

Studies of enhanced SASE at the soft x-ray beamline Athos at SwissFEL

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(Received 3 February 2026; accepted 24 July 2026; published 24 August 2026)

We present studies on enhanced SASE at the soft x-ray beamline Athos at SwissFEL. The generation of a series of current spikes with 790 nm spacing is injected into the Athos undulator beamline. Due to strong space-charge forces, the optimum performance occurs with a strong positive taper of the undulator field. There is a clear modal structure in the observed spectra, indicating the presence of a train of attosecond FEL pulses with no intrinsic phase-locking. The space-charge dynamics causes an elongation of the current spike and a redshift in the bunching spectra, which determines the optimum taper gradient.

DOI: 10.1103/qw1g-ffds

I. INTRODUCTION

X-ray free-electron lasers (FELs) generate intense, ultrashort radiation pulses at photon energies primarily determined by the energy of a relativistic electron beam propagating through the periodic magnetic field of an undulator, reaching up to several tens of keV photon energies. Today, several large-scale facilities provide hard x-ray FEL radiation to a broad scientific user community [1–5], enabling research in physics, chemistry, biology, and medicine.

The most widely used mode of operation is the self-amplified spontaneous emission (SASE) [6,7] process, in which the FEL amplifies the shot-noise-induced spontaneous radiation emitted in the undulator. While SASE has the advantage that no external seed source is required, its stochastic startup process results in many random spikes in the temporal and spectral profile, fluctuating from shot-to-shot. There is no control to stabilize the location of these spikes in the time domain, e.g., to select a single spike in a controlled way or to exclude parts of the beam from lasing.

To improve upon these limitations, the concept of enhanced self-amplified spontaneous emission (ESASE) was proposed [8,9]. ESASE locally increases the peak

current of the driving electron beam by introducing a strong current modulation at optical wavelengths. The modulation is achieved by overlapping the electron bunch with an external optical laser field in a short-period, high-field undulator (the modulator), which imprints an energy modulation at the laser wavelength. A subsequent magnetic chicane converts this energy modulation into a density (current) modulation by exploiting the path-length differences of electrons with different energies. The resulting current spikes, separated by the laser wavelength, then enter the main undulator to drive the FEL process (see Fig. 1).

ESASE offers several advantages over standard SASE operation: First, the higher peak current reduces the FEL gain length, leading to more efficient amplification with shorter spike durations and higher peak power. Second, it shapes the FEL power profile by forming a periodic train of attosecond-scale pulses. The current modulation and therefore the envelope of the generated FEL pulse train are locked to the phase of the external laser. Thus, it allows the synchronization of the FEL pulse profile with the external optical laser when the laser pulse duration is shorter than the electron bunch, since it eliminates the impact of the electron-beam arrival-time jitter. However, it requires a better arrival-time jitter of the optical laser or passive locking of the optical laser to the pump signal at the experimental station [10]. There is a particularly beneficial effect on the operation of ESASE in the soft x-ray range: The aspect of directly enhancing FEL performance through higher peak currents is attractive for compact FEL facilities [11] to avoid the transport of a high-current beam at lower energies.

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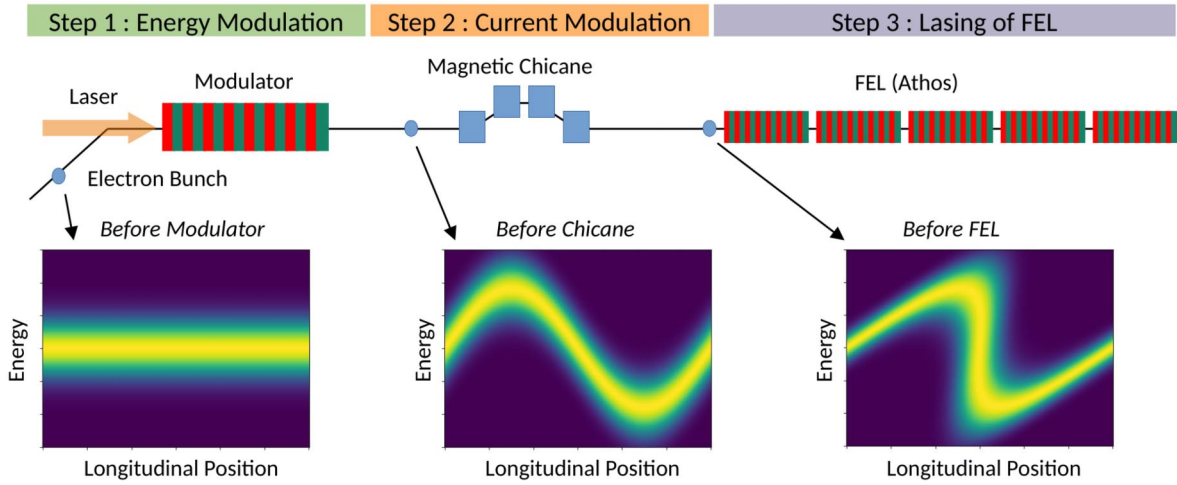


FIG. 1. Schematic for enhanced SASE, where an electron beam is overlapped with a laser in a modulator (step 1) to induce an energy modulation. The modulation is converted into a current modulation (step 2) and then injected into the main undulator (step 3). The longitudinal phase-space distributions before each step are shown over one laser wavelength.

The ESASE concept is closely related to the high-gain harmonic generation (HGHG) principle [12], demonstrated at FERMI in the soft x-ray regime [13], but it differs in that the current spikes produced in ESASE are much longer than the resonant radiation wavelength of the FEL. As a result, the FEL field still originates from noise and does not inherit the phase coherence of the external laser. ESASE has been experimentally demonstrated first at LCLS using a Ho:YLF laser at 2 μm wavelength [14]. The initial proof-of-principle ESASE demonstration at SwissFEL was performed at a wavelength of 790 nm [15].

Strong current modulations at optical or near-infrared wavelengths also excite longitudinal space-charge (LSC) forces, which significantly impact the electron beam dynamics. LSC fields induce an energy chirp across each current spike: electrons at the leading edge gain energy, while those at the trailing edge lose energy. This has been measured at a periodicity of about 20 fs with a modulation in a laser heater [16] and a compression with the main bunch compressor. Inside the undulator, this effect is enhanced by the reduced effective longitudinal velocity of the oscillating electrons, described by the modified Lorentz factor $\gamma_z = \gamma / \sqrt{1 + K^2/2}$ [17], where γ is the relativistic factor and K the undulator parameter. The resulting chirp may disrupt the FEL resonance condition, potentially limiting amplification. Nevertheless, because LSC fields evolve transiently as the electron bunch enters the undulator, there exists a window in which the FEL process can partially outrun the growing space-charge-induced chirp, since the transient behavior of the space-charge field has the same velocity as the radiation field with one wavelength per undulator period.

Several alternative approaches have been proposed to mitigate the detrimental impact of LSC. These include relying solely on energy modulation in combination with

undulator tapering [18] or intraundulator chicanes [19], replacing the longitudinal modulation with a transverse momentum kick from a laser [20], or utilizing angular dispersion [21]. Such methods primarily target the generation of attosecond pulse trains. For cases where the total slippage of the radiation field exceeds the current spike duration, a shorter effective undulator length would yield pulse durations even shorter than attainable with the above methods.

In this work, we demonstrate ESASE at the Athos soft x-ray beamline of SwissFEL, using a 790 nm modulation laser and achieving lasing at photon energies of 1 keV. We investigate the dominant role of space-charge forces in shaping the electron beam distribution, which is the changing energy chirp and the elongation of the current spikes during the amplification. Experimental results on ESASE performance and spectral properties are presented and compared with time-dependent simulations carried out with Genesis 1.3 [22], which successfully reproduce the key features observed. In the structure of this paper, the description of the soft x-ray beamline Athos at SwissFEL is followed by the measurement of the space-charge effects in ESASE configuration. Then we report on the observed ESASE FEL performance and its comparison to simulation results.

II. THE SOFT X-RAY BEAMLINE ATHOS AT SWISSFEL

The soft x-ray beamline Athos at SwissFEL consists of 16 undulator modules, each 2 m long, operating as a SASE FEL in the photon energy range from 250 eV to 1.8 keV [15]. A dedicated C-band rf linac, acting only on the beam injected into Athos, adjusts the beam energy between 2.9 and 3.4 GeV to cover the full tuning range. Each undulator module follows the Apple-X design [23,24], with a period

length of 38 mm and an undulator parameter K tunable up to 3.8. The design supports variable photon polarizations. More information on the beamline and its advanced operation modes can be found in [15].

The ESASE upgrade of the Athos beamline consisted of three main components: an optical laser with incoupling system, a modulator, and a dispersive chicane. The incoupling port is located 80 m upstream of the first Athos undulator module and uses the last dipole of the Athos switchyard to separate the beamline from the main linac by 3.75 m. This eliminates the need for an additional bypass chicane solely for the incoupling of the laser beam. The modulator, located about 1 m downstream of the last switchyard dipole, has nine periods with a period length of 20 cm and a maximum undulator parameter of $K = 36$ [25]. At an electron beam energy of 3.3 GeV, this allows resonant coupling to a laser of up to 1.6 μm wavelength. Each half-pole of the modulator can be controlled independently, allowing strong tapering or bicolor operation by splitting the modulator into two sections. For the measurements reported here, the modulator was tuned to 790 nm with $K \approx 25$. The modulator design is based on the intraundulator delaying chicanes [26] and ensures that any induced periodicity of energy modulation can be precisely matched with the delays in the Athos undulator for advanced schemes such as mode-locked lasing [19]. Due to the natural focusing by the modulator field, any change in the resonant wavelength requires rematching of the beam optics.

The dispersive chicane, which converts the energy modulation into a density modulation, is placed directly in front of the Athos undulator. It is 2 m long and consists of four dipoles, providing a maximum R_{56} of 790 μm at 3.3 GeV beam energy.

The laser system is a Ti:Sapphire source with a central wavelength of 790 nm, chosen for its flexibility in pulse duration (down to 20 fs FWHM) and pulse energy (up to 5 mJ). For the results presented here, the laser pulse was kept longer than 100 fs, mitigating arrival-time jitters and drifts of the electron bunch. Transverse overlap is established with Cromox screens placed before and after the modulator. The Rayleigh length of the laser beam is about 1 m with its focus in the center of the modulator. A photodiode in a secondary port of the downstream screen samples both the laser and the optical transition radiation of the electron beam, enabling coarse temporal overlap within 20–50 ps. Next, we scan the laser delay in steps of 50 fs and search for a drop in the FEL performance to establish the final overlap. This method is much faster and more robust than the measurement of the LPS with the transverse deflector [27,28] and the dispersive screens [29,30]. We repeated the overlap procedure over several hours to measure intrinsic timing drift between the laser and electron beam. With no arrival-time monitors or feedback systems running, we determined a combined

TABLE I. Parameters of the Athos beamline and ESASE configuration. The values in parentheses refer to the parameters used in the simulations.

Parameter	Value
<i>Electron beam</i>	
Energy E	3.3 GeV
Intrinsic energy spread σ_E	1 MeV
Peak current I	2.5 kA
Bunch charge Q	200 pC
Emittance ϵ_n	300 nm
<i>Athos undulator</i>	
Wavelength λ	0.7–5 nm (1.24 nm)
Period length λ_u	38 mm
Undulator parameter K	1–3.8 (1.86)
Periods per module N_u	52
Number of modules	16 (8)
<i>ESASE</i>	
Modulator period length λ_u	200 mm
Number of modulator periods N_u	9
Laser wavelength λ	790 nm
Laser pulse duration σ_t	20 fs or longer (full bunch)
Laser pulse energy U	≤ 5 mJ
Rayleigh length z_R	50 cm
Chicane R_{56}	≤ 790 μm (300 μm)

overlap jitter and drift of 39 fs (rms), which is sufficient for ESASE operation at SwissFEL without continuous timing readjustment. The relevant beam parameters are summarized in Table I. Peak current and energy were measured during the setup for the ESASE studies, while the remaining beam parameters are taken from previous measurements not related to ESASE. Since the intrinsic energy spread has a significant impact on this study we refer to a value of about 1 MeV, derived from the FEL gain curve in an optical-klystron configuration [31].

For measuring the FEL beam parameters, we primarily rely on two devices. The first is the photon-beam-intensity gas monitor based on the ionization of a noble gas by the FEL beam [32]. Based on the ionization cross section, the amount of observed ions is proportional to the FEL pulse energy. The second device, PMOS, utilizes the soft x-ray monochromator to measure the shot-to-shot spectrum of the FEL pulse with the exit slit fully open [33]. Since the spectrometer uses the effective source point of the FEL radiation for the imaging on the screen, it needs an optimization of the x-ray optics for a maximum resolution of about 100 meV. Any shift in the source point causes a loss of resolution if the optics are not actively rematched.

III. SPACE-CHARGE EFFECTS IN ESASE CONFIGURATION

In the ESASE configuration of SwissFEL, the external laser imprints an energy modulation with 790 nm

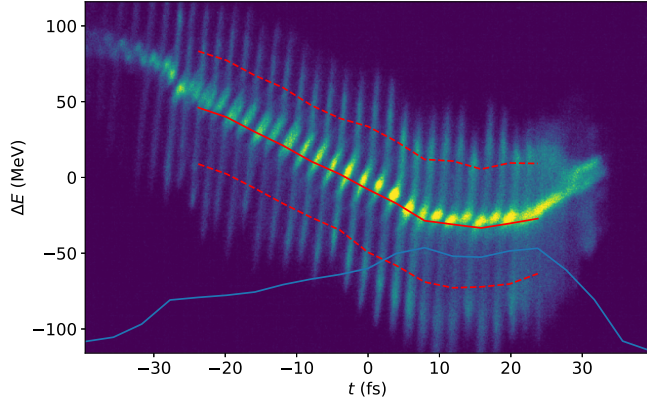


FIG. 2. Camera image of the horizontally streaked electron beam at the beam-dump screen in the Athos beamline. The energy dispersion is in the vertical direction. The slice mean energy and standard deviation are drawn in red (solid and dashed lines, respectively), and a projection of the distribution onto the horizontal axis in blue, resembling the current profile.

periodicity and amplitude δE . This modulation is converted into a current modulation by the longitudinal dispersion R_{56} of the magnetic chicane placed in front of the Athos undulator. We measured the longitudinal phase space (LPS) with the transverse deflector and the dispersive screen in the beam dump. A typical measurement is shown in Fig. 2.

The time resolution of the LPS measurement is better than 1 fs, sufficient to resolve the induced energy modulation in the electron beam with a period of 2.6 fs. With the energy calibration of the dispersion function in the vertical direction ($\eta_y = 0.35$ m), the measured modulation amplitude exceeds 10 MeV—well above the expected value of up to 2.5 MeV from the laser-modulator interaction alone. This increase originates from strong space-charge fields in the undulator and during beam transport to the dump screen.

The tangential modulation observed in the measurements can be reproduced with particle tracking simulations using the code Elegant [34], starting from the laser modulator and continuing through the bunching chicane, the undulator, the transverse deflector, and the dump dipole, up to the screen location in the dispersive region. With space charge enabled, the resulting LPS distribution is shown in the upper plot of Fig. 3. The lower plot shows the calculated spatial particle distribution at the screen location, where we have scaled the spatial coordinates using the calibration of the streaking strength of the deflector (x direction) and the dispersion value (y direction). The intrinsic slice beam size of the streaked beam, which is still present in the lower plot, effectively blurs the image. As a result, the modeled distribution more closely resembles the fine structure of the measured LPS distribution (Fig. 2), but this limits the achievable temporal resolution to about 500 as.

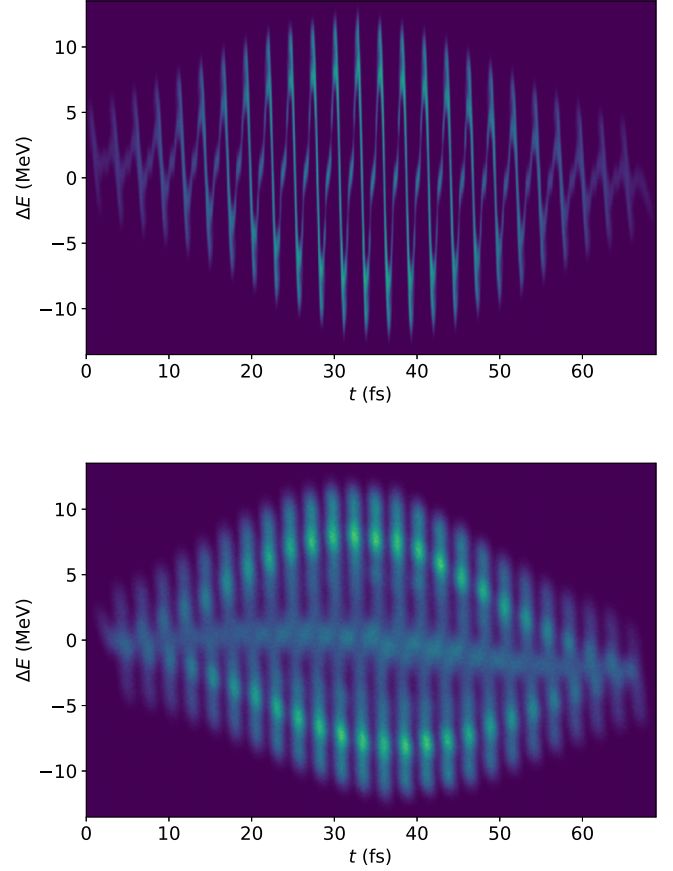


FIG. 3. Elegant simulation of the ESASE configuration, including the modeling of the LPS measurement with a transverse deflector at a dispersive screen. Longitudinal phase-space distribution (top) and the observed image (bottom) used for the LPS reconstruction, using a calibration to convert spatial coordinates into time and energy coordinates.

SwissFEL uses a rectangular magnet as opposed to a sector magnet to bend the beam downward by 8° to the screen and beam dump. Therefore, the beam wanders outside the good-field region of the dipole, in particular with a large energy spread or chirp. These higher terms in the dispersion function reduce the measured energy spread. In addition, very large energy spreads cause a low signal-to-noise ratio in the sliced beam analysis, effectively lowering the observed values by excluding any signal which is below the threshold value of the noise filter.

To analyze the space-charge effect, we apply a Fourier decomposition of the space-charge field around the seed-laser periodicity, following the approach used for microbunching analysis [35]. For a given bunching factor b_h at the h th harmonic, the induced energy modulation is given by

$$\frac{d\Delta\gamma}{dz} = \frac{I}{e\pi^2\sigma^2 I_A h k_L} \left[1 - 2I_1 \left(\frac{h k_L \sigma}{\gamma_z} \right) K_1 \left(\frac{h k_L \sigma}{\gamma_z} \right) \right] b_h, \quad (1)$$

where σ is the rms transverse beam size, I the beam current before the modulator, I_A the Alfvén current, $\gamma_z = \gamma/\sqrt{1 + K^2/2}$ the reduced electron energy, k_L the laser wave number, and I_1 and K_1 are the modified Bessel functions of the first and second kind, respectively. The bunching factor b_h at the exit of the chicane depends on the chicane strength R_{56} and the induced energy modulation δE :

$$b_h = J_h(hAB)e^{-\frac{1}{2}h^2B^2}, \quad (2)$$

with the normalized energy modulation $A = \delta E/\sigma_E$, the intrinsic energy spread σ_E , the normalized chicane strength $B = k_LR_{56}\sigma_E/E$, and the mean energy E .

Keeping the bunching factor harmonics constant during transport from the chicane to the dump screen overestimates the observed energy spread. We therefore build a model to estimate the space-charge effect with varying bunching factors using a particle distribution in which particles are allowed to slip longitudinally, particularly enhanced by the dispersion of the undulator field when compared to a free drift. In this 1D model, where the space-charge field is applied after each undulator module and drift section, the initial energy modulation from the external laser is removed [36] and even inverted [37] within the first three undulator modules, further increasing over the remaining undulator length. We observe that the beam transport elongates the ESASE current spikes, thereby damping the higher-harmonic content and reducing their contribution to the space-charge field further downstream of the undulator.

We measured and simulated the energy spread as a function of the undulator field strength K (Fig. 4). The observed rms energy spread grows for larger values of K . The agreement between model and measurement is good. It also confirms the prediction made in [17] that the space-charge field depends on the undulator field. While the space-charge term in Eq. (1) scales as

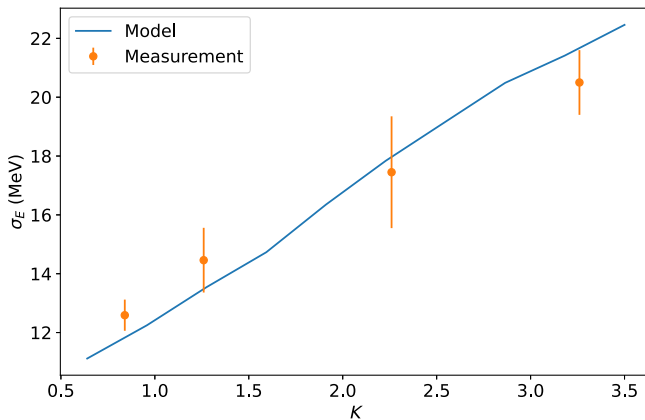


FIG. 4. Induced rms energy spread as a function of undulator field strength K in the Athos undulator.

$\gamma_z^{-2} = (1 + K^2/2)/\gamma^2$, large space-charge fields are dampened by the elongation of the current spike, exhibiting a rather linear dependence on K instead of a quadratic one. In effect, the spike elongation for stronger space-charge fields stabilizes the induced energy chirp gradient. A similar stabilization has been predicted in FEL studies of beams generated in plasma accelerators [38].

To quantify the induced bunching, we scanned the chicane strength for different laser pulse energies. The 1D model has two free parameters: the induced modulation δE , which scales with the square root of laser energy for a given laser geometry and pulse duration, and the intrinsic energy spread σ_E . The chicane strength is known within 1%. Measurements and simulations are compared in Fig. 5.

The locations of maximum space-charge effects for an induced energy modulation and chicane strength agree well between measurement and simulations and can be used to estimate the ratio A between energy modulation and energy spread. If the Landau damping term is negligible in Eq. (2), the condition for the maximum bunching of the h th harmonic scales as [39]:

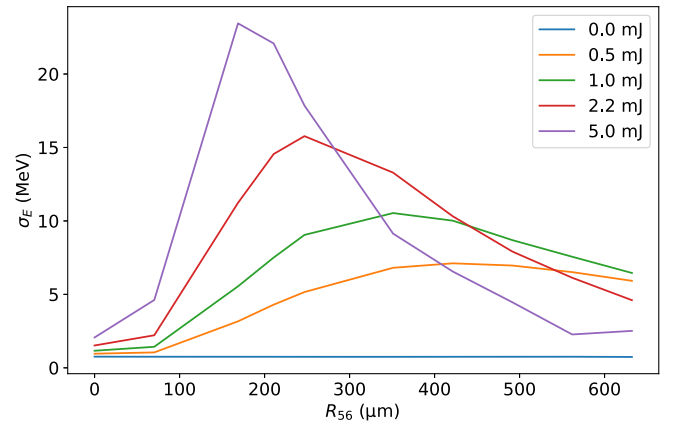
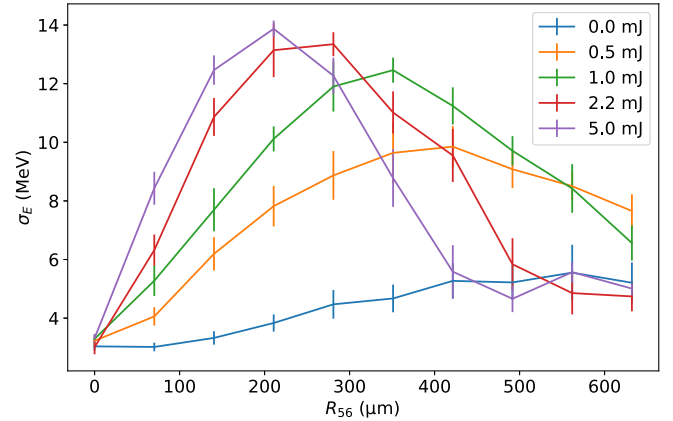


FIG. 5. Measured (top) and modeled (bottom) induced energy spread from space charge for various chicane strengths and laser pulse energies.

$$A \times B \approx 1 + 0.8086 h_m^{-\frac{2}{3}}. \quad (3)$$

With sufficient harmonic content, the dependence on the harmonic number becomes negligible and Eq. (3) can be simplified to $A \times B \approx 1$. For even higher harmonic numbers, the Landau damping term is no longer negligible, with the limit given around $h < 1/B \approx A$. Thus, the value of A itself is a good estimate of the highest harmonic present in the current profile modulation [40].

This condition is best fulfilled for the highest pulse energy of the optical laser, while the case for lowest energy is still affected by the Landau damping term. This places the value A for maximum energy modulation at 5 mJ in the range of 3–5 or roughly $A \times B = k_L R_{56} \delta E / E \approx 1.4$. We obtain an estimate for the laser strength calibration with $\delta E [\text{MeV}] \approx 1.3 \cdot \sqrt{U [\text{mJ}]}$.

To estimate the energy spread, we use the absolute values of the induced energy spread for small seed laser pulse energies, since large values of the energy spread are damped by the measurement with the transverse deflector and the nonlinear terms of the dispersion in the dump region. We found the best agreement for an energy spread of 700 keV (bottom plot in Fig. 5), which is lower than the value of 1 MeV found with other methods [31]. The difference can be attributed to the simplicity of the simulation model used. Better models would require the retardation of the space-charge field calculation, based on Liénard-Wiechert potentials.

When the seed laser was disabled, we still observed additional growth in the energy spread (blue curve in the top panel of Fig. 5). It indicates the presence of energy modulation, caused by the microbunching instability, which generates current ripples in the beam, driving space-charge effects. Its impact can be mitigated by tuning the laser heater for minimum energy spread [41], as shown in Fig. 6. The induced spread reaches a minimum at a laser energy of about 3 μJ of the laser heater and exhibits only a

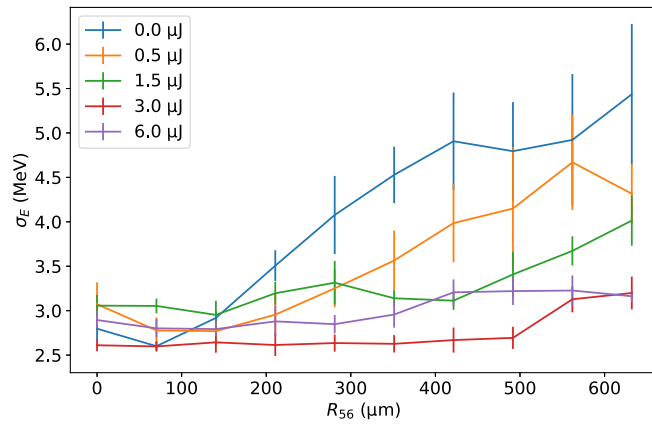


FIG. 6. Induced energy spread as a function of laser heater pulse energy and chicane strength with the external laser turned off.

weak dependence on the chicane strength. Beyond 3 μJ the induced energy spread at the laser heater is larger than necessary to suppress most of the gain of the microbunching instability and heats up the beam unnecessarily. For all ESASE measurements presented here, the laser heater was turned off.

IV. ESASE DEMONSTRATION

In preparation for the ESASE demonstration, we tuned the SASE performance of the soft x-ray beamline Athos to produce a pulse energy of about 900 μJ at a photon energy of 1000 eV, corresponding to an FEL wavelength of 1.24 nm. We optimized the chicane strength to an R_{56} of 190 μm for strongest growth of the energy spread due to space charge, which we assume to generate the shortest current spikes.

When the external laser was enabled, the FEL lasing signal almost vanished, which is expected since the strong chirp over each current spike requires a matching taper of the undulator field to preserve the FEL resonance condition along the undulator. However, a certain distance is required until the space charge has reversed the initial chirp, which is necessary for the ESASE compression of the current spikes. Therefore we detuned the first half of the Athos undulator to prevent any FEL amplification and scanned the undulator taper gradient for the second half, which is applied stepwise to the remaining eight undulator modules. A positive taper improves the FEL performance up to a pulse energy of 170 μJ for an optimum taper of $\Delta K = 0.014$ per module. Beyond a gradient of $\Delta K = 0.027$ per module, no significant FEL signal is observed. The dependence on the taper gradient is shown in Fig. 7. When measuring the ESASE spectra with the optimum positive taper, we observed a shift in the spectra by about 50 eV toward lower photon energies with respect to the SASE signal with no taper and no external laser signal.

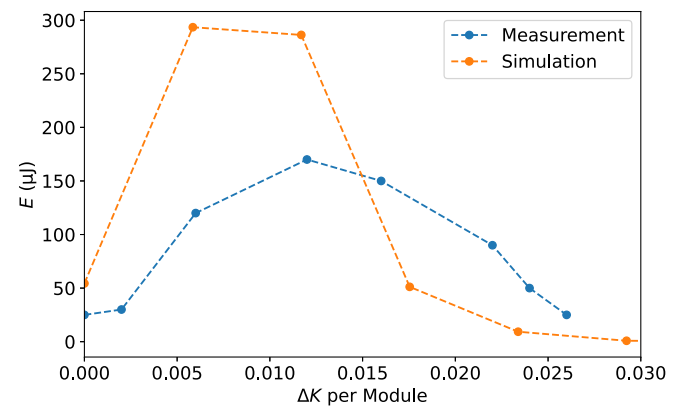


FIG. 7. FEL pulse energy at Athos in ESASE configuration for different undulator-field taper strengths (measurement and simulations, respectively).

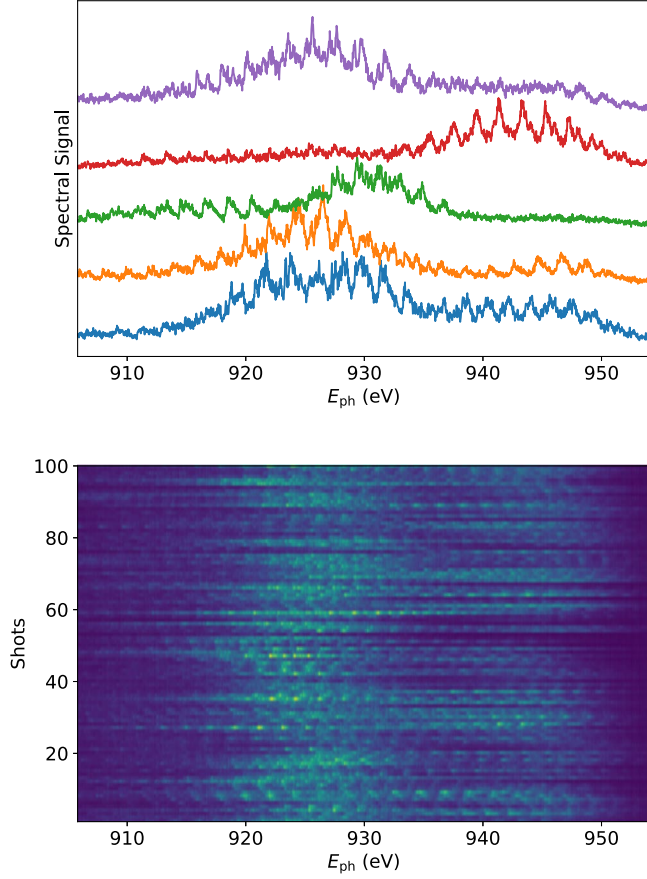


FIG. 8. Top: 5 consecutive single-shot ESASE spectra. Bottom: 100 consecutive measurements (waterfall plot).

In the ESASE configuration, the current spikes fix the location of the radiation spikes but do not control the radiation phase. This distinguishes it from HGHG [12], where the current spikes are shorter than the resonant wavelength and therefore define a well-defined phase in their coherent emission.

In the FEL spectrum, interference between ESASE spikes with random phases and fluctuating pulse energies appears as irregular spectral patterns. Nevertheless, in most shots, a quasiperiodic structure is visible, as shown in Fig. 8, which displays 100 consecutive spectra. While the phases of individual spikes are uncorrelated, there is a finite probability that, in a given shot, a fraction of spikes will share similar phases rather than being uniformly distributed. In the spectrum, these spikes add up coherently; for instance, three spikes with similar phases produce a modal pattern with sidebands and an amplitude equivalent to nine uncorrelated spikes. Consequently, such modal patterns are likely to appear in the measured spectra. Note that the spectra fill the entire range of the spectrometer, which has a smaller gain for signals toward the limits of the spectral range, thereby narrowing the measured spectra.

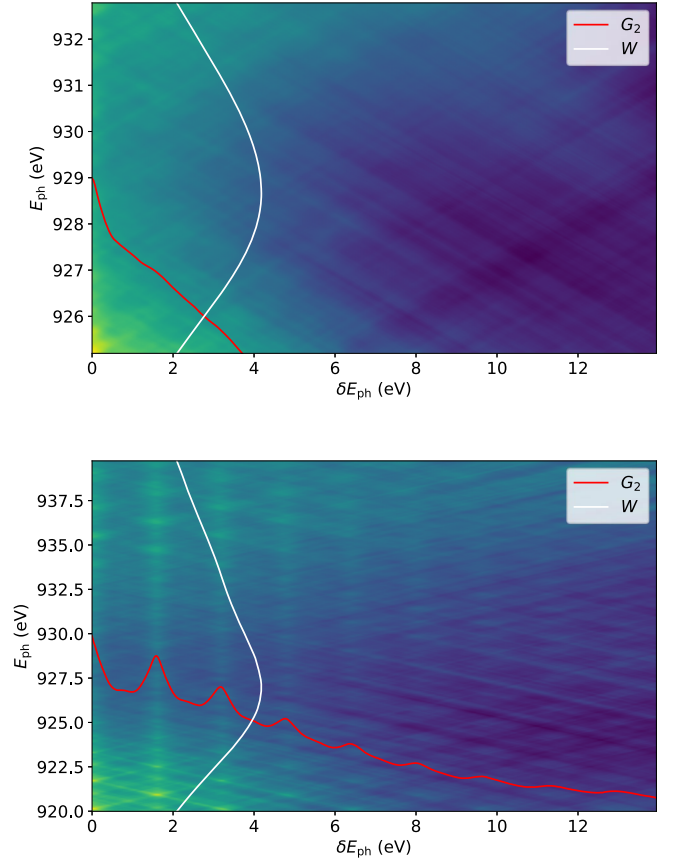


FIG. 9. Second-order spectral autocorrelation function $g_2(E_{ph}, \delta E_{ph})$ for SASE (top) and ESASE (bottom) operation at SwissFEL, displayed as a two-dimensional intensity plot. Also shown (on relative scales of arbitrary units) are the projected autocorrelation function $G_2(\delta E_{ph})$ (red line) and the weighting function $W(E_{ph})$ used in the projection (white line). The projection is applied to spectral components with $W > 0.5$ (which also defines the limits of the plots).

To separate the effect of intrinsic shot-to-shot fluctuations, we evaluate the second-order spectral autocorrelation function:

$$g_2(E_{ph}, \delta E_{ph}) = \frac{\langle I(E_{ph} - \delta E_{ph}) I(E_{ph} + \delta E_{ph}) \rangle}{\langle I(E_{ph} - \delta E_{ph}) \rangle \langle I(E_{ph} + \delta E_{ph}) \rangle}, \quad (4)$$

where $\langle \dots \rangle$ denotes an ensemble average over many measured spectra $I(E_{ph})$. For this analysis, we compared 100 spectra recorded in standard SASE operation (external laser disabled, normal taper restored) with spectra recorded in ESASE mode. The results are shown as two-dimensional intensity plots in Fig. 9.

Since the autocorrelation function g_2 has no visible dependence on the photon energy E_{ph} , we can average over the most prominent components of the average spectrum to obtain a signal less affected by the noise of

the spectrometer. We use the approach of a weighting function W :

$$W(E_{\text{ph}}) = \frac{\int d\tilde{E} \langle I(E_{\text{ph}} - \tilde{E}/2) \rangle \langle I(E_{\text{ph}} + \tilde{E}/2) \rangle}{\int d\tilde{E} dE_{\text{ph}} \langle I(E_{\text{ph}} - \tilde{E}/2) \rangle \langle I(E_{\text{ph}} + \tilde{E}/2) \rangle}, \quad (5)$$

following the method in [42]. Only photon energies where the mean spectral value is at least 50% of the maximum spectral value are included in this averaging process. This corresponds to the condition that $W(E_{\text{ph}})$ needs to be larger than 0.5.

The projected autocorrelation function then reads

$$G_2(\delta E_{\text{ph}}) = \frac{\int_{W>0.5} g_2(E_{\text{ph}}, \delta E_{\text{ph}}) W(E_{\text{ph}}) dE_{\text{ph}}}{\int_{W>0.5} W(E_{\text{ph}}) dE_{\text{ph}}}, \quad (6)$$

and is shown as a red curve in Fig. 9.

In the SASE case, G_2 shows a dominant central peak at $\delta E_{\text{ph}} = 0$ eV, which falls off quickly with some small but distinct changes in the slope around 1.6 and 3.2 eV. In the ESASE case, clear sidebands appear, and their spacing of 1.60 eV is close to the expected value of 1.57 eV, corresponding to a 790 nm periodicity, with the small difference attributed to calibration errors in the energy axis. During the measurement, the spectrometer was not fully optimized for spectral resolution, which had no impact on distinguishing individual spikes in the spectra, but the large pedestal in the point-spread function of the spectrometer reduces the contrast of the autocorrelation signal. Nevertheless, signals from eight sidebands are visible.

Since the SASE process still underlies the ESASE amplification, the spectral correlation function G_2 is linked to the average temporal profile of the radiation pulse [43]. A periodic pattern in the time domain with 790 nm spacing yields sidebands in the spectral correlation function with a separation of 1.57 eV. Since these sidebands are observed, we can conclude that the ESASE process restricts lasing to the locations of the current spikes.

V. ESASE SIMULATIONS

We modeled the ESASE case with the latest release of the time-dependent FEL code Genesis 1.3 [22], which includes space-charge calculations. The model slices the bunch into a series of uniformly charged disks, for which the on-axis field is known analytically [44]. In contrast to the Fourier approach, this method naturally accounts for the finite length of the electron bunch. The resulting space-charge field in the center of the bunch is shown in Fig. 10.

Table I summarizes the beam parameters used in the simulations. To prepare the input signal, we first applied energy modulation and chicane dispersion, which generated a sequence of current peaks with a periodicity

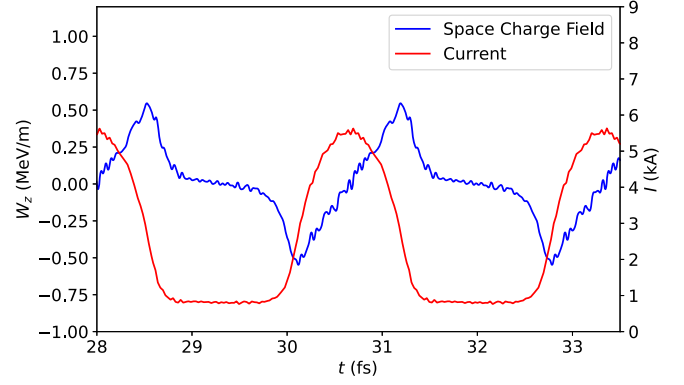


FIG. 10. Current profile and effective space-charge potential for a subsection of the electron bunch.

of 790 nm, and transported them to the beginning of the undulator, taking space-charge forces into account. Subsequently, the longitudinal beam distribution was sliced at the periodicity of the resonant wavelength, with current, mean energy, and energy spread being evaluated per slice. These values were then imported into Genesis 1.3 to initialize the particle distribution.

We simulated the FEL process in the second half of the Athos undulator for various reverse-taper gradients. The taper was applied stepwise with a constant K per undulator module. Figure 7 shows the resulting output pulse energies. A broad maximum appears at a gradient between 0.006 and 0.012 per module, reproducing the experimental observations. However, the curve has a steeper drop for gradients above 0.012 per module in the simulations, since in the experiment, the ESASE current spikes are not uniform for two reasons: First, the current profile is not uniform over the bunch duration before the ESASE energy modulation is applied. The blue curve in Fig. 2 resembles the initial current profile before the manipulation with external laser and dispersive chicane, since the analysis of that figure uses slice widths larger than 800 nm, thus averaging out the effect of the current and space-charge modulation of the ESASE process. Second, the energy modulation is altered by the microbunching instability, which has a periodicity of about 1 μm and is therefore comparable to the optical laser wavelength. The resulting spread in peak current and pulse duration of the ESASE current spikes yields varying energy chirps, not all of which can be compensated by a global taper gradient of the undulator field. Therefore, the dependence of FEL performance on the taper gradient features a sharper peak in our simulations, which do not take these two effects into account.

For the best-performing case of the simulations, the pulse energy approaches 300 μJ close to saturation. Figure 11 shows the current and FEL radiation profile for the central section of the bunch toward the end of the undulator. The evaluation of the central 20 pulses yields a

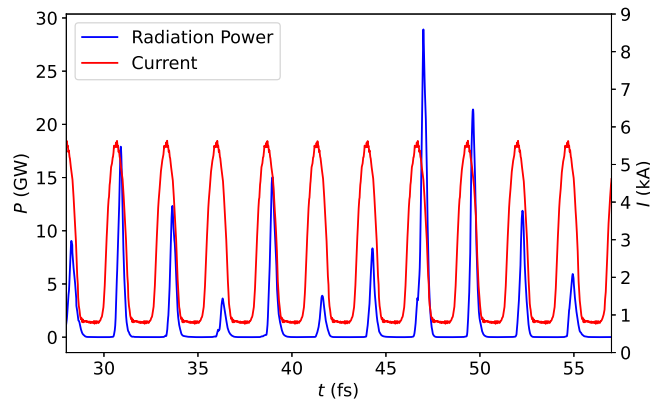


FIG. 11. Simulated FEL power profile for the optimum taper setting.

mean rms duration of 150 ± 24 as for the radiation spikes. The centroid position exhibits an rms jitter of 47 as, while the peak power fluctuates by 52%. Each spike occasionally features smaller subpeaks or shoulders preceding the main maximum, whose relative amplitudes are below 50%, in particular close to the end of the undulator when some spikes have already reached saturation.

The radiation spectrum is broad (top plot of Fig. 12), with an rms width of 7.3 eV. Combined with the pulse duration, the average time-bandwidth product for individual spikes is 1.1×10^{-15} eVs, which is about 1.7 times the Fourier limit. A regular pattern of spectral lines is also visible, separated by 1.55 eV. This corresponds to a temporal spacing of 2.66 fs between pulses. Although the relative alignment of the spikes varies shot-to-shot, the spectral correlation function consistently reveals sidebands, reproducing the experimental findings.

With eight undulator modules, the relative change in K amounts to $\Delta K/K = 7 \times 0.012/1.85 \approx 4.5\%$, corresponding to a shift in resonant wavelength of +5.9%. If the taper were merely compensating the energy chirp across an ESASE current spike, the detuning should match the observed energy variation of the radiation spike slipping along the induced chirp [45]. The initial chirp over each current spike is about 20 MeV/fs at the beginning of the FEL amplification and doubles to 40 MeV/fs at the undulator exit. Assuming that the origin of the radiation spike at minimum energy is at the trailing end of a current spike, this beam segment would have lost about 11 MeV, relative to the mean energy of the electron bunch, over the distance between the generation of the ESASE current spikes and the start of the second half of the undulator. In the second half, the chirp would double, and the endpoint of the slippage before the current spike would be at an energy of +22 MeV. Thus, the effective change in the electron energy would be 33 MeV or about 1%, and a change in K value of 1.02% would be needed to preserve the resonance condition. However, the optimum taper is about 6 times larger, both in measurement and simulation.

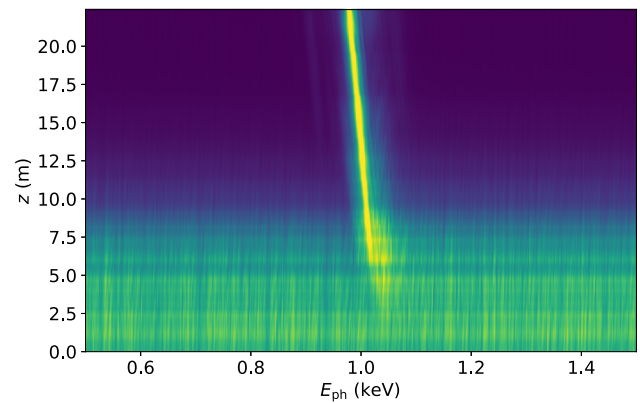
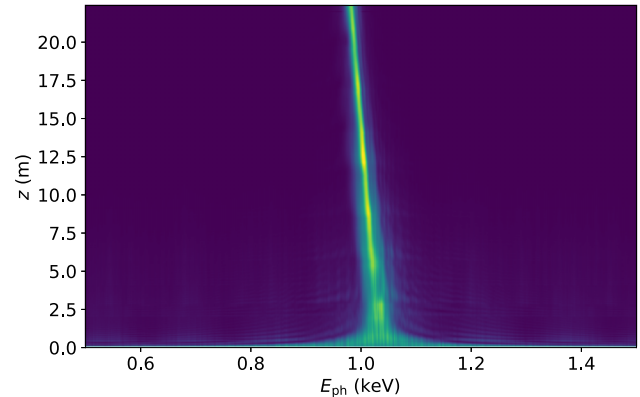
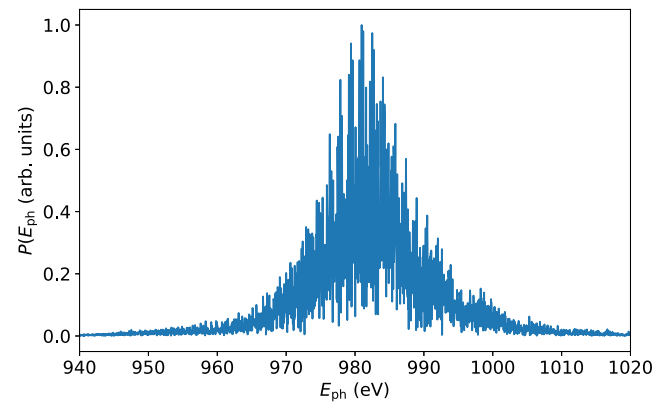


FIG. 12. FEL spectrum at undulator exit (top), evolution of the FEL spectrum (middle), and microbunching spectrum (bottom) along the undulator. The radiation spectrum has been normalized by its mean value at each step for clarity.

Here we assume a group velocity of one resonant wavelength per three undulator periods—the most optimistic case in 1D FEL theory [46], but it matches the slippage over the entire linear part of the energy chirp. Any higher group velocity would push the radiation out of the current spike in a region with low beam current and a reverse shift in resonance condition.

Figure 12 shows the spectral evolution of the radiation and microbunching. Both shift along the undulator to

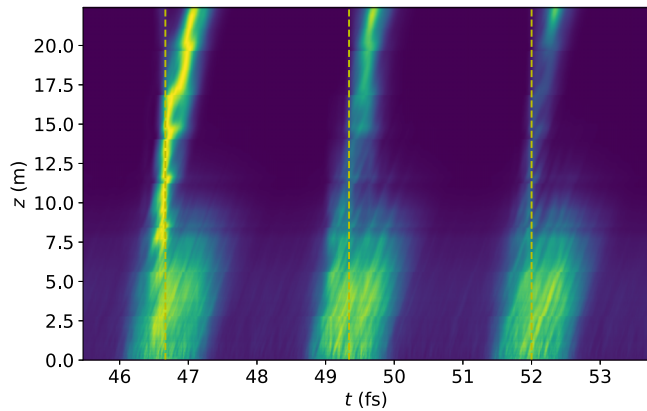


FIG. 13. Temporal evolution of the FEL radiation field along the undulator for a segment of the bunch. The field is normalized to its respective maximum at each step. Yellow dashed lines mark the ESASE current spikes.

lower photon energies, with the redshift of the bunching occurring slightly earlier. This contradicts the simple picture in which radiation is generated at the beginning of the undulator and remains in resonance while slipping along the chirped electron beam. Figure 13 illustrates the temporal radiation evolution for a segment of the bunch that covers three ESASE spikes. Initially, the radiation field is centered on the spikes, but in the later undulator sections, radiation appears predominantly in front of the spikes. Only a small fraction slips forward between modules. This results from the reduced coupling in the break sections.

We interpret these observations as follows: the microbunching is detuned by the strong energy chirp, causing the current spikes to stretch, similar to a compressed spring expanding. As a result, the bunching is stretched with the elongation of the ESASE current spikes and the frequency shifts downward. Radiation is emitted coherently at the redshifted frequency, and to maintain the resonance condition, the undulator taper must follow. The resulting strong optimum taper corresponds to a redshift of about 6%–7%, consistent with experimental and simulation results.

The stretching of the bunching also explains why radiation spikes appear mostly in the center or at the front of the current spikes. Before the current spikes, the microbunches experience a slight forward shift due to the elongation of the current spike and are pushed more toward the emission phase of the interaction with the radiation field. In contrast, the microbunches behind the current spike fall backward and tend to absorb the field more strongly. At the center of the spike, the bunching phase remains unchanged. This asymmetry favors the region in front of the current spike for the fastest FEL growth [47], in agreement with the simulations (Fig. 13).

The dynamics thus correspond more closely to *weak* superradiance [48], where the bunching drives the

radiation, rather than *strong* superradiance [49], where the radiation dominates the bunching dynamics.

VI. CONCLUSION

We have studied the performance of enhanced SASE (ESASE) at the soft x-ray beamline Athos of SwissFEL, using an external laser with a wavelength of 790 nm to drive lasing at a photon energy of 1 keV. The experiments and simulations confirm that the ESASE process is strongly influenced by space-charge forces, which introduce an energy chirp across each current spike during FEL amplification. This effect is amplified by the reduced longitudinal Lorentz factor γ_z within the undulator field.

Optimal FEL performance requires the application of a positive undulator taper to preserve resonance throughout the amplification process. The dominant mechanism is the elongation of the current spikes under their own space-charge field, which increases the separation of the microbunches and induces a spectral redshift. A secondary requirement for a positive taper—the compensation for radiation slippage across the chirped beam—was found to play only a minor role in the present case.

Despite a higher peak current, ESASE resulted in a radiated power comparable to SASE. This lack of enhancement is attributed to three effects: (1) the enhanced current also yields a higher energy spread, which degrades the performance given the already high initial energy spread; (2) the radiation slippage and elongation of the current spikes within each undulator module are not fully compensated by the stepwise positive taper of the undulator beamline; and (3) the chirp over the standard SASE cooperation length is larger than the FEL bandwidth, resulting in a shortening of the radiation spikes, as indicated by the broader overall spectrum during ESASE operation. The first point in particular has an impact on hard x-ray FEL facilities that have been designed to minimize the operating electron beam energy, such as SwissFEL. Facilities with significantly higher beam energies (e.g., European XFEL) are less sensitive to the energy spread and could allow for local enhancement of the beam current by applying the ESASE scheme. In addition, they are less affected by the space-charge fields of the ESASE current spikes.

More advanced schemes (e.g., [19,50]) can be developed based on the ESASE principle, yet they remain strongly affected by space-charge forces. In contrast, alternative approaches that rely solely on stronger energy modulation to generate a stable pulse train can mitigate this limitation and are therefore better suited for operation in the soft x-ray regime and at longer wavelengths.

ACKNOWLEDGMENTS

This work was funded by the European Research Council under the European Union’s Horizon 2020

research and innovation program, within Grant Agreement No. 810451 (HERO). We would like to thank all technical groups that supported us during the measurements and Thomas Schietinger for proofreading the manuscript.

DATA AVAILABILITY

The data that support the findings of this article are available upon request.

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