

Longitudinal emittance improvement at an x-ray free-electron laser by shortening the injector laser pulse duration

Anastasiia Riabchikova^{1,2}, Philipp Dijkstal¹, Wenxiang Hu^{3,4},
Thomas G. Lucas¹, Sven Reiche¹, and Eduard Prat^{1,*}

¹*PSI Center for Accelerator Science and Engineering, 5232 Villigen PSI, Switzerland*

²*Particle Accelerator Physics Laboratory, EPFL, 1015 Lausanne, Switzerland*

³*PSI Center for Photon Science, 5232 Villigen PSI, Switzerland*

⁴*Laboratory for Solid State Physics and Quantum Center, ETH Zurich, 8093 Zurich, Switzerland*



(Received 8 October 2025; accepted 14 January 2026; published 10 February 2026)

The performance of x-ray free-electron lasers (XFELs) strongly depends on the longitudinal emittance of the electron beam. We show that by reducing the injector drive laser pulse duration, the electron beam peak current can be increased by a factor of 2 or more, resulting in a significant improvement in longitudinal emittance. Comprehensive simulations and measurements carried out at SwissFEL confirm the expected trade-off of moderately higher transverse emittance. This simple approach can be readily adapted to other XFEL facilities.

DOI: [10.1103/PhysRevAccelBeams.29.020703](https://doi.org/10.1103/PhysRevAccelBeams.29.020703)

I. INTRODUCTION

X-ray free-electron lasers (XFELs) are advanced light sources that produce high-power x-ray pulses of femto-second duration [1–3]. Their unique properties enable transformative research in multiple scientific disciplines such as structural biology, ultrafast chemistry, and quantum materials. The XFEL pulses are generated by a multi-gigaelectronvolt (GeV) and high-brilliance electron beams traversing a long undulator.

The performance of an XFEL is fundamentally determined by the quality of the electron beam, often characterized by its six-dimensional (6D) brightness or brilliance, which quantifies the charge density in full phase space and can be defined as [4]:

$$B = \frac{Q}{\epsilon_{n,x}\epsilon_{n,y}\epsilon_{n,s}}, \quad (1)$$

where Q is the electron bunch charge, $\epsilon_{n,x}$ and $\epsilon_{n,y}$ are the normalized transverse emittances in the horizontal and vertical planes, respectively, and $\epsilon_{n,s}$ is the longitudinal emittance. The latter can be expressed as

$$\epsilon_{n,s} = \frac{Qc\sigma_E}{Im_e c^2}, \quad (2)$$

where c is the speed of light, σ_E represents the uncorrelated or intrinsic energy spread of the electrons, I is the peak current of the electron beam, and $m_e c^2$ is the rest-mass energy of an electron (0.511 MeV). The above two equations emphasize the need for electron beams with low transverse and longitudinal emittance, the latter corresponding to high peak currents and low-energy-spread values.

Standard XFEL facilities employ radiofrequency (rf) photoinjectors [5,6], in which the electrons are produced via the photoelectric effect by a laser impinging on a photocathode located in an rf gun. The electron beams have low transverse emittance (typically below 1 μm), durations of a few picoseconds and energies of several MeV. After the rf photoinjector, the electron beams are accelerated to several GeV and compressed to the femtosecond level in the linac section, which consists of rf accelerating cavities and magnetic bunch compressors.

This work focuses on improving the longitudinal emittance at XFELs by increasing the peak current of the electron beam at the injector. We propose to increase the initial peak current mostly by shortening the laser pulse at the photoinjector but also by operating off-crest in the gun to enable velocity bunching [7]. The transverse laser size needs to be increased to compensate for the stronger longitudinal space-charge forces, which can elongate the electron bunch, resulting in larger transverse emittance. For efficient FEL amplification, $(\epsilon_n/\gamma) \leq (\lambda/(4\pi))$ [8], where $\epsilon_n = \sqrt{\epsilon_{n,x}\epsilon_{n,y}}$ is the transverse emittance averaged over the horizontal and vertical directions, γ is the Lorentz factor of the electron beam, and λ is the FEL radiation wavelength. According to this condition, in general, the degradation in transverse emittance will have less of an impact on soft x-rays, i.e., longer wavelengths.

*Contact author: eduard.prat@psi.ch

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

From Eq. (2), the reduction in longitudinal emittance should in principle be linearly proportional to the increase in peak current I (assuming that the electrons' energy spread stays the same and the bunch charge is constant). However, the energy spread of the electron beam can be increased to a greater extent in the high peak current regime by effects like longitudinal space charge, intrabeam scattering (IBS) [9,10], and microbunching [11–14]. Assuming that the energy spread before compression is dominated by IBS (as found in Ref. [15] for uncompressed bunches up to 20 A with magnetic chicanes set straight), it scales as

$$\sigma_E \propto I^{1/2} \epsilon_n^{-3/4}. \quad (3)$$

Therefore, the actual reduction in longitudinal emittance would be proportional to the square root of the increase in peak current and further improved due to the degradation in transverse emittance. Once the electron beam is compressed, the effective increase due to IBS is significantly reduced: the energy spread increases linearly with the compression factor, whereas the growth rate increases only with the square root of the compression factor.

Reducing the longitudinal emittance corresponds, for the same final peak current, to a reduced energy spread of the electron beam. This has several benefits: in externally seeded FEL schemes [16–19], low-energy- spread values imply reduced seed-laser powers and give access to shorter wavelengths (the larger the initial energy spread, the higher the seed-laser power to achieve a certain relative energy modulation and the higher the final energy spread, which limits the shortest achievable wavelength); electron beams with reduced energy spread are shorter when fully compressed [20] and, conversely, electron beams can be compressed more while maintaining the same final energy spread; the efficiency of the optical klystron effect to reduce the FEL saturation length is improved for electron beams with reduced energy spread [21,22]; lower-energy- spread values improve the performance of coherence-enhancement FEL modes that delay the electron beam with respect to the radiation using magnetic chicanes in the undulator [23,24], since stronger delays can be applied without overbunching the beam [25]. Increasing the initial peak current implies less compression to achieve the same final peak current. This has the additional advantage that the robustness against rf jitters is improved: the rf stations used to induce the energy chirp for compression operate more closely to on-crest acceleration in this case, resulting in more stable conditions and higher energy efficiency.

The following work was carried out at SwissFEL, the XFEL facility in Switzerland [26,27]. We present simulations and experimental results that demonstrate the validity of the proposed method. For the standard bunch charge of 200 pC, we show that the peak current can be increased from about 20 A to more than 50 A by reducing the gun laser pulse duration from 3.3 to 1.4 ps (rms values)

in combination with velocity bunching. We demonstrate that the peak current can be doubled to about 40 A while keeping the increase in transverse emittance at a reasonable level (experimentally from 235 to 340 nm). The energy spread is measured to be about 5 keV for the standard 20 A case, and to be about 7 keV for the 40 A configuration, corresponding to a longitudinal emittance improvement of about 40%. The method is easy to implement and therefore may benefit other XFEL facilities in cases where the longitudinal emittance is important and the degradation in the transverse emittance has an acceptable impact on the performance. At SwissFEL, this approach has already been used to improve the generation of short pulses with a low-charge electron beam [28].

In Sec. II, we describe the SwissFEL injector and our measurement techniques, Sec. III covers simulation and experimental results, and discussion and conclusion follow in Sec. IV.

II. SWISSFEL INJECTOR AND ELECTRON BEAM CHARACTERIZATION

SwissFEL [26] is the XFEL facility at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. It includes two parallel branches: the hard x-ray beamline, Aramis, operating in the wavelength range of 0.1 to 0.7 nm; and the soft x-ray beamline, Athos, covering wavelengths from 0.65 to 5.0 nm [27]. In standard mode, SwissFEL operates with electron beam charges of 200 pC, but for the generation of short pulses, bunches of 10 pC charge are used [29,30].

A sketch of the SwissFEL injector is shown in Fig. 1. A Yb:CaF₂ laser produces the electron beams via the photoelectric effect in a cesium telluride cathode deposited on copper. The nominal longitudinal distribution of the laser has a Gaussian shape with an rms duration of 3.3 ps for 200 pC bunch charge and 1.4 ps for 10 pC. The transverse laser profile has a truncated Gaussian shape, the size of which can be controlled with a variable iris. An S-band (3 GHz) photoelectron rf gun accelerates the electrons to an energy of 7.1 MeV. The generated electron beams have a peak current of about 20 A for the standard bunch charge of 200 pC, and of about 3 A for the 10 pC operation. A solenoid magnet at the gun is employed to optimize the transverse emittance of the electron beam by compensating for the space-charge forces [31]. A dipole magnet and a two-dimensional transverse profile monitor placed 3 m after the gun allow us to measure the energy and projected energy spread of the generated electron bunch.

The electron beam is accelerated to approximately 300 MeV by four S-band rf accelerating stations (corresponding to six accelerating structures). A laser heater [32], located between the second and third S-band stations, can be used to increase the uncorrelated energy spread of the beam, but is typically turned off, because it has proven ineffective for standard SwissFEL operation. It was also turned off during our studies. As in normal operation, the

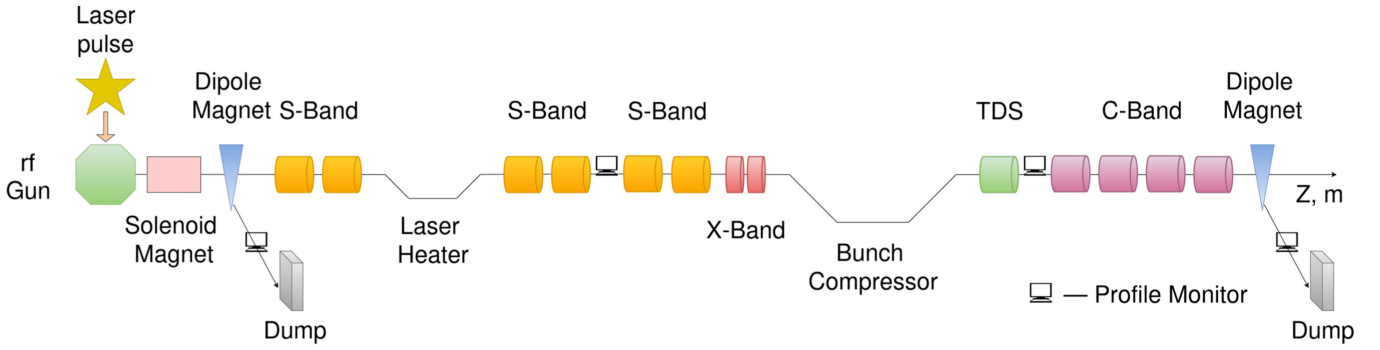


FIG. 1. Schematic layout of the SwissFEL injector (not to scale). See text for more details.

magnetic chicane associated with the laser heater was kept to a relatively low magnetic field to minimize an increase in the electron beam's energy spread due to microbunching effects that depend on the longitudinal dispersion of the chicane [15]. An X-band rf station is used to linearize the longitudinal phase space of the electrons. The bunch compressor, a magnetic chicane consisting of four dipole magnets, typically compresses the electron beam by approximately a factor of 10. Since the focus of the injector measurements presented here is on the peak current and energy spread of uncompressed beams, the injector is operated at or near on-crest acceleration, and the dipole magnets are set to zero current to avoid compression in the chicane, unless otherwise noted. Moreover, operating the bunch compression chicane straight without longitudinal dispersion minimizes any increase in energy spread due to microbunching.

An S-band rf transverse-deflecting structure (TDS) with a resolution of about 10 fs [33] is used to streak the electron beam after the bunch compressor. This allows us to measure the current profile of the electron beam, and thus its peak current, using a profile monitor after the TDS. It also allows measurement of the longitudinal phase space (LPS) of the electron beam (energy and energy spread along time) when using the profile monitor at a location with transverse dispersion at the injector dump, which is placed further downstream after the first part of the C-band linac of SwissFEL. The uncorrelated energy spread of the electron beam is obtained from the LPS as the energy spread at the core slice of the beam with the highest peak current.

We typically take five to ten shot-to-shot measurements for the determination of current profile and slice energy spread. The error bars given on peak current and energy spread correspond to statistical uncertainties across the measurement shots.

The TDS increases the energy spread of the electron beam. We reconstruct the true energy spread of the electron beam (and the TDS contribution) by measuring the slice energy spread for different TDS voltages, as done, for instance, in Ref. [15]. The measurements presented here were not significantly affected by other contributions such

as profile monitor resolution or the natural beam size of the electron beam; thus, scanning the beam energy to deconvolve those contributions (as done previously in SwissFEL [15,34]) was not required. In particular, we empirically minimized the measured slice beam size by slightly modifying the magnetic strength of a quadrupole magnet that changes the natural beam size but not the dispersion at the measurement location, thereby ensuring that the measured value was dominated by energy spread and not optics.

An X-band TDS with subfemtosecond resolution [35] is used to perform peak current and LPS measurements after the Athos undulator. At this location, the energy spread of the electron beam is reconstructed from the optical klystron effect (see Ref. [36] and references therein) by measuring the radiation pulse energy produced in the undulator as a function of the longitudinal dispersion R_{56} of a magnetic chicane placed in the middle of the undulator. The pulse energy is measured with a gas monitor [37]. We obtain the relative energy spread as

$$\frac{\sigma_E}{E} = \frac{\lambda}{2\pi R_{56}^*}, \quad (4)$$

where R_{56}^* is the optimum longitudinal dispersion of the chicane giving the maximum radiation power (this simplified approach is sufficient for our relatively low-energy-spread values, and the more refined but complicated methods presented in Ref. [38] are not necessary). The optical klystron method offers better resolution than the LPS approach and is required to measure the relatively low-energy-spread values at the undulator, where the beam energy is more than 3 GeV, which is much higher than in the injector.

The transverse emittance of the electron beam can be measured at several locations along SwissFEL. For the results presented here, we measure the projected emittance after the laser heater area using the symmetric single-quadrupole-magnet scan technique [39]. The transverse beam sizes for the different optics are obtained from Gaussian fits to the projections of the transverse distribution onto the horizontal and vertical planes. Whenever we quote a single value for emittance, it corresponds to the

geometric average between the horizontal and vertical emittance. The measurement uncertainties are calculated by error propagation of the statistical beam-size variations. We assume a minimum beam-size error of 5% and add shot-to-shot measurement errors in quadrature.

III. RESULTS

A. Simulation and experimental parameters

Our simulation and experimental studies were performed for the standard bunch charge of 200 pC. We limit ourselves to two different gun laser rms pulse durations: the standard duration of 3.3 ps and a shorter pulse duration of 1.4 ps, which is available as a presetting of the laser system. These two pulse durations correspond to peak currents at the cathode of 24.2 and 57.0 A, respectively, if we assume perfect Gaussian longitudinal beam distributions and disregard effects from space charge or velocity bunching.

For each of the two pulse durations, we performed systematic scans of three parameters, which together determine the final electron beam brightness: (i) Magnetic field strength of the gun solenoid: The solenoid field is varied to minimize the projected normalized transverse emittance for the different configurations. (ii) Transverse beam size of the gun laser: This parameter must be increased when operating with shorter pulses to compensate for the elongation of the electron bunch due to stronger longitudinal space-charge forces and effectively achieve higher peak currents. However, an increase in the transverse size implies an increase in transverse thermal emittance. During measurements, the transverse beam size of the laser is changed by modifying the laser iris size. To measure the transverse beam size, a part of the laser beam is reflected from before entering the rf photoinjector and sent to a profile monitor located at a distance equivalent to that to the cathode. (iii) Gun rf phase: The reference or zero gun rf phase is defined as the one that gives the minimum projected energy spread at the measurement location 3 m after the cathode. Operation with negative phases induces a stronger energy chirp in the electron beam, which leads to shorter electron bunches and thus higher peak currents due to velocity bunching, but generally also leads to an increase in transverse emittance. This is because a stronger variation in energy does not allow the solenoid field to focus all slices the same way, causing an optics mismatch along the bunch and thus an increase in transverse emittance. Going off-crest in rf acceleration phase reduces the rf energy gain, which in principle can be compensated by the rf gradient (for instance, 15° off-crest acceleration corresponds to 3.4% energy reduction). For both the standard and short laser pulse duration, the reference phase is measured or simulated for the standard transverse laser beam size and then kept constant for the other conditions. An exception are the measurements with the short-pulse duration, for which the reference phase was remeasured when changing to some of the transverse laser beam sizes (the change was typically only a few degrees).

Moreover, for the case of the short-pulse configuration, the phase and the solenoid field of the first S-band accelerating structure were fine-tuned to achieve the best performance.

Our objective was to use the short laser pulse to achieve a peak current of at least 40 A while minimizing the degradation in transverse emittance.

B. Simulation results

We performed three-dimensional space-charge simulations using the ASTRA code [40]. We tracked 20,000 macroparticles per configuration to ensure statistically reliable results without excessive computational effort. The beams were simulated up to the exit of the second S-band accelerating station at the injector, corresponding to a distance of 13 m from the gun. At this location, the electron beam's energy is around 150 MeV, such that space-charge effects are no longer significant for the transverse emittance. Since the current version of ASTRA does not consider IBS or microbunching effects, we focus on the peak current and transverse emittance values. For the transverse emittance, we give values corresponding to the central 90% of the transverse electron beam distribution (the 10% cut is applied to the transverse offset of the electrons).

The reference case with 200 pC corresponds to an rms laser pulse duration of 3.3 ps and an rms transverse beam size of $140\ \mu\text{m}$. This gives a peak current of 20.0 A and a transverse emittance of 207 nm. Figure 2 shows how the peak current changes when varying the transverse beam size from 110 to $300\ \mu\text{m}$ (for the reference gun rf phase) and the gun rf phase between -15° and 5° (for a fixed transverse size of $200\ \mu\text{m}$). For each configuration, the gun

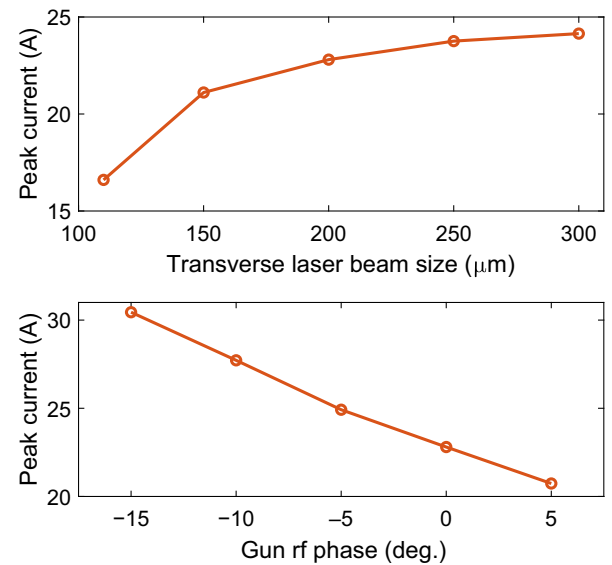


FIG. 2. Simulated peak current as a function of the transverse laser beam size (for zero gun rf phase) and as a function of the gun rf phase (for a fixed transverse laser beam size of $200\ \mu\text{m}$) for the standard configuration.

solenoid was readjusted to optimize the transverse emittance. We observe that the peak current increases with beam size, with a greater rate of increase for smaller spot sizes. This is expected since longitudinal space-charge forces that elongate the electron beam (and reduce its peak current) are reduced for larger transverse laser beam sizes. The peak current of the electron beam grows from 16.6 to 24.1 A (practically the maximum achievable value at the cathode) when enlarging the transverse beam size from 110 to 300 μm . We also see an increase of the peak current via velocity bunching when reducing the gun rf phase. For a fixed transverse beam size of 200 μm , the peak current increases from 20.7 to 30.4 A when the gun rf phase is adjusted downwards from $+5^\circ$ to -15° . This shows that with velocity bunching, we can achieve higher peak currents after the injector (30.4 A) than what can be generated directly at the cathode (24.2 A).

The optimum setting in terms of five-dimensional (5D) brightness (proportional to $I/(\epsilon_{n,x}\epsilon_{n,y})$) corresponds to the reference configuration. Nevertheless, with regard to the longitudinal emittance, even for the standard gun laser pulse duration, it would be possible to increase the peak current of the electron beam, albeit by sacrificing transverse emittance and overall 5D brightness. For instance, we could achieve a 25% increase of peak current (from 20 to 25 A) at the expense of increasing the transverse emittance from 207 to 393 nm by increasing the transverse beam size from 140 to 200 μm and reducing the gun rf phase by 5° with respect to the reference phase.

We then considered a reduced laser pulse duration of 1.4 ps. Similar to the standard case, Fig. 3 exhibits the dependence of the peak current of the electrons on the transverse beam size (for zero gun rf phase) and on the gun rf phase (for a beam size of 300 μm). As with the standard laser pulse duration, the gun solenoid was readjusted to optimize the transverse emittance for each point. We observe an increase in the peak current with larger beam sizes and reduced gun rf phases, as with the standard gun laser pulse duration. However, significantly higher peak current values can now be achieved. The peak current increases from 31.7 to 47.6 A when enlarging the transverse laser beam size from 150 to 400 μm (at zero gun rf phase). For a 300 μm transverse laser beam size, the peak current can be increased to 57.5 A with velocity bunching by reducing the gun rf phase by 15° with respect to the reference phase.

Finally, we performed a systematic optimization of the transverse laser beam size, the gun solenoid, and the gun rf phase, with the goal of achieving the best transverse emittance for a peak current of at least 40 A. The optimum is achieved close to the reference gun rf phase with a transverse laser beam size of 220 μm and results in a peak current of 40.2 A and a transverse emittance of 349 nm.

The simulations, which include space charge but no IBS or microbunching effects, show a slice energy spread at the

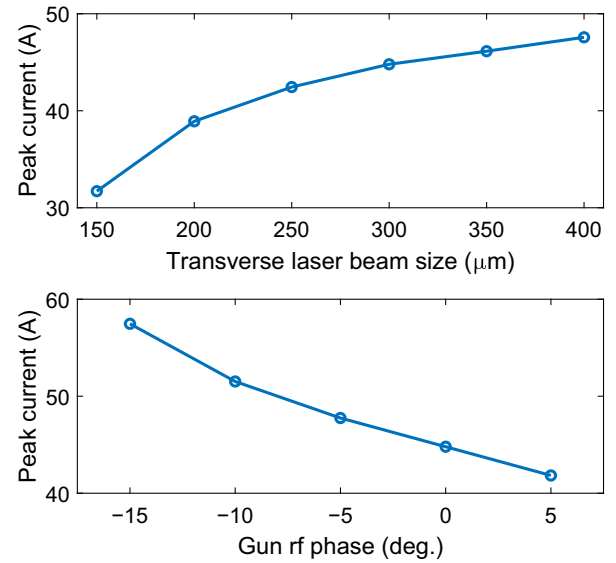


FIG. 3. Simulated peak current as a function of the transverse laser beam size (for zero gun rf phase) and as a function of the gun rf phase (for a fixed transverse laser beam size of 300 μm) for the short-pulse configuration.

bunch core of 0.87 keV for the standard configuration and 1.6 keV for the short laser pulse configuration. Although the energy spread is significantly larger for the short-pulse case, it remains well below the expected contribution from IBS and microbunching, which is estimated to be about 5 keV or higher.

C. Experimental results

The reference case for the standard pulse duration corresponds to a transverse laser beam size of around 180 μm and zero gun rf phase. This typically results in electron beams with peak currents of around 20 A and transverse emittances between 200 and 250 nm. In the measurement shown here, we obtain 19.4 ± 0.1 A and 235 ± 9 μm . The experimental transverse laser beam size for the reference case (180 μm) is 25%–30% larger than in simulations (140 μm). The difference could be due to a suboptimal setup of the transverse beam-size measurement, leading to measured values higher than the real ones.

In line with the simulations, we measured how the peak current changes as a function of the transverse beam size of the laser and the gun rf phase, for the standard and short laser pulse configurations. The results are shown in Figs. 4 and 5 for the standard and short laser pulse cases, respectively. For the standard laser pulse duration, the emittance was optimized in all cases using the gun solenoid. For the short-pulse case, the reference gun rf phase was remeasured for some of the different transverse laser sizes, and the solenoid was readjusted only for the largest sizes to improve the electron beam quality.

The results displayed in Figs. 4 and 5 empirically confirm the findings of the simulations. In both cases,

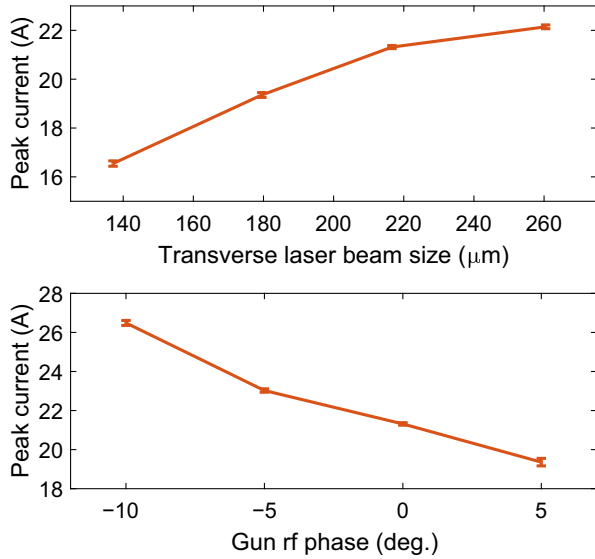


FIG. 4. Measured peak current as a function of the transverse laser beam size (for zero gun rf phase) and as a function of the gun rf phase (for a fixed transverse laser beam size of 217 μm) for the standard configuration.

the peak current increases with the transverse laser beam size and with reduced gun rf phase. Moreover, much larger peak currents can be achieved in the short laser pulse case. The measured and simulated curves show good qualitative agreement. However, as previously mentioned for the reference configuration, a better quantitative match is only achieved by reducing the measured transverse laser beam sizes.

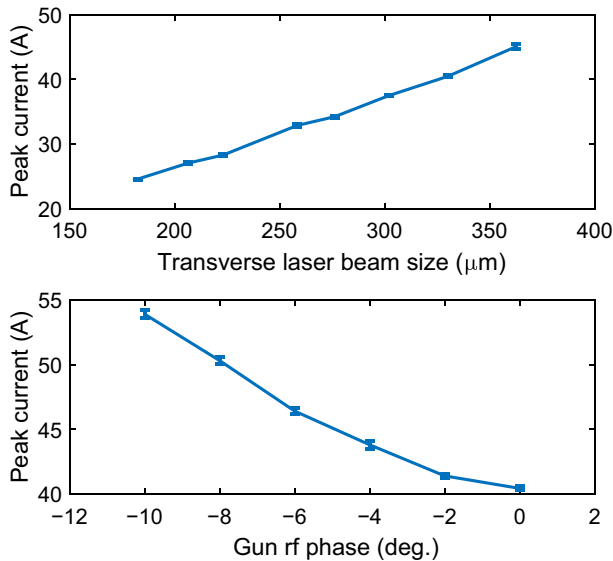


FIG. 5. Measured peak current as a function of the transverse laser beam size (for zero gun rf phase) and as a function of the gun rf phase (for a fixed transverse laser beam size of 330 μm) for the short laser pulse configuration.

For the standard pulse duration, the peak current can be enhanced from 16.5 ± 0.1 to 22.1 ± 0.1 A when increasing the transverse laser beam size from 137 to 260 μm, and to 26.5 ± 0.1 A when reducing the gun rf phase by 10° with a transverse laser beam size of 217 μm. A systematic optimization of the transverse beam size of the laser, the gun rf phase, and the solenoid field gave the best 5D brightness for zero gun rf phase and for a transverse laser beam size of 217 μm (smaller transverse laser beam sizes resulted in equivalent 5D brightness). This means that the peak current can be increased by about 30% (from 16.5 to 21.3 A) by increasing the transverse laser beam size while maintaining equivalent 5D brightness. Further increases in peak current are possible but would result in a deterioration of the 5D brightness. For instance, a transverse laser beam size of 217 μm and a 5° reduction in the gun rf phase would give a peak current of 23.0 ± 0.1 A and a transverse emittance of 273 ± 11 nm.

For the short-pulse configuration, the peak current increases from 24.6 ± 0.1 A for 182 μm transverse laser beam size to 45.1 ± 0.4 A for 363 μm size, and from about 40.4 ± 0.2 to 53.9 ± 0.3 A when the gun rf phase is reduced by 10° (for a size of 330 μm). We optimized the gun solenoid, the gun rf phase, and the transverse laser beam size to obtain the best emittance for a peak current of at least 40 A. The outcome is a transverse laser beam size of 276 μm and a gun rf phase of about -5° , resulting in a final peak current of 43.0 ± 0.4 A, and a measured projected emittance of 337 ± 14 nm. These values are equivalent (within a few percent) to the simulated values (40.2 A, 349 nm). Nevertheless, also here, we observe that the optimal transverse laser beam size (276 μm) is significantly larger than the simulated one (220 μm). Figure 6 shows a single-shot current profile measurement for the standard and optimized short-pulse configurations (other shots show very similar behavior).

We measured the electron beam energy spread for the reference configuration (standard laser pulse duration, transverse beam size of 180 μm, reference gun rf phase), and for the optimized 5D-brightness case for the short laser pulse. For the standard case, with a peak current of 19.4 A, the energy spread was measured for a bunch compressed by a factor of 10.6 to 205 A peak current. It is easier to measure the larger energy spread values for compressed bunches. The energy spread was measured to be 53.2 ± 0.4 keV, corresponding to an energy spread of 4.9 keV before compression (assuming preservation of the longitudinal emittance during compression) and after scaling with the distance from the bunch compressor to the screen to consider IBS effects (without this scaling, the energy spread would be 5.0 keV). This value is consistent with what we reported in Ref. [15]: 5.9 keV for 19 A, corresponding to 4.5 keV when scaled with the distance from the measurement location to the bunch compressor to account for IBS effects.

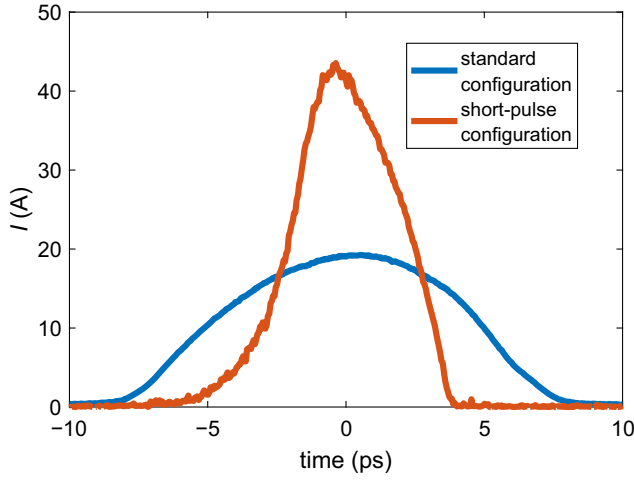


FIG. 6. Single-shot current profile measurement for standard and short-pulse configurations.

Figure 7 illustrates a measurement of the slice energy spread at the beam core as a function of the TDS voltage for the short-pulse mode. The measurement shown was performed for the uncompressed case. The reconstructed energy spread of the electron beam is 9.3 ± 0.3 keV, which corresponds to 7.0 ± 0.2 keV after scaling with the distance to the bunch compressor to account for IBS. We may compare this value to what we would obtain by scaling the energy spread measured for the standard configuration adjusting for the higher peak current and transverse emittance of the short-pulse mode according to Eq. (3), i.e., $4.9 \text{ keV} \times (43.0/19.4)^{1/2} (337/235)^{-3/4} = 5.6 \text{ keV}$. This is qualitatively consistent with our measurements, in the sense that we see an increase in energy spread for the high-peak-current case (from 4.9 to 5.6 keV), but significantly lower than the measured value (7.0 keV). Space-charge effects account for only a minimal part of this discrepancy. When including such effects based on our

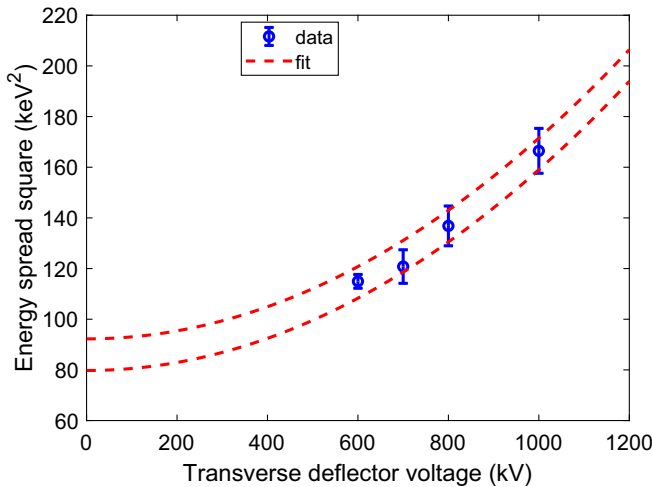


FIG. 7. Energy spread measurement as a function of the TDS voltage for the short-pulse case. See text for more details.

ASTRA simulation results (0.87 keV for the standard case and 1.6 keV for the short-pulse configuration), the scaled energy spread for the short-pulse case would be 5.8 keV. This value is still significantly lower than the measured 7 keV. The remaining discrepancy may be attributed to microbunching effects, which are more pronounced at high peak currents.

To summarize, our measurements at the injector show that, by reducing the laser pulse duration from 3.3 to 1.4 ps, the peak current can be enhanced by more than a factor of 2 (from 19.4 to 43.0 A), with the longitudinal emittance improved by approximately 40% (from 4.9 keV/19.4 A to 7.0 keV/43.0 A). The transverse emittance deteriorates (in each plane) by less than 50%, corresponding to an overall degradation in 6D brightness of only about 30%. Table I lists the most important simulated and measured parameters of the electron beam at the injector.

Furthermore, longitudinal emittance measurements were performed at the Athos undulator section for the two configurations on separate measurement shifts. The electron peak current was measured with the X-band TDS, registering 382 ± 9 A and 450 ± 9 A for the standard and short-pulse configurations, respectively. These peak current levels are sufficient to produce FEL radiation for the long wavelength range of Athos (e.g., for λ of around 3 nm or longer). The energy spread of the electron beam was reconstructed from the optical klystron effect. The optical klystron scans are displayed in Fig. 8. The FEL pulse energy was measured with a gas monitor. We were forced to employ the fast, uncalibrated signal for the standard configuration due to time constraints, which resulted in larger error bars, while the more accurate, slow, calibrated signal was used for the short-pulse case. The electron beam energy was 3.17 GeV and the radiation wavelength was 3.80 nm (3.48 nm) for the standard (short-pulse) configuration. The optimum longitudinal dispersion R_{56}^* , obtained from a second-order polynomial fit around the maximum radiation value, is found to be $13.6 \pm 1.5 \mu\text{m}$ and $18.3 \pm 1.8 \mu\text{m}$ for the standard case and the short-pulse case, respectively. This yields, based on Eq. (4), energy spread values of 140 ± 15 keV (standard case) and 96 ± 10 keV (short-pulse case). These measured parameters show two

TABLE I. Summary of simulated and measured electron beam parameters at the injector for the standard and short-pulse configurations.

Simulation	Standard	Short pulse
Transverse emittance (nm)	207	349
Peak current (A)	20.0	40.2
Measurement	Standard	Short pulse
Transverse emittance (nm)	235 ± 9	337 ± 14
Peak current (A)	19.4 ± 0.1	43.0 ± 0.4
Energy spread (keV)	4.9 ± 0.04	7.0 ± 0.2

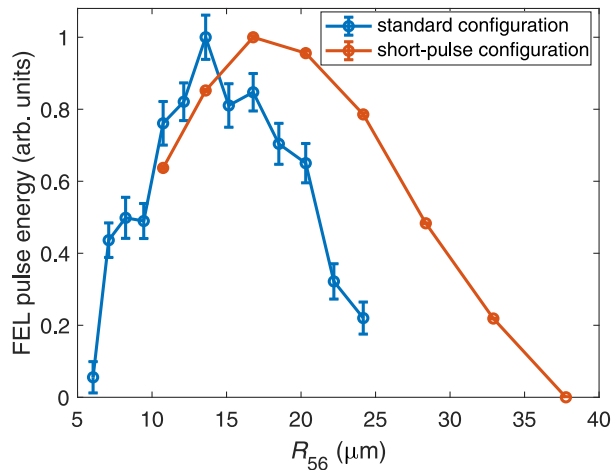


FIG. 8. Optical klystron scans to determine the energy spread of the electron beam at the Athos undulator. See text for more details.

key findings. First, the longitudinal emittance improvements of about 40% are preserved from the injector to the Athos undulator, as demonstrated by the concurrent transition from 140 keV/382 A to 96 keV/450 A. Second, there is a comparable degradation of the longitudinal emittance from the injector to the undulator for both cases (of about 40% for the standard configuration and of about 30% for the short-pulse case). This degradation is likely due to collective effects such as IBS and microbunching.

IV. CONCLUSION

To conclude, we have shown in both simulations and experiments that the peak current of the electron beam at the SwissFEL injector can be increased by more than a factor of 2 by shortening the gun laser pulse, while maintaining the degradation in transverse emittance at a reasonable level (about 50% increase in the measurements). Our experimental studies show that this leads to a reduction in the longitudinal emittance of about 40%. This method has already been employed at SwissFEL to enhance the generation of short hard x-ray FEL pulses with low-charge electron bunches [28] in terms of a significantly higher percentage of single spikes (for that case, we used the shortest gun laser pulse of only 0.36 ps duration). The demonstrated ability to tailor the electron beam for optimal longitudinal emittance constitutes a new operational pathway, unlocking enhanced performance for specialized applications, including seeding and generating ultrashort pulses, despite the trade-off in overall 6D brightness.

The proposed approach is straightforward and can be easily implemented in other XFEL facilities. The method can be particularly useful for those facilities interested in external seeding, such as the future SHINE [41], or in producing ultrashort pulses, such as the European XFEL [42].

Future work at SwissFEL may include optimizing the laser pulse duration and the electron bunch charge for best performance of the presented approach. Moreover, future efforts to further reduce the longitudinal emittance without compromising the 6D brightness may include hardware modifications such as a new rf gun, a bunching cavity between the rf gun and the first accelerating structure, or reducing the distance from the rf gun to the first bunch compressor.

ACKNOWLEDGMENTS

The work of W. H. was supported by funding from the European Research Council under the European Union's Horizon 2020 research and innovation program, within the Hidden, Entangled and Resonating Orders (HERO) project with Grant Agreement No. 810451. We acknowledge Alejandra Ocampo for her help in preparing the reference setup for the simulations. We thank Mike Seidel for fruitful discussions. We thank Thomas Schietinger for improving the language and consistency of the manuscript. We acknowledge all groups involved in the operation of SwissFEL, in particular the gun laser group, for providing the different laser pulse durations at the injector.

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.

-
- [1] Z. Huang and K.-J. Kim, Review of x-ray free-electron laser theory, *Phys. Rev. ST Accel. Beams* **10**, 034801 (2007).
 - [2] B. W. J. McNeil and N. R. Thompson, X-ray free-electron lasers, *Nat. Photonics* **4**, 814 (2010).
 - [3] C. Pellegrini, A. Marinelli, and S. Reiche, The physics of x-ray free-electron lasers, *Rev. Mod. Phys.* **88**, 015006 (2016).
 - [4] S. Di Mitri, On the importance of electron beam brightness in high gain free electron lasers, *Photonics* **2**, 317 (2015).
 - [5] J. S. Fraser, R. L. Sheffield, E. R. Gray, and G. W. Rodenz, High-brightness photoemitter injector for electron accelerators, *IEEE Trans. Nucl. Sci.* **32**, 1791 (1985).
 - [6] C. Hernandez-Garcia, P. G. O'Shea, and M. L. Stutzman, Electron sources for accelerators, *Phys. Today* **61**, No. 2, 44 (2008).
 - [7] S. G. Anderson, P. Musumeci, J. B. Rosenzweig, W. J. Brown, R. J. England, M. Ferrario, J. S. Jacob, M. C. Thompson, G. Travish, A. M. Tremaine, and R. Yoder, Velocity bunching of high-brightness electron beams, *Phys. Rev. ST Accel. Beams* **8**, 014401 (2005).
 - [8] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Coherence properties of the radiation from x-ray free electron laser, *Opt. Commun.* **281**, 1179 (2008).

- [9] A. Piwinski, Intra-beam-scattering, Technical Report No. CERN-1992-001.226, CERN, 1974, [10.5170/CERN-1992-001.226](#).
- [10] Z. Huang, Intrabeam scattering in an x-ray FEL driver, Technical Report No. SLAC-TN-05-026, Stanford Linear Accelerator Center, Stanford University, Stanford, CA, 2002.
- [11] S. Heifets, G. Stupakov, and S. Krinsky, Coherent synchrotron radiation instability in a bunch compressor, *Phys. Rev. ST Accel. Beams* **5**, 064401 (2002).
- [12] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Klystron instability of a relativistic electron beam in a bunch compressor, *Nucl. Instrum. Methods Phys. Res., Sect. A* **490**, 1 (2002).
- [13] Z. Huang and K.-J. Kim, Formulas for coherent synchrotron radiation microbunching in a bunch compressor chicane, *Phys. Rev. ST Accel. Beams* **5**, 074401 (2002).
- [14] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, Longitudinal space charge-driven microbunching instability in the TESLA test facility linac, *Nucl. Instrum. Methods Phys. Res., Sect. A* **528**, 355 (2004).
- [15] E. Prat, P. Craievich, P. Dijkstal, S. Di Mitri, E. Ferrari, T. G. Lucas, A. Malyzhenkov, G. Perosa, S. Reiche, and T. Schietinger, Energy spread blowup by intrabeam scattering and microbunching at the SwissFEL injector, *Phys. Rev. Accel. Beams* **25**, 104401 (2022).
- [16] L. H. Yu, Generation of intense UV radiation by subharmonically seeded single-pass free-electron lasers, *Phys. Rev. A* **44**, 5178 (1991).
- [17] G. Stupakov, Using the beam-echo effect for generation of short-wavelength radiation, *Phys. Rev. Lett.* **102**, 074801 (2009).
- [18] E. Allaria, D. Castronovo, P. Cinquegrana, P. Craievich, M. D. Forno, M. B. Danailov, G. D'Auria, A. Demidovich, G. D. Ninno, S. D. Mitri, B. Diviacco, W. M. Fawley, M. Ferianis, E. Ferrari, L. Froehlich *et al.*, Two-stage seeded soft-x-ray free-electron laser, *Nat. Photonics* **7**, 913 (2013).
- [19] P. R. Ribič, A. Abrami, L. Badano, M. Bossi, H.-H. Braun, N. Bruchon, F. Capotondi, D. Castronovo, M. Cautero, P. Cinquegrana, M. Coreno, M. E. Couprie, I. Cudin, M. B. Danailov, G. D. Ninno *et al.*, Coherent soft x-ray pulses from an echo-enabled harmonic generation free-electron laser, *Nat. Photonics* **13**, 555 (2019).
- [20] S. Di Mitri, Bunch length compressors, in *Proceedings of the CAS—CERN Accelerator School: Free Electron Lasers and Energy Recovery Linacs, Hamburg, Germany*, edited by R. Bailey, CERN Yellow Reports: School Proceedings (CERN, Geneva, 2018), Vol. 1/2018, CERN-2018-001-SP.
- [21] Y. Ding, P. Emma, Z. Huang, and V. Kumar, Optical klystron enhancement to self-amplified spontaneous emission free electron lasers, *Phys. Rev. ST Accel. Beams* **9**, 070702 (2006).
- [22] E. Prat, E. Ferrari, M. Calvi, R. Ganter, S. Reiche, and T. Schmidt, Demonstration of a compact x-ray free-electron laser using the optical klystron effect, *Appl. Phys. Lett.* **119**, 151102 (2021).
- [23] N. R. Thompson and B. W. J. McNeil, Mode locking in a free-electron laser amplifier, *Phys. Rev. Lett.* **100**, 203901 (2008).
- [24] B. W. J. McNeil, N. R. Thompson, and D. J. Dunning, Transform-limited x-ray pulse generation from a high-brightness self-amplified spontaneous-emission free-electron laser, *Phys. Rev. Lett.* **110**, 134802 (2013).
- [25] E. Prat, W. Hu, C. Arrell, M. Calvi, P. Dijkstal, R. Follath, and S. Reiche, Experimental demonstration of mode-coupled and high-brightness self-amplified spontaneous emission in an x-ray free-electron laser, *Phys. Rev. Lett.* **133**, 205001 (2024).
- [26] E. Prat, R. Abela, M. Aiba, A. Alarcon, J. Alex, Y. Arbelo, C. Arrell, V. Arsov, C. Bacellar, C. Beard, P. Beaud, S. Bettoni, R. Biffiger, M. Bopp, H.-H. Braun *et al.*, A compact and cost-effective hard x-ray free-electron laser driven by a high-brightness and low-energy electron beam, *Nat. Photonics* **14**, 748 (2020).
- [27] E. Prat, A. A. Haddad, C. Arrell, S. Augustin, M. Boll, C. Bostedt, M. Calvi, A. L. Cavalieri, P. Craievich, A. Dax, P. Dijkstal, E. Ferrari, R. Follath, R. Ganter, Z. Geng *et al.*, An x-ray free-electron laser with a highly configurable undulator and integrated chicanes for tailored pulse properties, *Nat. Commun.* **14**, 5069 (2023).
- [28] E. Prat, A. Malyzhenkov, G. L. Orlandi, T. Weilbach, and S. Reiche, Enhanced generation of single-spike hard x-ray free-electron laser pulses with lower charge and shorter electron beams in the injector, *Phys. Rev. Res.* **7**, L042060 (2025).
- [29] A. Malyzhenkov, Y. P. Arbelo, P. Craievich, P. Dijkstal, E. Ferrari, S. Reiche, T. Schietinger, P. Juranić, and E. Prat, Single- and two-color attosecond hard x-ray free-electron laser pulses with nonlinear compression, *Phys. Rev. Res.* **2**, 042018(R) (2020).
- [30] E. Prat, A. Malyzhenkov, C. Arrell, P. Craievich, S. Reiche, T. Schietinger, and G. Wang, Coherent sub-femtosecond soft x-ray free-electron laser pulses with nonlinear compression, *APL Photonics* **8**, 111302 (2023).
- [31] L. Serafini and J. B. Rosenzweig, Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: mA theory of emittance compensation, *Phys. Rev. E* **55**, 7565 (1997).
- [32] Z. Huang, M. Borland, P. Emma, J. Wu, C. Limborg, G. Stupakov, and J. Welch, Suppression of microbunching instability in the linac coherent light source, *Phys. Rev. ST Accel. Beams* **7**, 074401 (2004).
- [33] P. Craievich, R. Ischebeck, F. Löhl, G. L. Orlandi, and E. Prat, Transverse deflecting structures for bunch length and slice emittance measurements on SwissFEL, in *Proceedings of the FEL 2013, New York, USA* (JACoW, Geneva, Switzerland, 2013), pp. 236–241, TUPS014.
- [34] E. Prat, P. Dijkstal, E. Ferrari, A. Malyzhenkov, and S. Reiche, High-resolution dispersion-based measurement of the electron beam energy spread, *Phys. Rev. Accel. Beams* **23**, 090701 (2020).
- [35] E. Prat, Z. Geng, C. Kittel, A. Malyzhenkov, F. Marcellini, S. Reiche, T. Schietinger, and P. Craievich, Attosecond time-resolved measurements of electron and photon beams with a variable polarization x-band radiofrequency deflector at an x-ray free-electron laser, *Adv. Photonics* **7**, 026002 (2025).
- [36] E. Prat, C. Kittel, M. Calvi, P. Craievich, P. Dijkstal, S. Reiche, T. Schietinger, and G. Wang, Experimental characterization of the optical klystron effect to measure the intrinsic energy spread of high-brightness electron beams, *Phys. Rev. Accel. Beams* **27**, 030701 (2024).

- [37] A. A. Sorokin, Y. Bican, S. Bonfigt, M. Brachmanski, M. Braune, U. F. Jastrow, A. Gottwald, H. Kaser, M. Richter, and K. Tiedtke, An x-ray gas monitor for free-electron lasers, *J. Synchrotron Radiat.* **26**, 1092 (2019).
- [38] G. Geloni, M. Guetg, S. Serkez, and E. Schneidmiller, Revision of optical klystron enhancement effects in self-amplified spontaneous emission free electron lasers, *Phys. Rev. Accel. Beams* **24**, 090702 (2021).
- [39] E. Prat, Symmetric single-quadrupole-magnet scan method to measure the 2D transverse beam parameters, *Nucl. Instrum. Methods Phys. Res., Sect. A* **743**, 103 (2014).
- [40] K. Flötman, *ASTRA, A Space Charge Tracking Algorithm* (DESY, Hamburg, 2017).
- [41] T. Liu, N. Huang, H. Yang, Z. Qi, K. Zhang, Z. Gao, S. Chen, C. Feng, W. Zhang, H. Luo, X. Fu, H. Liu, B. Faatz, H. Deng, B. Liu *et al.*, Status and future of the soft x-ray free-electron laser beamline at the shine, *Front. Phys.* **11**, 1172368 (2023).
- [42] J. Yan, W. Qin, Y. Chen, W. Decking, P. Dijkstal, M. Guetg, I. Inoue, N. Kujala, S. Liu, T. Long, N. Mirian, and G. Geloni, Terawatt-attosecond hard x-ray free-electron laser at high repetition rate, *Nat. Photonics* **18**, 1293 (2024).