

# Experimental demonstration of an L-shaped corrugated wakefield structure for beam shaping at a high-repetition-rate free-electron laser

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We demonstrate the first realization of electron beam and x-ray pulse shaping with a corrugated wakefield structure at a pulsed-mode megahertz-repetition-rate hard x-ray free-electron laser (XFEL). This is achieved by an L-shaped corrugated structure with low-beta optics and a collimator. Variable streaking direction and signature of quadrupole wakefield compensation are observed by controlling the position of the electron beam relative to the corrugated plates. Spectral analysis at 7 keV indicates a reduction of the reconstructed x-ray pulse duration by an approximate factor of 4 compared to the standard self-amplified spontaneous emission mode of the European x-ray free-electron laser. X-ray pulses with uniform properties along a train of 100 pulses at a 1.125 MHz repetition rate are generated under 10 Hz pulse mode. These results are a step toward tailoring the temporal and spectral domain of x-ray pulses at megahertz repetition rates with high flexibility and compatibility.

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## I. INTRODUCTION

X-ray free-electron lasers (XFELs) serve a broad range of scientific experiments with highly customizable x-ray pulses with unprecedented peak brightness. The customization of the x-ray pulse properties, such as pulse duration and radiation bandwidth, often involves shaping the electron beam phase space via interacting the beam with an external laser, self-induced fields, and the surrounding environment.

Corrugated structures (CS) [1] serve as a distinctive type of beam-shaping device at XFEL facilities around the world. They produce strong longitudinal and transverse wakefields when an electron beam passes through the proximity of the metallic corrugation, enabling selective control of the lasing part of the electron beam. The fast development over the past decade has enabled the control of electron beam linear and nonlinear energy chirp [2,3], the control of beam slice matching [4], the improvement of self-seeding performance [5], the generation of multicolor x-ray pulses [6,7], high-power soft x-ray pulses [8], and

soft x-ray pulse trains [9]. So far, all these corrugated structures operate at a relatively low repetition rate of around 100 Hz.

Achieving beam shaping using corrugated structures at high repetition rates could open up new possibilities in x-ray sciences. For example, this could extend the multicolor x-ray pulse generation [6] and multistage x-ray amplification [8] techniques to a much higher repetition rate, leading to an orders-of-magnitude increase in the photon flux produced by stimulated x-ray emission [10] (both amplified spontaneous emission and seeded stimulated emission). Such pulses could be used as new nonlinear x-ray spectroscopy probes of electronic structure and dynamics [11] or serve as high-flux coherent x-ray sources [12–15] even though the driver is self-amplified spontaneous emission (SASE) [16,17]. Double pulses produced with variable delay and wavelength separation could be used in pump-probe experiments [18] to investigate damage and dynamic ordering mechanisms in proteins with increased chemical sensitivity. Besides, an increase in repetition rate could largely reduce the data-taking time, relaxing the requirement on the stability of the sample environment over long acquisition.

Realizing a corrugated structure at megahertz (MHz) repetition rates is challenging, mainly because the electron beam that travels at a distance of a few 100  $\mu\text{m}$  to the corrugations could generate losses at the structure, which scale with the repetition rate, and are further transported

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downstream, resulting in undulator degradation [19]. Alternative methods using beam energy chirp combined with lattice dispersion [20,21] are possible to produce less beam loss, where usually dispersion is produced from compression chicanes or dispersive transport lines. However, the corrugated structure holds the advantage of flexibility and compatibility with multibeamline operation, since it does not require drastic changes to bunch compression and a dispersive section.

In this paper, we report the first experimental demonstration of a corrugated wakefield structure operating at a pulsed-mode megahertz repetition rate at the European XFEL facility. The corrugated structure system features an L-shaped geometry with specially designed low-beta beam optics and a collimator, achieving operation at a MHz repetition rate under a 10 Hz pulsed mode with a few hundred bunches in each pulse train. Control of the wakefield streaking direction is realized by setting the relative position between the electron beam and the L-shaped structure, where the signature of quadrupole wakefield compensation is also observed. We demonstrate control of the XFEL pulse duration with the corrugated structure at high repetition rate. Our analysis of hard x-ray spectra showed that the reconstructed XFEL pulse duration at 7 keV was reduced by approximately a factor of 4. Uniform x-ray pulse properties along the pulse train were achieved. These results provide a new path toward tailoring the temporal and spectral domain of x-ray pulses at megahertz repetition rates with high flexibility and compatibility.

## II. EXPERIMENTAL SETUP

The European XFEL operates at a beam energy up to 17.5 GeV with 10 Hz pulsed mode carrying a maximum of 2700 bunches per pulse train at 4.5 MHz repetition rate [22]. The bunches in a train are distributed to three undulator lines: the hard x-ray lines SASE1, SASE2, and the soft x-ray line SASE3. The SASE1 and SASE3 lines share the same beam path and normally operate in parallel using a fresh bunch mode [23]. Figure 1(a) shows the schematic layout of the experimental setup at SASE1, where the high-energy electron beams experience transverse wakefields from the corrugated structure and their bunch tails are streaked. The electron transverse projection is measured on a screen located before the undulator. The FEL pulse energy is characterized by an x-ray gas monitor (XGM) [24] downstream of the undulator. The FEL spectrum is then analyzed by the high resolution hard x-ray single-shot (HIREX) spectrometer [25] located after the XGM. Nowadays, the European XFEL typically operates with about 1200 bunches in each pulse train at a 2.25 MHz repetition rate, in which a few hundred pulses are available for the SASE1 undulator. A schematic of the bunch pattern in each pulse train is shown in the closed-up inset of Fig. 1(a), with colored bars and labels indicating the destination of each bunch. Here, the SASE1 and SASE3 pulses are interleaved, therefore reducing the SASE1 repetition rate to 1.125 MHz. However, the bunch pattern is highly flexible in repetition rate, thanks to the

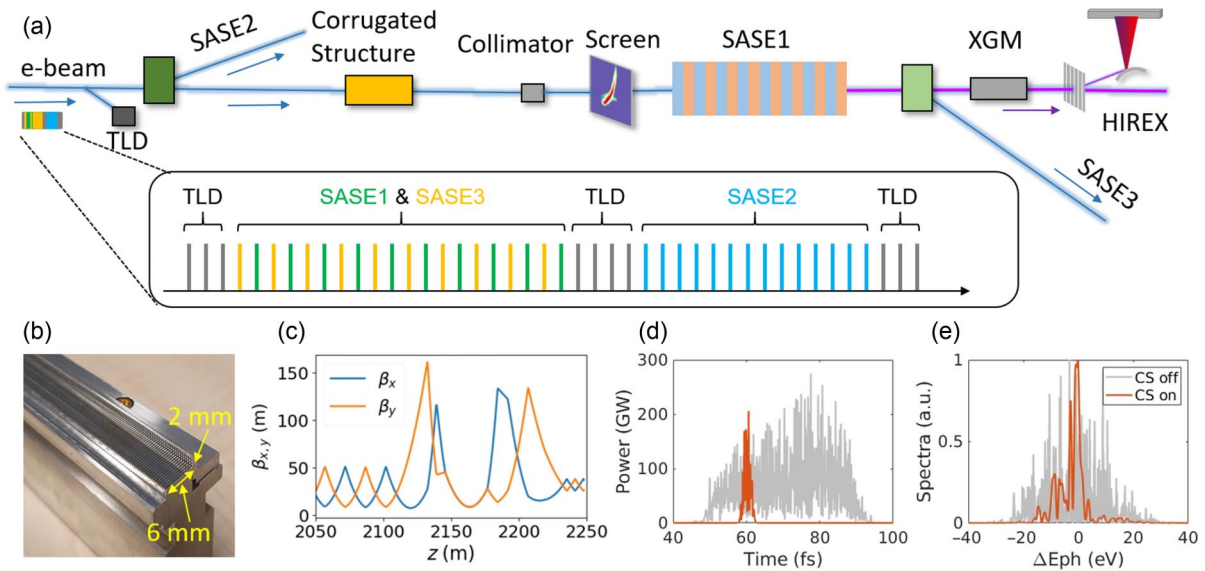


FIG. 1. Layout of the experimental setup for beam shaping at the SASE1 undulator line at the European XFEL (a), where the electron beams up to 4.5 MHz repetition rate are delivered by the superconducting linear accelerator under a 10 Hz burst mode (with the bunch pattern in each macropulse shown as colored bars in the closed-up inset); photo of the L-shaped corrugated structure sample unit (b); designed electron optics that provides low-beta function at the corrugated structure located at 2163–2169 m and matching into the SASE1 undulator (c); and simulated single-shot temporal profiles (d) and spectra (e) at 9 keV using start-to-end simulated beam distribution, for the cases with and without corrugated structure in red and gray, respectively.

combined fast and slow kicker systems and the beam dump (TLD) before the undulators.

The beam-shaping corrugated structure is 6 m long and features a novel L-shaped design [26,27], which combines streaking strength enhancement and cancellation of the quadrupole point-charge wakefields. By varying the beam distances toward the two plates, the operation mode can be switched between the traditional single-plate mode and the L-shaped mode. In the single-plate mode, the quadrupole point-charge wakefield exists, causing undesired slice mismatch [28] at the bunch tail. Such time-dependent mismatch could hinder fresh-slice applications in multicolor pulse generation [6], multistage amplification of femtosecond pulses [8], and phase-locked pulse generation with self-seeding [29]. Previous experiments demonstrated quadrupole bunch-wake compensation [30,31] using a cross-orientation layout. Recent analysis for fresh-slice application indicated that such a scheme could make the transverse kick nonmonotonic [32]. Here, in the L-shaped mode, it is possible to eliminate the quadrupole point-charge wakefield component [27], therefore removing the root cause of the time-dependent mismatch.

Figure 1(b) shows a sample unit of the beam-shaping corrugated structure, with a plate width of 6 mm in the horizontal plate and 2 mm in the vertical plate. The corrugation parameters are period of 0.5 mm, an opening of 0.25 mm, and a depth of 0.5 mm. Another feature of the corrugated structure is that it is nonmovable; therefore, an orbit bump is used to bump the electron beam toward the corrugations. Since SASE1 and SASE3 share the same beam path, parallel operation and selective streaking are realized via a fast kicker system to separate the beam orbits of the two beamlines and recombine them before entering the undulator.

Based on extensive experiments and simulations [19] on beam-loss control for the corrugated structure implementation, we designed special beam optics shown in Fig. 1(c) and a collimator. This configuration maintains a small beam size at the corrugated structure and further reduces the beam loss entering the undulator section. Figures 1(d) and 1(e) show GENESIS [33] simulated single-shot FEL power profiles (d) and spectra (e) at 9 keV for the cases with (red) and without (gray) the corrugated structure. The 14 GeV electron beam used in the FEL simulations is obtained from a start-to-end beam dynamics simulation with OCELOT [34]. The electron beam position is set to have a 0.5 mm distance to both corrugated plates. Multishot simulations with 200 random seeds show that the average pulse energy is reduced from 2.8 to 0.23 mJ, the full-width at half-maximum (FWHM) duration is reduced from 37 to 2 fs, and the FWHM bandwidth is reduced from 28 to 14 eV.

### III. EXPERIMENTAL RESULTS

#### A. L-shaped structure dynamics

The dynamics of the L-shaped corrugated structure are verified through the diagnostic screen 50 m downstream of the structure. The screen has a phase advance to the structure of  $0.5$  and  $0.6\pi$  in the horizontal and vertical planes, respectively. Therefore, it is suitable to visualize the streaking in both planes. The variable streaking and signature of quadrupole wakefield compensation are demonstrated through a distance scan to the vertical plate (which streaks the beam horizontally) while fixing the distance to the horizontal plate. Since the quadrupole effect is proportional to the beta function at the structure, we tuned one quadrupole on purpose to increase the beta function in the corrugated structure area, with  $\beta_x = 71$  m

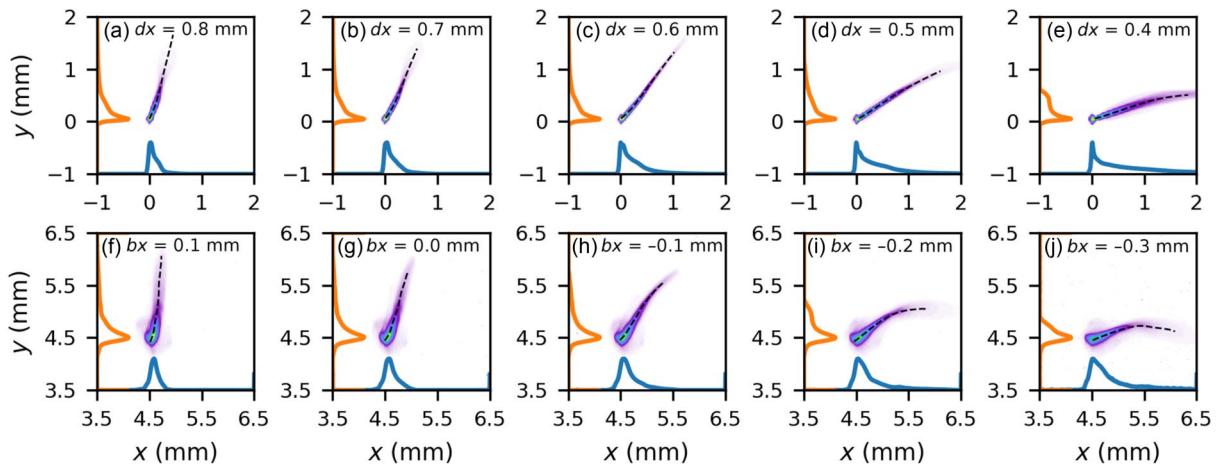


FIG. 2. Simulated (top row) and measured (bottom row) beam images at the diagnostic screen downstream of the corrugated structure for different distances to the vertical plate (which streaks the beam horizontally). For the simulated cases,  $dx$  is the distance toward the vertical plate, while for the measured cases,  $bx$  is the bump set points.

and  $\beta_y = 18$  m. No lasing was established in the structure dynamics study.

Here in Fig. 2, we show the simulated beam transverse projections while scanning the absolute distance to the vertical plate  $dx$  in the top row and the measured beam images while scanning the set points of orbit bumps  $bx$  in the bottom row. In the measurement, the absolute distance to the structure was not calibrated mainly due to the uncertainties arising from the nonlinearity of beam position monitor readings at large offsets. From the simulation, it is clear that at a distance of  $dx = 0.8$  mm, the streaking is mostly dominated by the transverse wakefield of the horizontal plate. As the beam approaches the vertical plate, it progressively experiences a stronger kick in the horizontal plane, and the beam image rotates toward the vertical plate. The measured images reproduce the expected streaking direction rotation, confirming the beam dynamics of the corrugated structure.

For the simulation, the distance to the horizontal plate is fixed at 0.6 mm; therefore, Fig. 2(c) represents the quadrupole wakefield compensated case. From the measured images, a clear trend that the bunch tail gets focused and then defocused can be observed from Figs. 2(f)–2(j). To show this more quantitatively, we first fit a ridge line to each image (shown as black dashed lines overlaid on the beam images in Fig. 2) and take beam slices perpendicular to the ridge line. All images are divided into 20 slices, and the slice beam sizes are extracted and normalized to the head slice beam size  $\sigma_0$ . Here,  $\sigma_0$  is calculated by averaging over the head slice beam sizes of the five images for each scan. The variation of the slice relative beam size during the distance scan is plotted in Fig. 3 for the simulated (a) and measured case (b), respectively. It can be observed that the slice size change mainly happens at the bunch tail part for both cases, due to the intrinsic nature of wakefields. It is also clear that at the position of

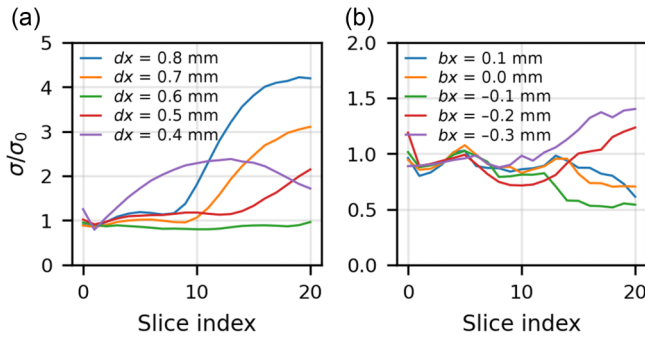


FIG. 3. Slice beam size analysis for the distance scans, with (a) and (b) shown for the simulated and measured case, respectively. The slices are obtained by first fitting a ridge line to each image and dividing the beam along the ridge line. The sizes are normalized to the head slice beam size  $\sigma_0$ , which is obtained by averaging over the head slice beam sizes of the five images.

quadrupole compensation (green lines in both subpanels of Fig. 3), the bunch tail shows the smallest beam size, confirming the signature of quadrupole wakefield compensation.

Discrepancies between simulation and measurements were also observed in beam sizes and projected beam densities on both planes. At small distances in Figs. 2(i) and 2(j), the bunch tail also showed higher-order curvature that bends away from the horizontal plane. Such deviations could originate from electron beam current profile differences in the experiment, incoming mismatches of the beta functions with the lattice, and existing beam tilts and mismatches introduced upstream of the accelerator.

## B. Pulse shaping at high repetition rate

The application to x-ray pulse shaping is demonstrated through pulse duration control under standard SASE mode, which typically produces tens of femtosecond pulses with millijoule-level pulse energy. The special low-beta optics setup is used to minimize the beam loss and the quadrupole effect. Figures 4(a) and 4(b) show 300 consecutive spectra (a) and their average (b) taken under such regular conditions at 7 keV, where the average pulse energy is 2.3 mJ. A Gaussian fit of the averaged spectrum indicates an rms bandwidth of 13.2 eV. Since there is no

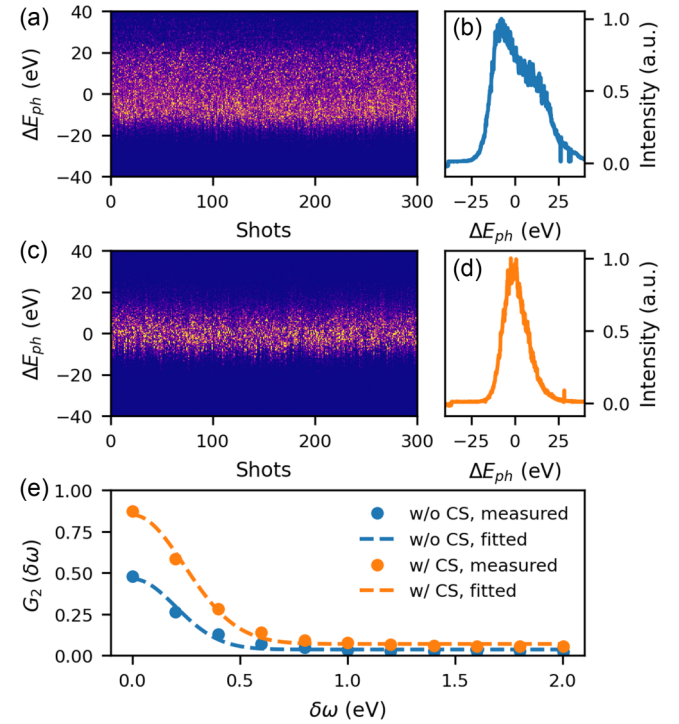


FIG. 4. FEL pulse shortening results with the corrugated structure at 7 keV. The spectra of 300 consecutive shots (a) and the corresponding averaged spectrum (b) taken without the corrugated structure; the same for the case with corrugated structure in (c) and (d); and the second-order spectral correlation function  $G_2$  calculated from spectral intensity fluctuation (e).

time-domain pulse duration diagnostic tool available for SASE1, we performed pulse duration and energy chirp analysis, employing the reconstruction method using spectral intensity fluctuations proposed in Ref. [35]. The second-order spectral correlation function  $G_2(\delta\omega)$  is shown in blue in Fig. 4(e). The analysis yields a reconstructed rms pulse duration of 27.2 fs, beam chirp of 1.5 MeV/ $\mu\text{m}$ , and spectrometer resolution of 0.13 eV.

When the electron beam is bumped toward the L-shaped structure, transverse beam tilt is generated along the beam. For the longitudinal slices with large offset, their orbits oscillate from the lasing orbit, preventing the slices from lasing. As a result, the x-ray pulse duration is shortened. We show 300 consecutive spectra, their average, and the second-order spectral correlation function  $G_2(\delta\omega)$  in Figs. 4(c)–4(e), respectively. The rms spectral bandwidth is significantly narrowed to 6.7 eV from the Gaussian fit of the averaged spectrum. The average pulse energy is 0.2 mJ. The same reconstruction process yields a reconstructed rms pulse duration of 6.3 fs, beam chirp of 2.8 MeV/ $\mu\text{m}$ , and spectrometer resolution of 0.11 eV. These measurements indicate an approximately fourfold reduction in the reconstructed pulse duration when the corrugated structure is used.

It should be noted that the reconstruction method assumes a Gaussian x-ray temporal profile and a linear chirp in the beam. Besides, the reconstruction could not give the sign of the chirp. Measurement of the electron beam current profile using a coherent radiation intensity spectrometer [36] installed at the end of the main linac showed a Gaussian-like current shape. Simulations [37] and measurements [38] at the SASE2 undulator line have indicated that some nonlinear component in the electron beam longitudinal phase space is present (c.f. Fig. 5 in Ref. [38]), while the lasing window mainly sits at the linear chirp part where the peak current is located. For the case with the corrugated structure, the lasing window is much shorter, therefore less constrained by the global current profile and the global nonlinear chirp. For the longer pulse case, part of the nonlinear chirp tail could contribute to lasing, adding uncertainty to the reconstructed pulse duration. Our further analysis using the spectrally resolved reconstruction of spectrogram autocorrelation [39] method failed to detect a strong quadratic chirp (c.f. Figs. 4 and 7 in Ref. [39]) from the data shown in Fig. 4. Overall, these checks support the main assumptions of the reconstruction for the present dataset, but they do not replace a direct temporal diagnostic at SASE1.

Figure 5 shows the data taken at high-repetition-rate mode with the streaking from the corrugated structure in a separate experiment at 9.3 keV, where each pulse train contains 100 electron beams with a 1.125 MHz repetition rate within the train. The spectra of the 100 bunches in one pulse train are shown in Fig. 5(a). There is a central photon energy shift along the pulse train, which is the result of the

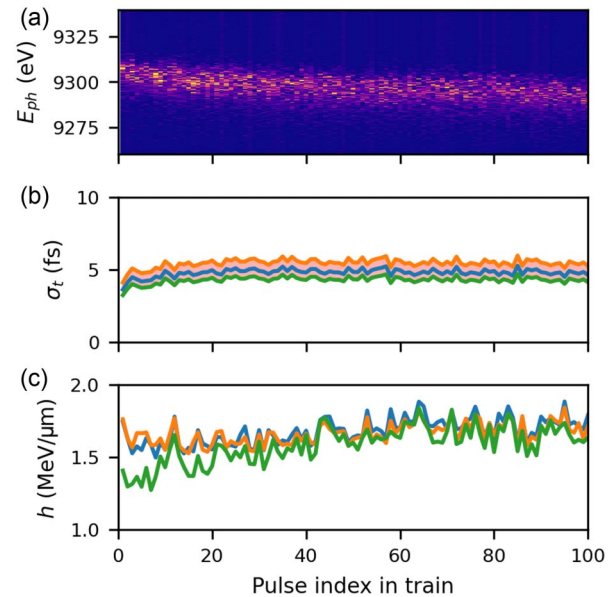


FIG. 5. Spectra of one pulse train with 100 bunches at 1.125 MHz repetition rate when the corrugated structure is used (a). Reconstructed pulse duration (b) and beam chirp (c) for positions along the pulse train using 300 consecutive pulse trains. The blue, red, and green curves represent results with assumed SASE bandwidths of 4.2, 3.7, and 4.7 eV, respectively.

electron beam energy slope from the accelerator and can be corrected through accelerator rf settings. The reconstructed rms pulse duration and beam chirp along the pulse train are shown in Figs. 5(b) and 5(c) using 300-pulse train data. The blue, red, and green curves in Figs. 5(b) and 5(c) represent results with assumed SASE bandwidths of 4.2, 3.7, and 4.7 eV, respectively. We can see a small relative uncertainty in pulse duration and the beam chirp from the uncertainty of SASE bandwidth estimation, indicating relatively uniform x-ray pulse properties along the pulse train. The reconstructed spectrometer resolution is about 0.15 eV, which is independent of the assumed SASE bandwidth and agrees with expected values.

As radiation damage is a major concern when operating the corrugated structure at high repetition rate, we measured the neutron dose rate along the tunnel, which is the dominant source of undulator damage, using a mobile autonomous robot Marwin [40] when operating the structure with 200 bunches in each pulse train for few-femtosecond pulses at 7 keV. As shown in Fig. 6, after the collimator (black dashed line), the dose rate caused by the corrugated structure (red solid line) decayed to a level of about 40  $\mu\text{Sv/h}$  at the undulator line entrance (black dot-dashed line). Such a dose rate level is well below the estimated limit for radiation damage of the undulators [41]. Other components upstream of the undulator can be protected by proper shielding. We expect a scaling to full 1200 pulses per train with 10 Hz burst rate (i.e., 12 kHz, effectively) to be feasible with accumulated losses below the

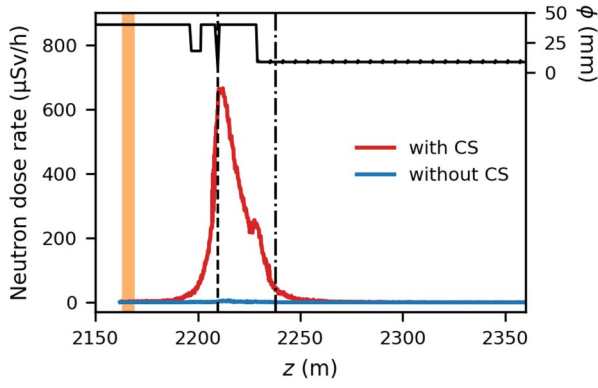


FIG. 6. Measured neutron dose rate (left axis) in the corrugated structure and undulator region when the electron beam is streaked (red) and not streaked (blue) by the structure. The positions of the corrugated structure, the collimator, and the undulator start are marked with an orange rectangle, a black dashed line, and a black dot-dashed line, respectively. The black solid line shows the vacuum chamber aperture change along the tunnel (right axis).

estimated threshold for undulator operation at the European XFEL. We note that for applications like two-color pulse generation, the beam-to-structure distance can be much relaxed and a scale-up of the effective repetition rate is expected. Further scaling up to continuous wave (cw) operation of 100 kHz to 1 MHz is under active study. Recently, reduction of beam losses has been observed [42] by using smaller apertures of the main collimators [43] after the linac.

### C. Parallel operation

As the electron bunches delivered to the hard x-ray undulator line SASE1 and soft x-ray undulator line SASE3 share the same beam path, the beam-shaping corrugated

structure is naturally capable of streaking the bunches delivered to SASE1 and SASE3 undulator lines simultaneously. In practice, it is favorable to allow selective streaking of either SASE1 or SASE3 bunches, where one undulator line delivers corrugated structure-shaped pulses while the other remains unaffected. Such a parallel operation scheme is realized with a combined kicker system around the structure that separates the beam orbit of SASE1 and SASE3 bunches up to a few millimeters at the dechirper location and recombines the orbit for transportation through the undulator lines. Experimental demonstration of parallel operation is illustrated in Fig. 7. SASE1 and SASE3 bunches in the same macropulse arrive at the corrugated structure with a time separation of about 30  $\mu$ s and fall in the off and on region of the kicker system, respectively. As a result, the SASE1 bunches are bumped close to the corrugated structure [blue orbit in Figs. 7(a) and 7(b)], while the SASE3 bunches are kicked away from the corrugations [red orbit in Figs. 7(a) and 7(b)] by the kickers. The beam projections are measured at the downstream diagnostic screen, as shown in Fig. 7(c), where the orbit separations are not fully closed for visualization purposes. It is clear that one bunch was streaked in both  $x$  and  $y$  directions, while the other remained unstreaked. One advantage of the system is that it is straightforward to exchange the bunches being streaked by setting the timing of the kicker voltage properly with respect to the arrival time of the bunches. The switch of the streaked pulse was tested successfully with full transmission of both pulses through the full undulator lines. However, due to the availability of the spectrometer in the soft x-ray undulator line and limited experiment time, parallel lasing and switching of pulse length shaping between the two undulator lines were not established, which we leave to future studies.

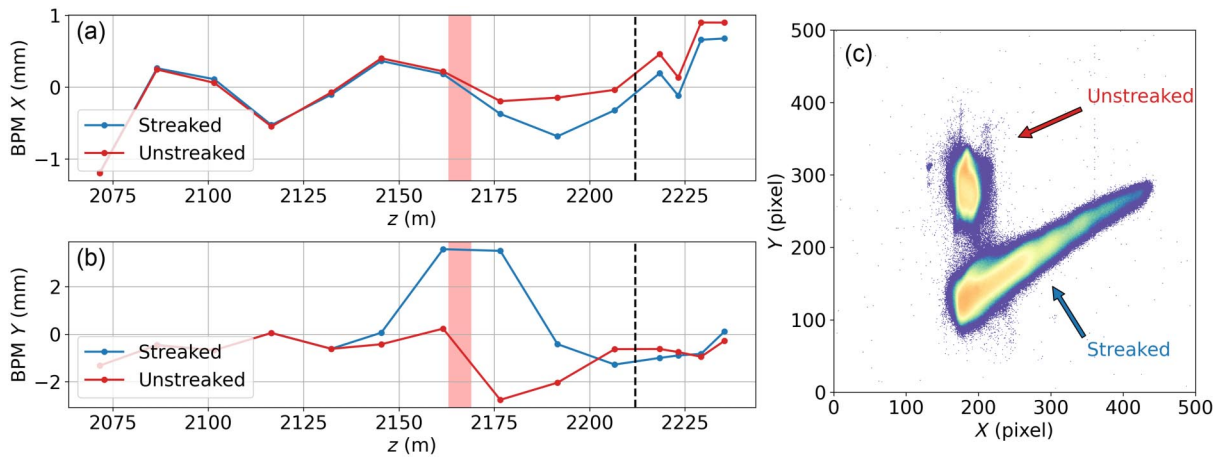


FIG. 7. Parallel operation of the corrugated structure. Beam orbits in the  $x$  and  $y$  directions for both the streaked beam (SASE1, kicker off) and the unstreaked beam (SASE3, kicker on) are shown in panels (a) and (b), respectively. The red rectangle marks the region of the corrugated structure. The dashed line marks the position of the diagnostic screen. Panel (c) shows the beam image at the diagnostic screen under parallel operation.

#### IV. SUMMARY

In summary, we demonstrated the first successful use of a corrugated structure for beam shaping at a pulsed-mode megahertz-repetition-rate x-ray free-electron laser. The dynamics of the L-shaped structure is verified. Few-femtosecond hard x-ray pulses with MHz repetition rate in pulsed mode were generated regularly at multiple beam energies and photon energies. The operation of the beam-shaping corrugated structure does not interfere with other undulator lines, being intrinsically suitable for high-repetition-rate facilities with multiple undulator lines working in parallel. The demonstrated results provide exceptional pulse-shaping capabilities for undulator lines without a dispersive or compressive section that can be easily tuned for methods recently demonstrated in SASE2 [44] and SASE3 [45]. Besides, the L-shaped geometry with variable streaking direction could serve as a new tool for multidimensional beam phase-space diagnostics. While the experimental demonstration is performed under the burst-mode operation at the European XFEL, the underlying physical constraints addressed in this work are not specific to burst-mode operation but common to high-repetition-rate XFELs. The combination of special optics and collimator works as an insertion section into the beamline and can in principle be adapted to other megahertz-class FEL facilities, subject to facility-specific layout and space constraints.

Further work will be required with more precise position control to better characterize the dynamics of the L-shaped structure and validate its wakefield model in detail. With the magnetic chicane and self-seeding system inside the SASE1 undulator installed recently, two-color pulse generation and fresh-slice self-seeding at MHz repetition rate could be pursued. Direct temporal diagnostic of the electron beam longitudinal phase space and FEL pulse duration is foreseen with the planned postundulator corrugated wakefield structure at the SASE1 branch (as in SASE2 [38]) in the near-future upgrade of the European XFEL. Further beam-loss reduction measures, such as reduction of aperture gaps of the main collimator [43], could be taken in order to reach shorter x-ray pulse duration and prepare for an eventual cw operation.

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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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