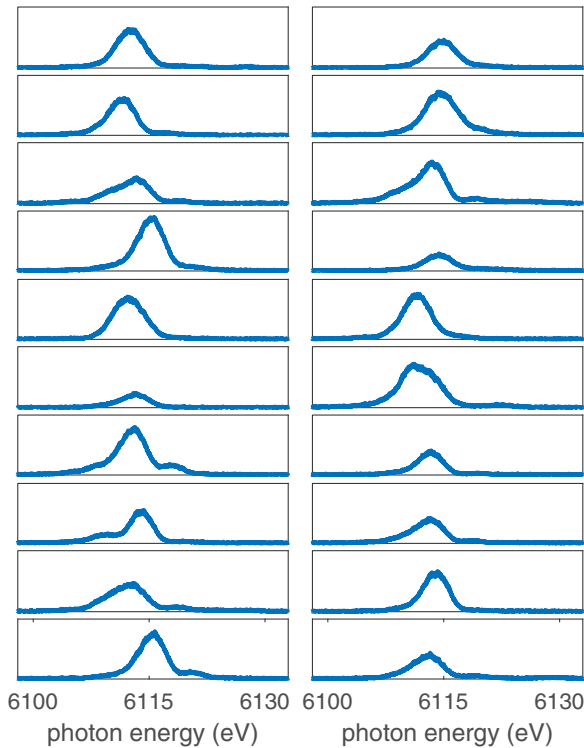


FIG. 3. FEL spectral measurements. Twenty consecutive single-shot spectra. All plots have the same horizontal axis (photon energy in eV) and vertical axis (spectral intensity).

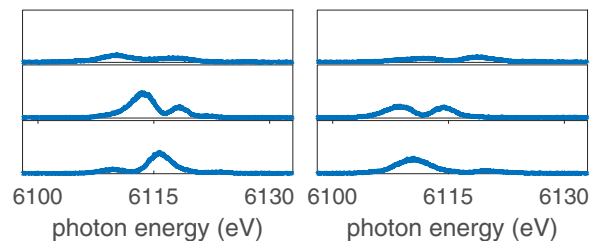


FIG. 4. Measured six single-shot spectra, each consisting of two spikes. The horizontal and vertical axes are the same as in Fig. 3

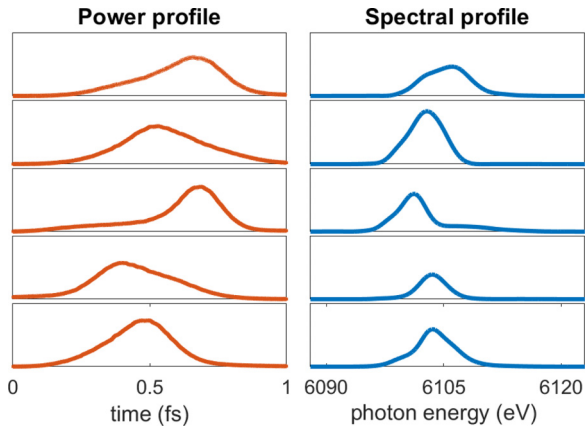


FIG. 5. Simulation results. Power profile (left plots) and spectral profiles (right plots) for five different shots. All power profile plots have the same horizontal axis (time in femtoseconds) and vertical axis (power between 0 and 10 GW). All spectral profile plots have the same horizontal axis (photon energy in eV) and vertical axis (spectral intensity).

of 320 as (FWHM), in good agreement with the experimental results, including the derived estimates. The FEL pulse duration (about 300 as FWHM) is shorter than the electron bunch duration (about 300 as rms) because of the nonlinear nature of the FEL process (i.e., different gain along the time coordinate of the electron beam depending on the peak current).

The results presented here can be compared to standard low-charge operation at SwissFEL using an electron beam charge of 10 pC and an initial electron beam duration of 1.4 ps. In Ref. [32], we reported a single-spike ratio of 0.3 with FWHM bandwidths of about 5.5 eV for 7 keV photon energies, and pulse energies of about 1 μ J. After general improvements to the machine, including the reduction of the initial energy spread of the beam by reducing the R_{56} of the laser heater in the injector [35], we typically obtain, for photon energies above 5–6 keV, 20%–30% of single spikes, bandwidths between 5 and 6 eV, and pulse energies of several μ J. The performance reported here with shorter pulses in the injector and lower charges is much better than standard 10 pC operation: We can generate FEL pulses with

similar estimated durations and comparable or slightly lower pulse energies, but with a much higher percentage of single spikes.

To conclude, we have demonstrated the enhanced production of single-spike hard x-ray FEL pulses starting from an electron beam with reduced charge and duration at the injector. Using 4 pC electron beams, we have generated hard x-ray FEL pulses with 80%–90% of the shots consisting of a single spike, with estimated pulse durations from spectral measurements of 330 as. Corresponding simulations yield equivalent pulse durations. Our approach is very simple and requires no special hardware, besides a relatively short laser pulse at the RF injector and diagnostics with sufficient sensitivity to characterize low-charge electron beams. Low-charge operation has the additional advantage of generally causing fewer problems related to beam loss.

Future work at SwissFEL may include further improvements of the initial energy spread to enable even shorter pulses, for instance by moving BC1 further upstream to limit IBS growth before compression, or by operating with even shorter gun laser pulses. Our method could readily be employed at other x-ray FEL facilities to obtain fully coherent pulses with much shorter pulse durations than shown here. This is because other facilities operate with higher electron beam energies (up to 15 GeV or higher compared to the 6 GeV of SwissFEL), which allows for shorter electron beams and also shorter coherence durations. Therefore, the proposed approach opens the door to achieve fully coherent pulses with pulse durations at the 100 as level or below. The current world record of 43 as [48] for photon energies at the 100 eV level, achieved with HHG sources, is within reach of FELs with their much higher powers and photon energies, opening up entirely different research perspectives.

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Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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