Single Longitudinal Mode Generation in Slippage-dominated Tapered Undulator SASE Soft X-ray FEL

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A paradigm shift in light source utilization is required for the continuation of Moore's law scaling: the foundation of our modern society

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Outline

- Soft X-ray (BEUV) Lithography
- Slippage in Short-pulsed SASE FEL
- Slippage + Tapered Undulators + SASE = STU-SASE
- STU-SASE Amplitude Fluctuations
- STU-SASE Spectral Linewidth
- Summary

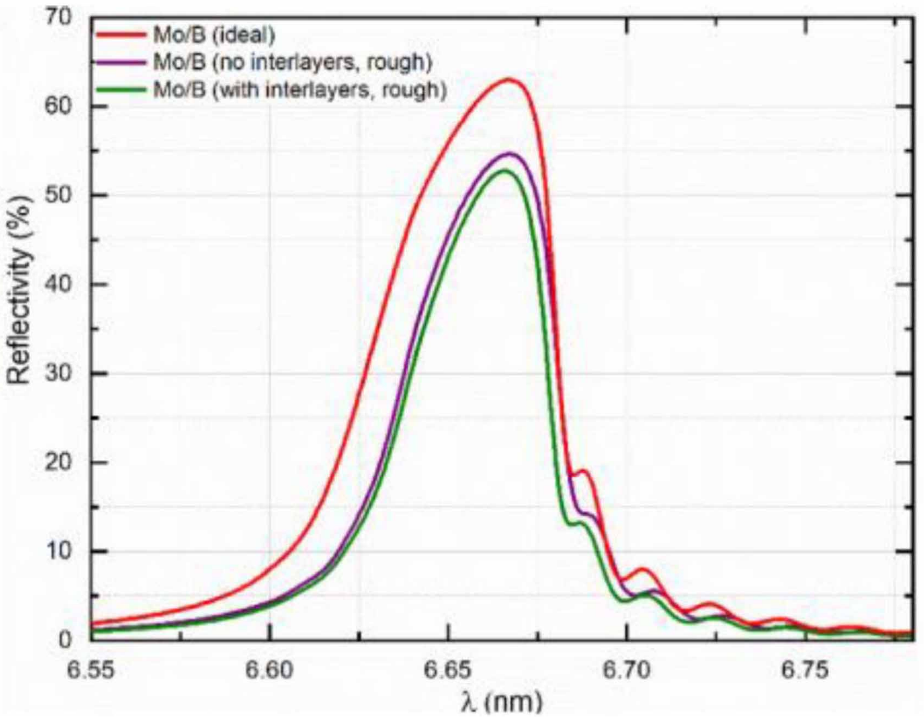
Soft X-ray (BEUV) Lithography

Goal: Study the properties of a SASE FEL at 6.7 nm as the light source for BEUV lithography.

Challenge: Mo/B coatings have narrow reflectivity curves.

Current Methods: SASE self-seeding [1] and harmonic seeding [2] can deliver coherent, narrow-linewidth pulses.

Question: Can a SASE FEL without seeding produce >10 μJ output pulse energy and narrow-lined spectra at 6.7 nm?



Source: P.C. Uzoma et al. “Multilayer reflective coatings for BEUV lithography: a review” Nanomaterials (2021) 11, 2782

[1] D. Ratner et al., Phys. Rev. Lett., 114 (2015) 050801
[2] E. Alaria et al., Nat Photon 7 (2013) 913-918

STU-SASE Simulations with Genesis v4*

Beam Parameter	Value
Beam energy	1.333 GeV
Peak current	1.5 kA
Bunch shape	Gaussian
Bunch length FWHM	10 fs
Bunch charge	16 pC
Norm. emittance x	1 μm
Norm. emittance y	0.5 μm
Initial rms $\Delta\gamma/\gamma$	0.08%

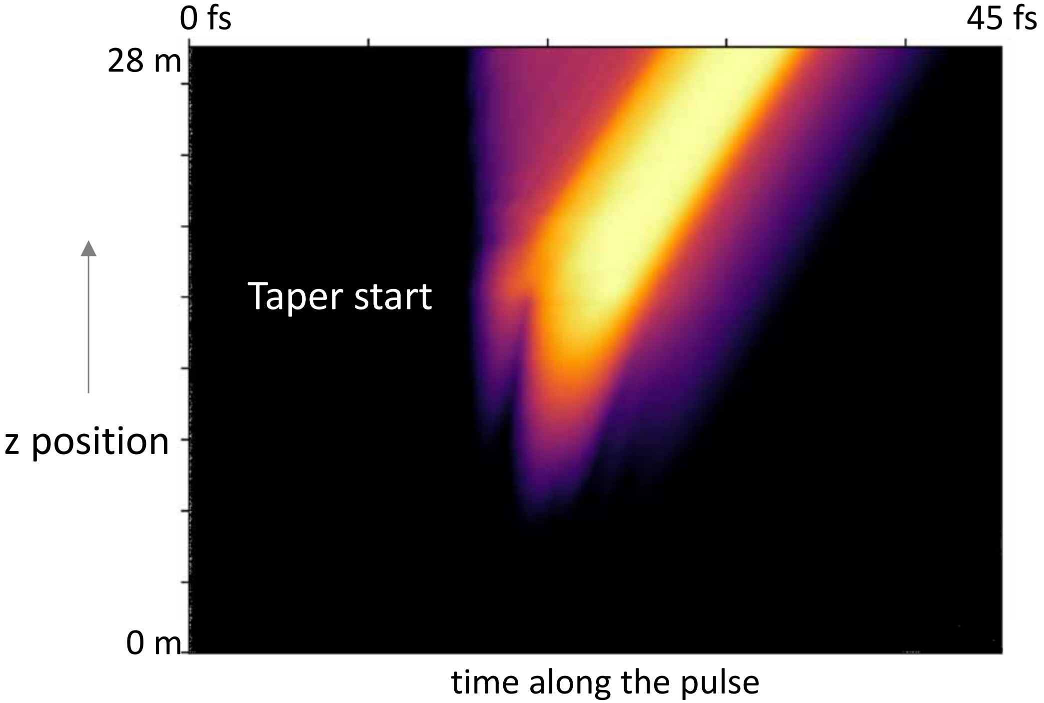
Undulator Parameter	Value
Undulator period	2.6 cm
Untapered length	16 m
Tapered length	12 m

* https://github.com/svenreiche/Genesis-1.3-Version4

SASE gain bandwidth

$$\frac{\sigma_\omega}{\omega} \cong 1.5\rho$$

FEL Parameter	Value
Photon energy	186 eV
FEL rho	0.002
SASE gain bandwidth	0.6 eV



Slippage in Short-pulsed SASE & STU-SASE FEL

Number of longitudinal modes (coherence lengths) in a SASE pulse.

$$N_m \approx \frac{l_b}{l_c}$$ ← Electron bunch length

Coherence length in SASE

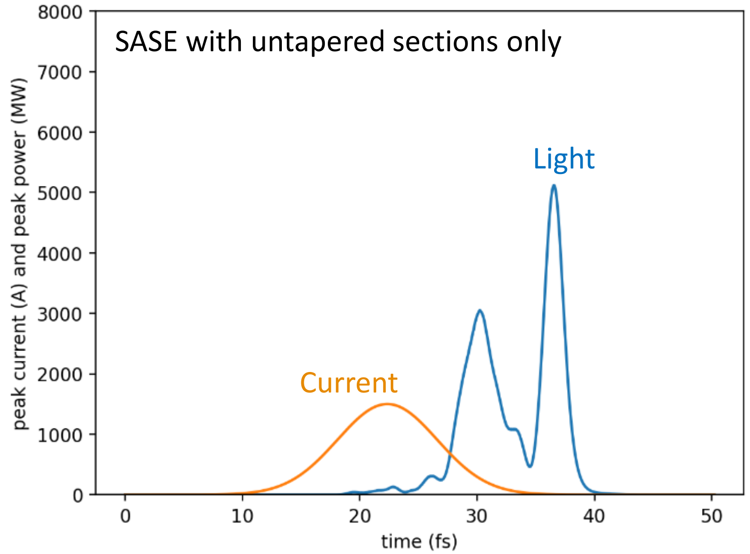
$$l_c = N_{gl}\lambda = \frac{\lambda}{2\sqrt{3}\rho}$$

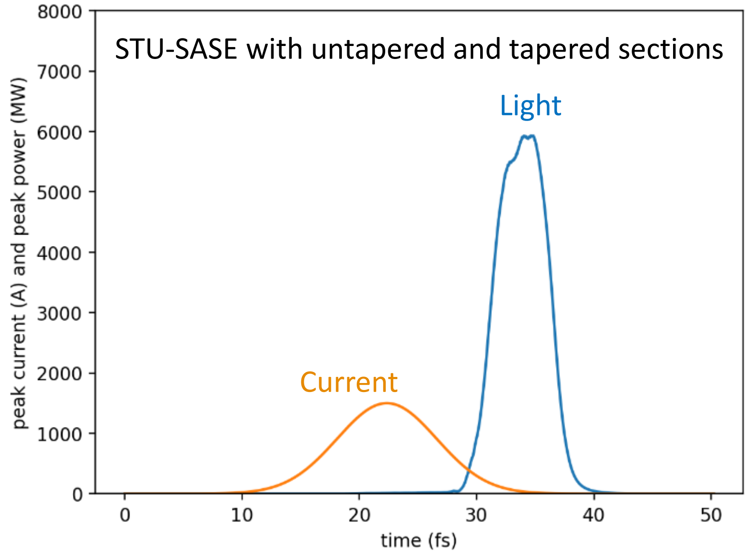
Coherence length in STU-SASE

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

The first spike microbunches the electron beams at the bunch head. The first spike's trailing edge is amplified in the normal taper sections as the spike slips ahead of the bunch, increasing the coherence length.

We show (A) single spikes can be generated with 10-fs, 16-pC electron bunches in SASE without seeding; and (B) the output spectra exhibit narrow lines due to a longer coherence length.





Step Taper to Select a Single Longitudinal Mode

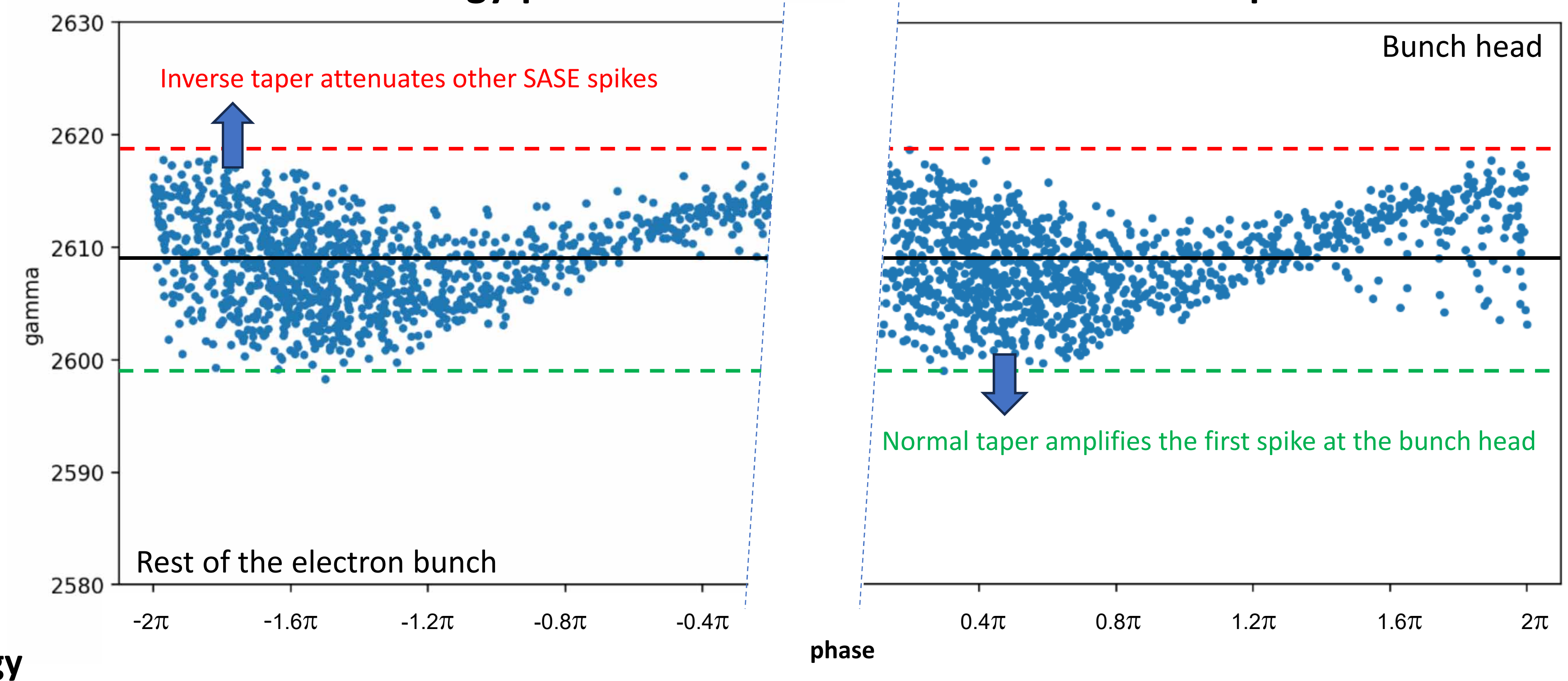
Initial Resonance Energy

$$\gamma_0 = \sqrt{\frac{\lambda_u}{2\lambda}\left(1 + \frac{K_0^2}{2}\right)}$$

Step Taper Resonance Energy

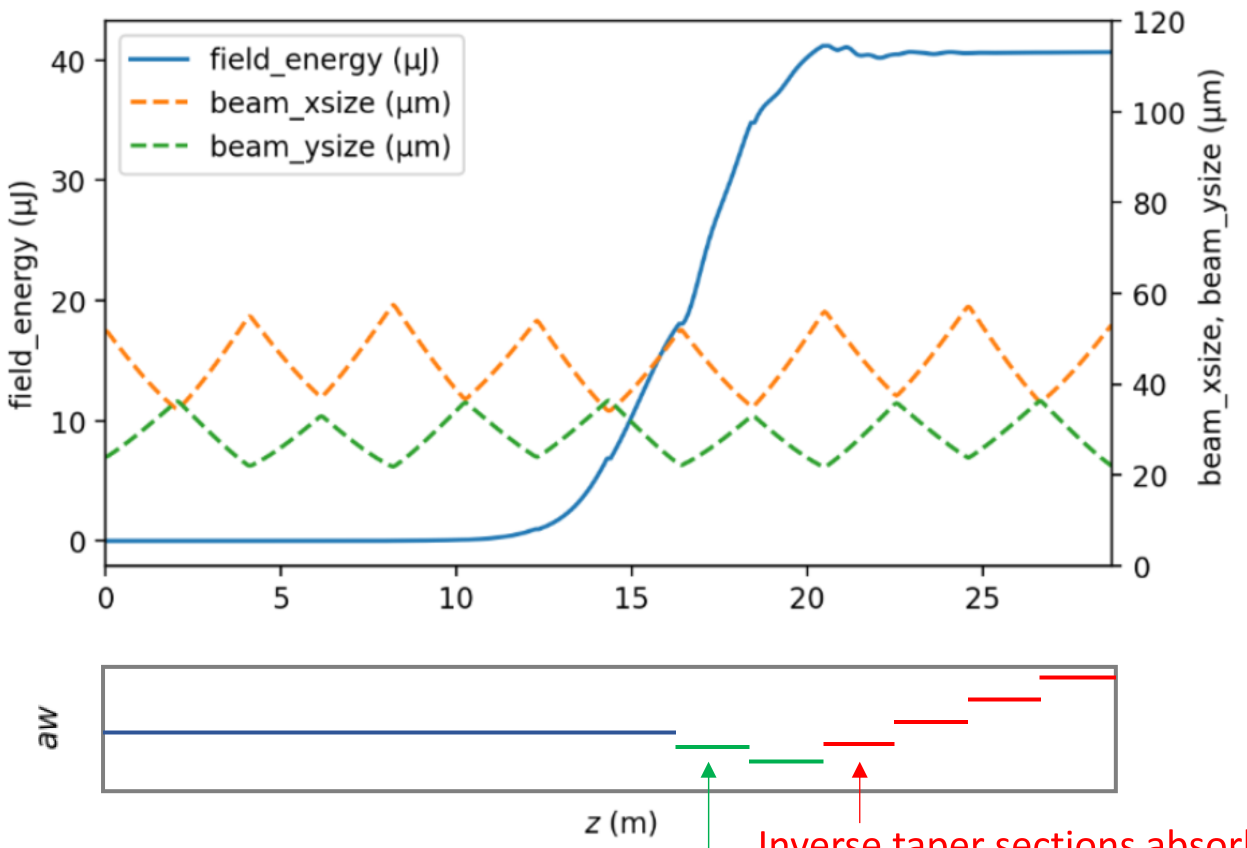
$$\gamma_{taper} \cong \sqrt{\frac{\lambda_u}{2\lambda}\left(1 + \frac{K_0^2}{2} \mp K_0\, \Delta K\right)}$$

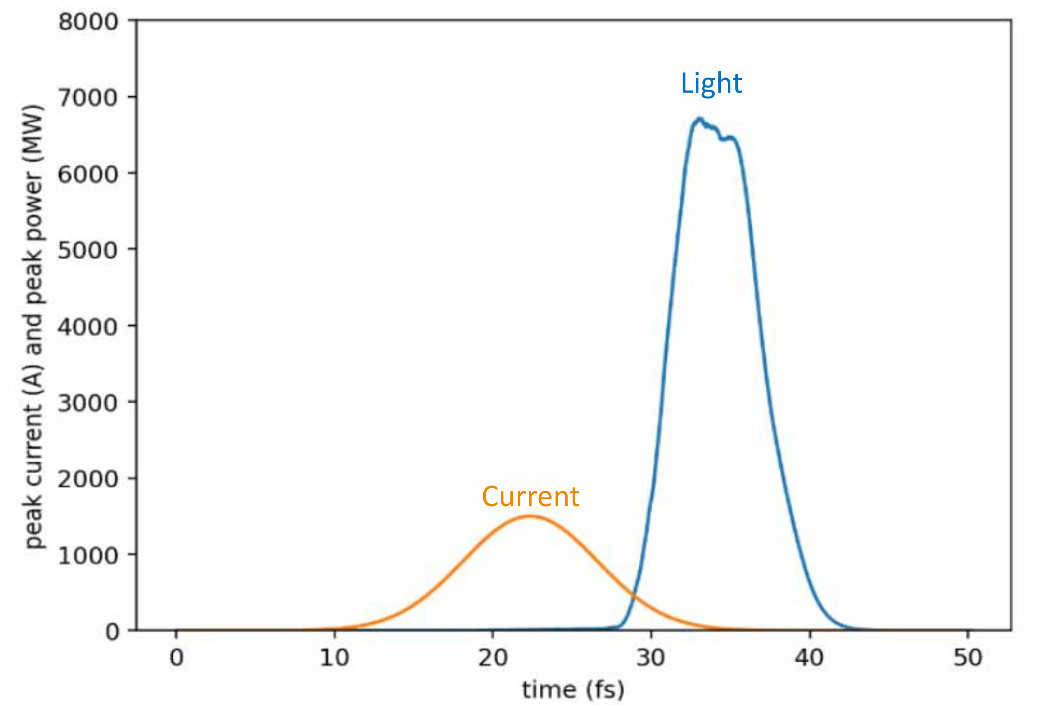
Electron beam energy-phase distribution at the end of the untapered undulators



The normal taper sections amplify the first spike and the inverse taper sections attenuate subsequent spikes from growing in the rest of the electron bunch, resulting in a single longitudinal mode in each pulse.

Single Mode SASE FEL with Step Tapers



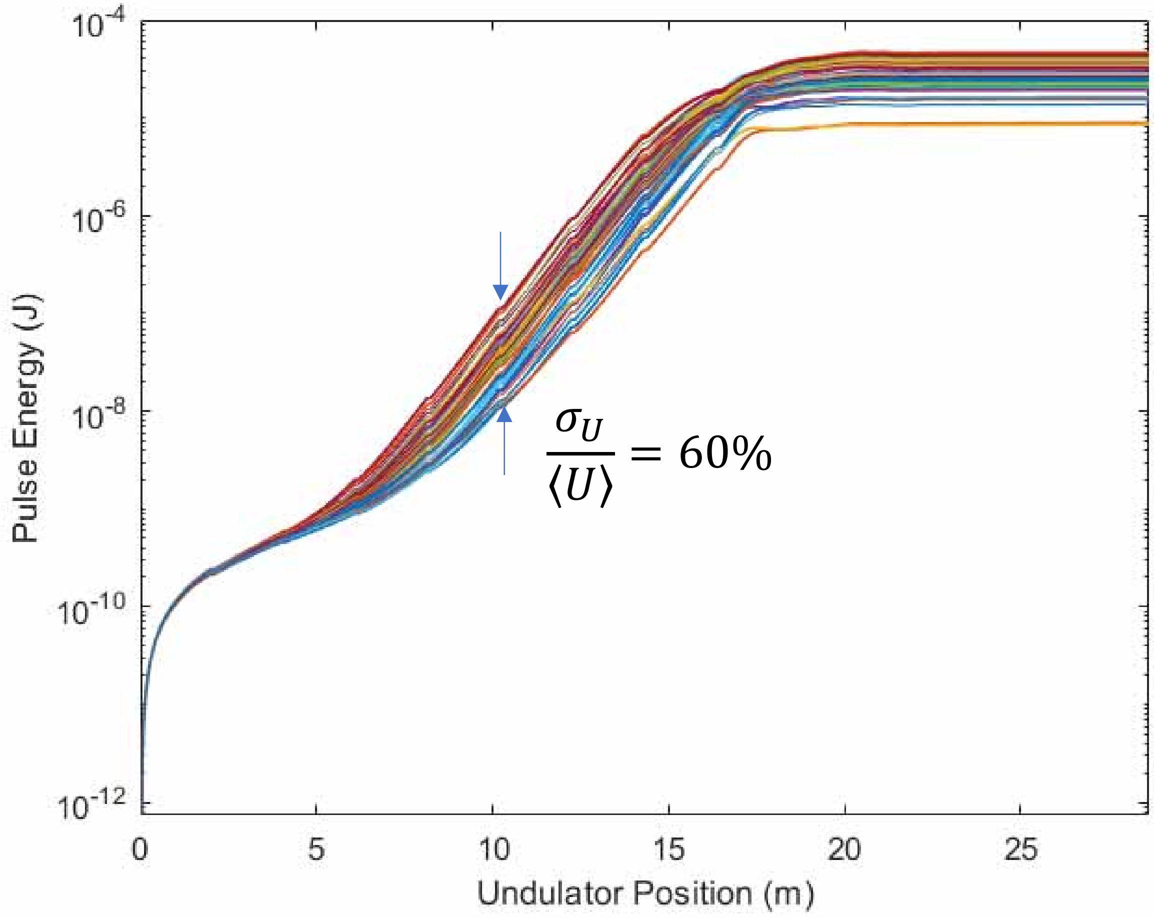


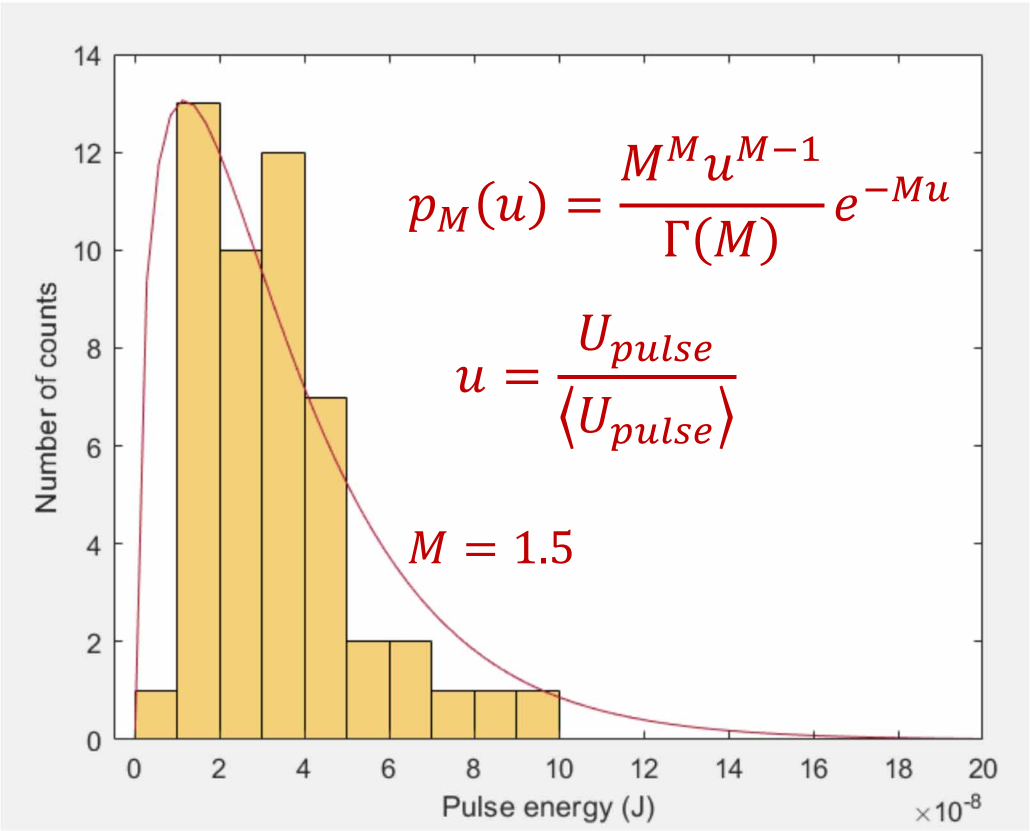
Inverse taper sections absorb subsequent spikes

Normal taper amplifies the first spike as it slips ahead of the bunch

A single spike with long coherence length

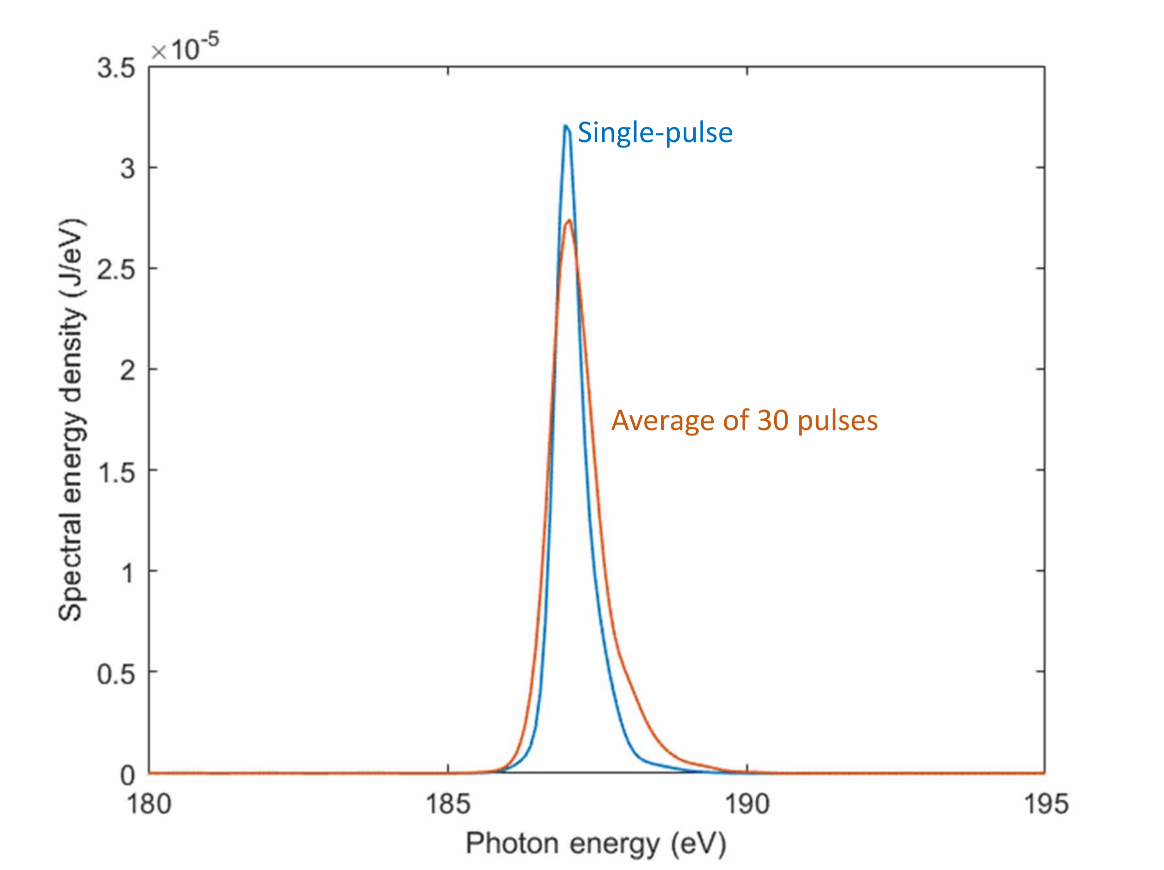
STU-SASE Pulse Energy Fluctuations



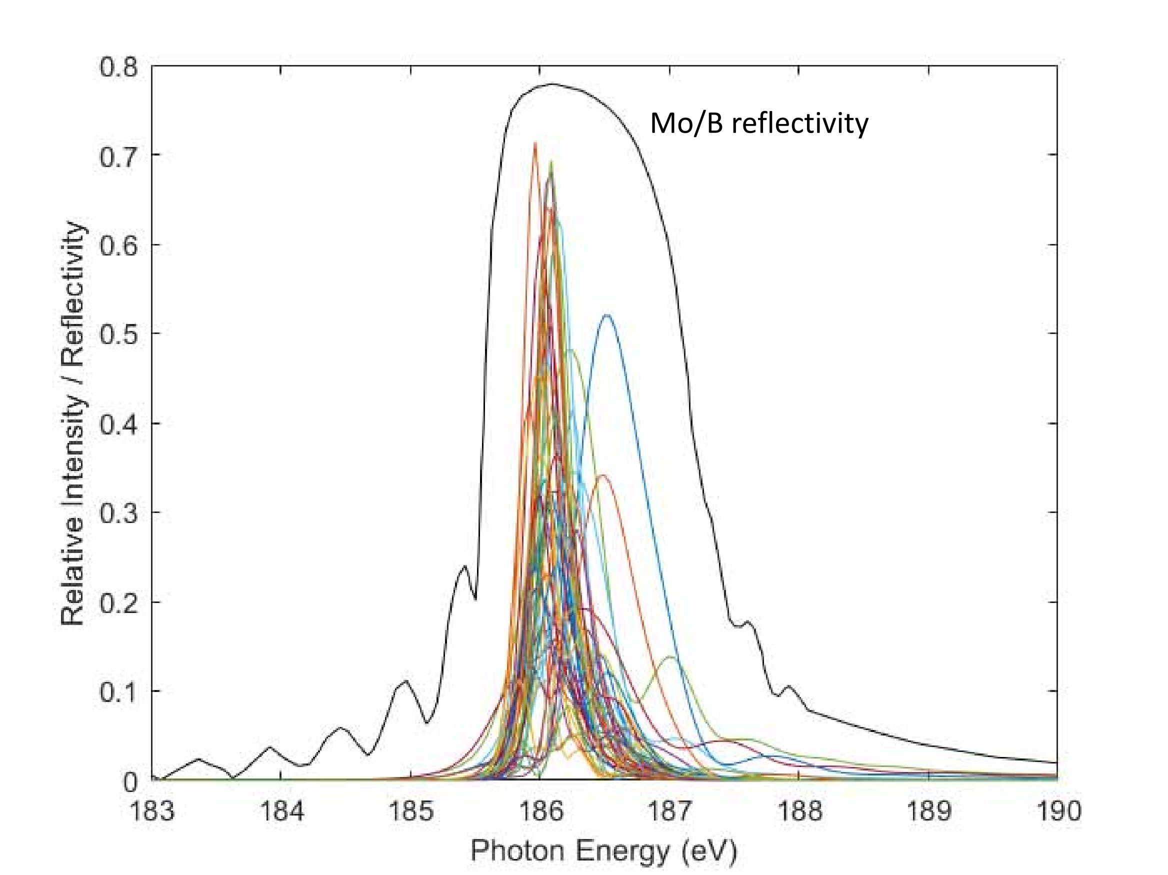


Amplitude fluctuations in the exponential regime are consistent with M = 1.5 longitudinal modes in each pulse.

STU-SASE Spectra & MoB Reflectivity Curve



STU-SASE spectra from a single pulse (blue) and multiple pulses (orange) exhibit narrow linewidths (0.25 eV) compared to SASE bandwidth (0.6 eV).



Normalized STU-SASE spectra from 50 different simulation runs (colors) inside the reflectivity curve of Mo/B multilayer mirrors (black).

Summary

- We show that a new SASE technique called slippage-dominated tapered undulators (STU-SASE) can generate coherent, single-spike soft X-ray pulses without seeding.

- The pulse-to-pulse amplitude fluctuations in the exponential regime are consistent with Poisson statistics of 1 to 2 longitudinal modes per pulse.

- STU-SASE exhibits narrow-lined spectra that fall within the reflectivity curves of multilayer Mo/B coatings to be used in BEUV lithography.