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SINGLE LONGITUDINAL MODE GENERATION IN SLIPPAGE-DOMINATED TAPERED UNDULATOR SASE SOFT X-RAY FEL

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Abstract

We study a short-pulsed SASE method called Slippage-dominated Tapered Undulator (STU) SASE to produce single longitudinal mode in each soft X-ray SASE pulse driven by an electron bunch with 10 fs bunch length and 16 pC bunch charge. STU-SASE uses both normal and inverse tapered undulators to select a single spike and increase its coherence length. Numerical simulations showing single-mode generation and narrow-lined spectra in a soft X-ray SASE FEL without seeding are presented.

SOFT X-RAY (BEUV) LITHOGRAPHY

A paradigm shift in light source utilization is required for the continuation of Moore's law scaling, the prediction that the number of transistors in an integrated circuit doubles every two years. To obtain smaller feature sizes, BEUV (beyond EUV) lithography at 6.x nm has been proposed [1]. SASE FELs can generate high-power soft X-rays, but they must produce spectrally narrow output to work with the narrow reflectivity curve of molybdenum-boron (MoB) multilayer mirrors [2]. While many ideas have been proposed to achieve fully coherent and narrow-band X-ray FELs [3, 4], only harmonic seeding [5] and self-seeding [6] have been experimentally demonstrated to narrow the output spectra of soft X-ray FELs. In this paper, we study a linac-based SASE FEL designed to produce substantial soft X-ray pulse energies and sufficiently narrow spectra to meet the need of BEUV lithography.

SINGLE-SPIKE SASE FEL

Slippage-dominated, Tapered Undulator SASE

It is well known that the coherence length in a SASE FEL is the slippage length over one gain length in the exponential regime. At saturation, the slippage length increases but the coherence length remains the same. In the tapered undulator where the FEL power continues to grow, the coherence length becomes longer by slippage in the tapered undulator length. Previous simulations using pC electron bunches with sub-fs electron bunch length have shown the possibility of generating a single spike (longitudinal mode) in each SASE pulse [7]. A more recent study suggests using an inverse taper to produce sub-fs X-ray pulses [8]. For many FELs, the electron bunch charge needs to be greater than a few pC and the FEL pulse energy at least 10 μJ. In this paper, we study a new method to generate single-spike SASE X-ray pulses based on slippage-induced lengthening of the coherence length, and single-mode selection via amplification and absorption in the tapered undulators of a SASE FEL without seeding.

The single mode selection is illustrated in the 2D plot of a single SASE spike in log-scale color codes (see Fig. 1). Slippage, as measured by the tilt of the radiation spike, is $\lambda/3\lambda_u$ before the taper start and increases to the full value of λ/λ_u in the taper. A second spike appears right before the taper start but is not amplified in the tapered sections.

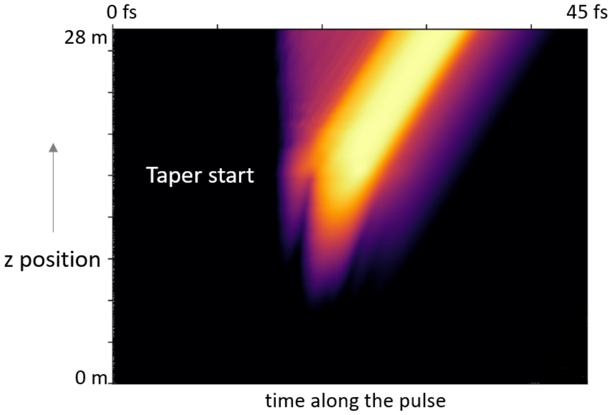

Figure 1: Evolution of a single spike along z and time.

We use the FEL code Genesis 1.3 version 4 [9] to model the STU-SASE FEL process. The electron beam, undulator and FEL parameters are listed in Table 1 below.

Table 1: STU-SASE FEL Parameters

Parameter	Value
Beam energy	1.333 GeV
Peak current	1.5 kA
Gaussian bunch FWHM	10 fs
Bunch charge	16 pC
Norm. emittance in x and y	1 μm, 0.5 μm
Undulator period	2.6 cm
Untapered undulator length	17 m
Untapered undulator K_0	2.22
Tapered undulator length	13 m
ΔK per taper section	0.02
Photon energy	186 eV
FEL ρ parameter	0.002
Average FEL pulse energy	40 μJ

Single-mode Generation in STU-SASE

Both normal and inverse tapered undulator are used in the single longitudinal mode generation. Figure 2 shows the energy phase space at the exit of the untapered undulators and the resonant energies of the untapered (black) and tapered (green=normal; red=inverse) undulator sections.

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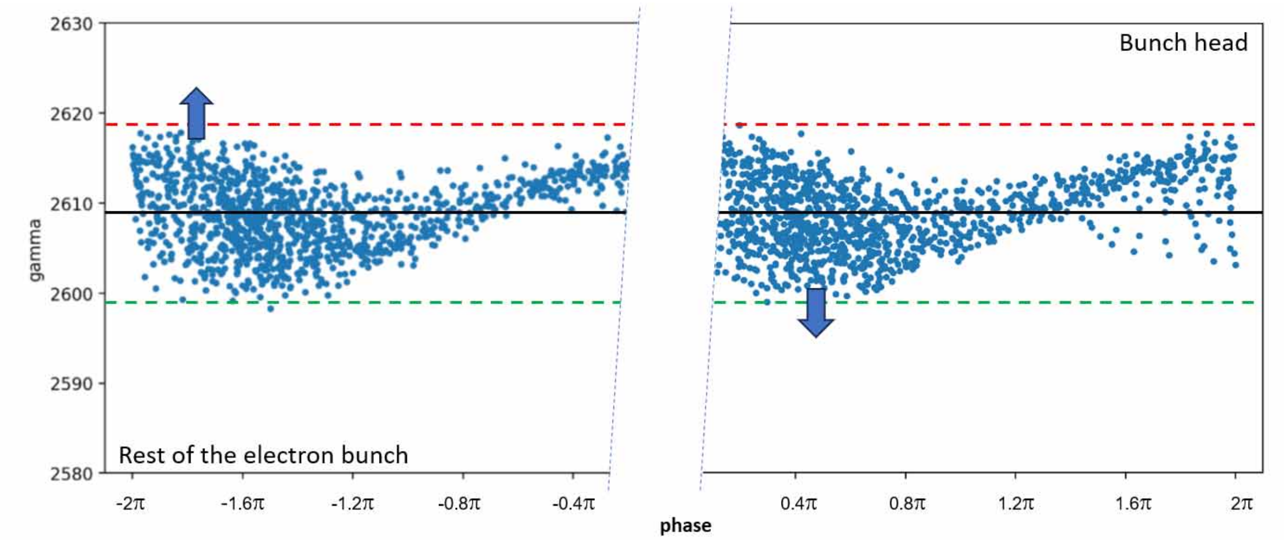

Figure 2: Energy-phase space of electrons exiting the untapered undulators. The normal taper (green) amplifies the first spike at the bunch head (right) and the inverse taper (red) attenuates the subsequent spikes in the rest of the bunch (left).

For $\Delta K \ll K_0$, the resonant energies (in gamma) of the tapered undulator sections are approximately given by

$$\gamma_{taper} \cong \sqrt{\frac{\lambda_u}{2\lambda}\left(1+\frac{K_0^2}{2} \mp K_0 \Delta K\right)} \qquad (1)$$

where λ_u is the undulator period, λ the FEL wavelength, K_0 the untapered undulator dimensionless parameter, and the sign is – for normal or + for inverse taper. Figure 3 shows the plot of FEL pulse energy, beam radii in x and y, and the layout of the normal and inverse taper sections.

The single-mode generation occurs as the back of the first spike is amplified in the normal taper sections while the front slips ahead of the electron bunch. The spike coherence length is equal to the slippage length in the SASE exponential gain length and the taper sections, as given by

$$l_c = \frac{\lambda}{2\sqrt{3}\rho} + N_{taper}\lambda \qquad (2)$$

The inverse taper absorbs FEL power and suppresses the growth of subsequent SASE spikes in the rest of the bunch.

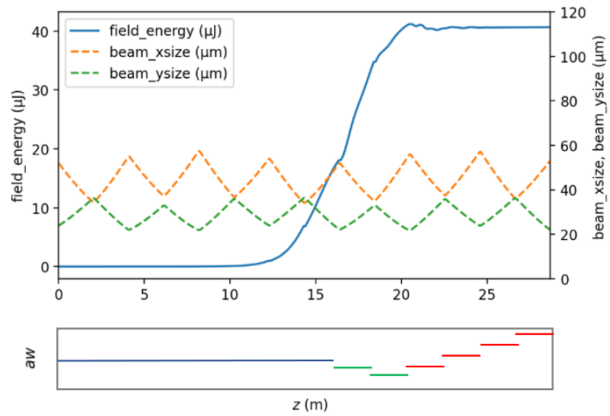

Figure 3: (top) Plots of radiation pulse energy (blue), and electron beam radii in x (orange) and y (green) along z; (bottom) a plot of the undulator K parameter along z.

Simulation results for SASE with untapered undulators are shown in Fig. 4a (top) and simulations results for STU-SASE with untapered undulators followed by normal and inverse taper sections are shown in Fig. 4b (bottom). The single spike in STU-SASE (Fig. 4b) exhibits longer coherence length than any of the six SASE spikes in Fig. 4a.

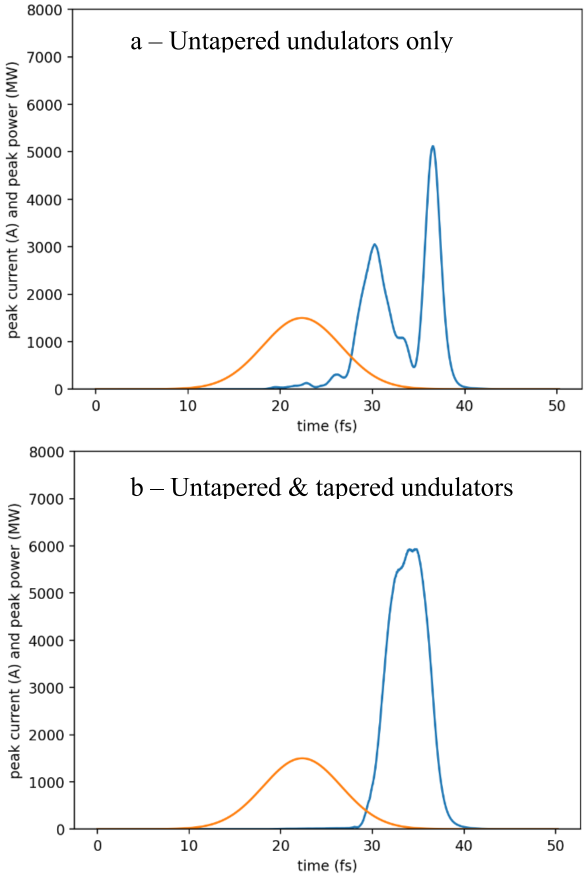

Figure 4: Plots of peak current (orange) and FEL power in MW (blue) vs. time at z = 28 m; (4a) 14 untapered sections, (4b) 8 untapered plus 2 normal and 4 inverse tapers.

Pulse-to-pulse Amplitude Fluctuations

The single-longitudinal-mode SASE is evident by the increase in amplitude fluctuations of STU-SASE pulses in the exponential region. Figure 5 plots the pulse energy as a function of z for 50 simulation runs with the same parameters but different start-up seeds. At z = 10 m, the average of pulse energy is 33 nJ with a standard deviation of 20 nJ.

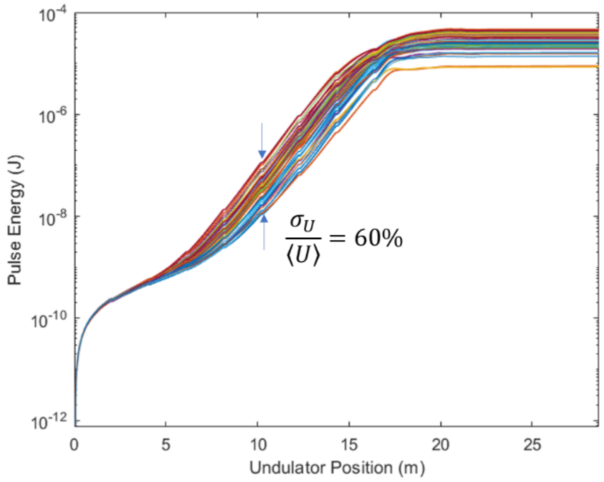

Figure 5: Semi-log plots of pulse energy of 50 simulation runs with different start-up seeds versus z position.

We analysed the amplitude of 50 simulation runs in the exponential regime and plotted the histogram of the pulse energy, superimposed with the plot of probability of these events based on Poisson statistics (Fig. 6) in the exponential regime. The plot with the best fit to the histogram is for M = 1.5, consistent with the observation of one or at most two longitudinal modes in each SASE pulse.

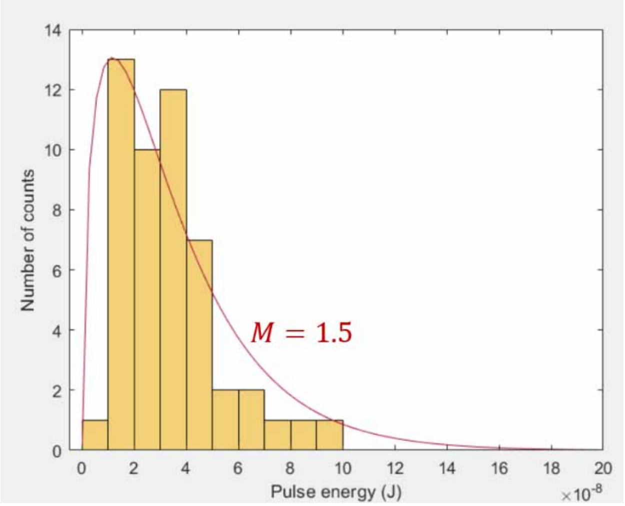

Figure 6: Histogram of pulse energy in the exponential regime at z = 10 m, superimposed with the calculated probability based on Poisson statistics with M = 1.5.

Output Spectral Linewidth

The improved temporal coherence and amplitude fluctuations between one and two longitudinal modes are also visible in the spectra of individual STU-SASE pulses. Figure 7 shows the individual spectrum and the average of thirty STU-SASE spectra. In Fig. 8, the normalized spectra of 50 runs are plotted against the reflectivity curve of MoB (black). Most of the STU-SASE power is inside the narrow reflectivity curve of MoB multilayer mirrors.

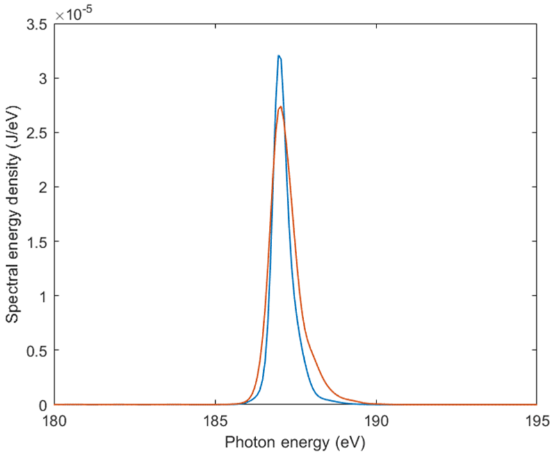

Figure 7: Output spectra from a single STU-SASE pulse (blue) and average of thirty pulses (orange).

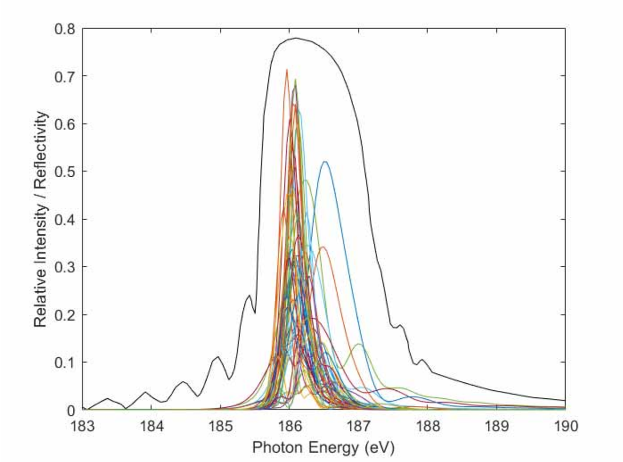

Figure 8: Normalized spectra from 50 simulation runs and a plot of MoB reflectivity vs. photon energy (black).

CONCLUSION

In conclusion, we show with Genesis simulations that the STU-SASE concept can produce a single longitudinal mode and deliver narrow spectra from a SASE FEL without seeding. Using both normal and inverse tapered undulators, the STU-SASE process can select a single longitudinal mode by amplifying the first longitudinal mode in the normal taper sections as it slips ahead of the electron bunch and suppressing the subsequent modes in the inverse tapered sections. The single longitudinal mode exhibits longer coherence length by virtue of the additional slippage length in the normal taper sections. The longer coherence length results in output spectra with spectral linewidth narrower than the SASE gain bandwidth. We show the STU-SASE spectra will fit within the reflectivity curve of the MoB multilayer mirrors.

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