MICROBUNCHING-INSTABILITY-INDUCED SIDEBANDS IN A SEEDED FREE-ELECTRON LASER*

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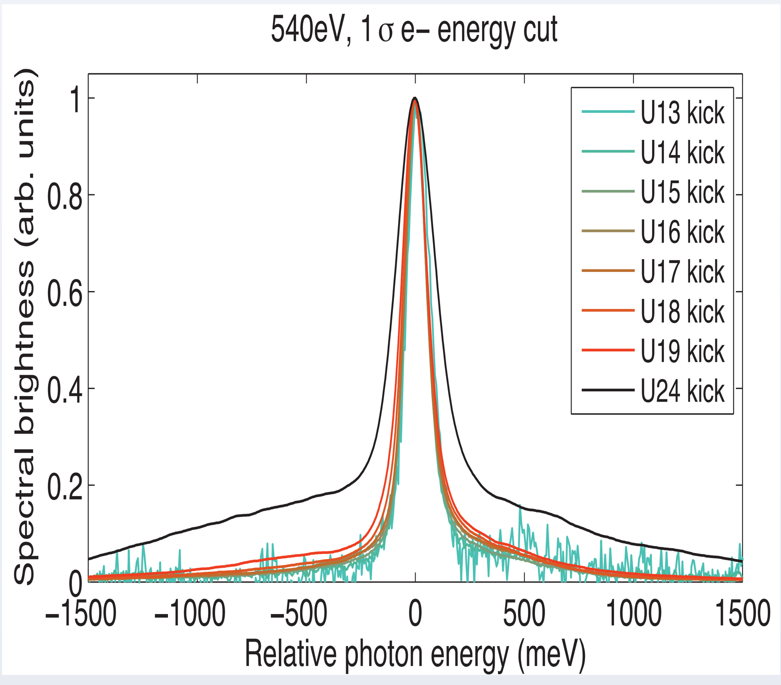
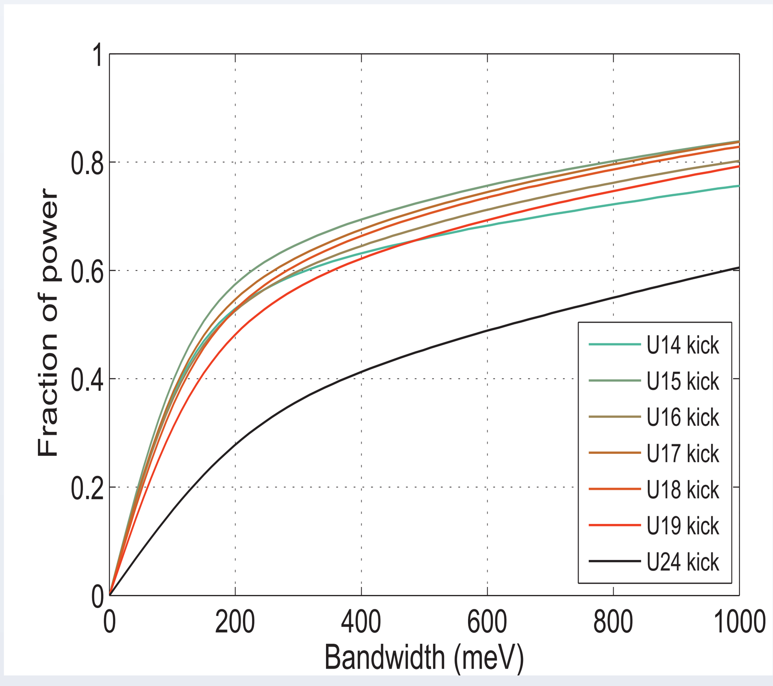
Introduction

The measured spectrum of the soft X-ray self-seeding at the LCLS has a pedestal-like distribution around the seeded frequency, which limits the spectral purity and seeding applications without a post-undulator monochromator. We study the origins of the pedestals and focus on the contributions of microbunching instability prior to the FEL undulator.





Parameters: 540eV, 180pC cut to 120pC, 1.4kA, 90fs

Theoretical Analysis

A two-frequency system: the seed ω_1 and the sideband ω_s

Use the dimensionless variables

$$\hat{z} \equiv 2k_u\rho z \qquad \hat{\eta} \equiv \frac{\eta}{\rho} \qquad \nu \equiv \frac{\omega}{\omega_1}$$

The pendulum equations of the two-frequency system are

$$\frac{d\theta}{d\hat{z}} = \hat{\eta}\,,\quad \frac{d\hat{\eta}}{d\hat{z}} = a_1 e^{i\theta} + a_s e^{i\nu\theta} + c.c.\,,\quad \frac{da_1}{d\hat{z}} = -b_1\,,\quad \frac{da_s}{d\hat{z}} + i\Delta\nu a_s = -b_s\,,$$

$$a_{1,s} \equiv \frac{eK[JJ]}{8\gamma_0^2 mc^2 k_u \rho^2} E_{1,s} \qquad b_{1,s} \equiv \langle e^{-i\nu\theta} \rangle \qquad p_{1,s} \equiv \langle \hat{\eta} e^{-i\nu\theta} \rangle$$

Initial energy modulation

Consider an initial energy modulation

$$A(s) = A_0 \cos(k_s s) = \Delta\gamma/\gamma \cos(k_s s)$$

Initial condition in scaled energy variable

$$\widehat{\eta_0} = \frac{\hat{A}}{2} e^{i\Delta\nu\theta} + c.c. \qquad \hat{A} \equiv A_0/\rho$$

With the assumptions that $|a_s| \ll |a_1|$, $|b_s| \ll |b_1|$ and $|p_s| \ll |p_1|$

$$\frac{d^3 a_1}{d\hat{z}^3} \approx i a_1\,,\qquad \frac{d^3 a_s}{d\hat{z}^3} + i\Delta\nu \frac{d^2 a_s}{d\hat{z}^2} \approx i\nu a_s + \nu^2 \hat{A} p_1\,.$$

Assume high-gain regime ($\hat{z} \gg 1$) and small detune ($\Delta\nu < \rho$)

$$a_s(\hat{z}) = -\frac{i\hat{A}D_3}{3}\hat{z}e^{-i\mu_3\hat{z}} = -\frac{i\hat{A}}{3}\hat{z}a_1\,.$$

The power ratio between the sideband and the seed

$$\frac{P_s(\hat{z})}{P_1(\hat{z})} = \frac{\hat{A}^2}{9}\hat{z}^2 = \frac{(2k_u\rho z)^2}{9}\frac{A_0^2}{\rho^2}\,.$$

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Theoretical Analysis

Generalized to broadband sidebands

$$\frac{P_s(\hat{z})}{P_1(\hat{z})} = \frac{\hat{A}^2}{9}\hat{z}^2 = \frac{(2k_u\rho z)^2}{9}\int_0^{\Delta s}\frac{A(s)^2}{\rho^2}\frac{ds}{\Delta s}\,.$$

Initial density modulation

The above analysis can be applied to modulations in density

$$\frac{d^3 a_s}{d\hat{z}^3} \approx i\nu a_s + i\nu a_1 b_0\,. \qquad b_0 = \langle e^{-i\Delta\nu\theta} \rangle$$

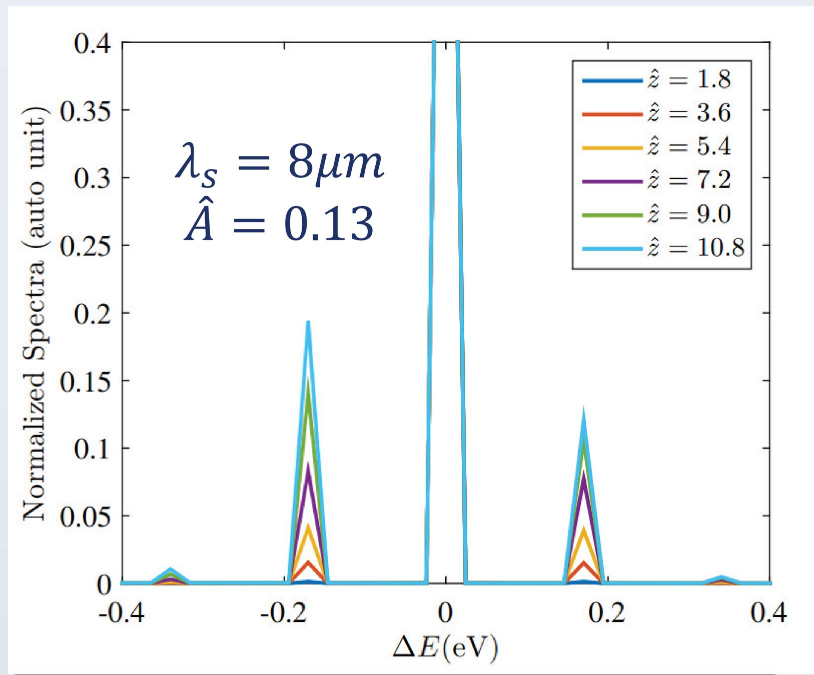
The power ratio between the sideband and the seed

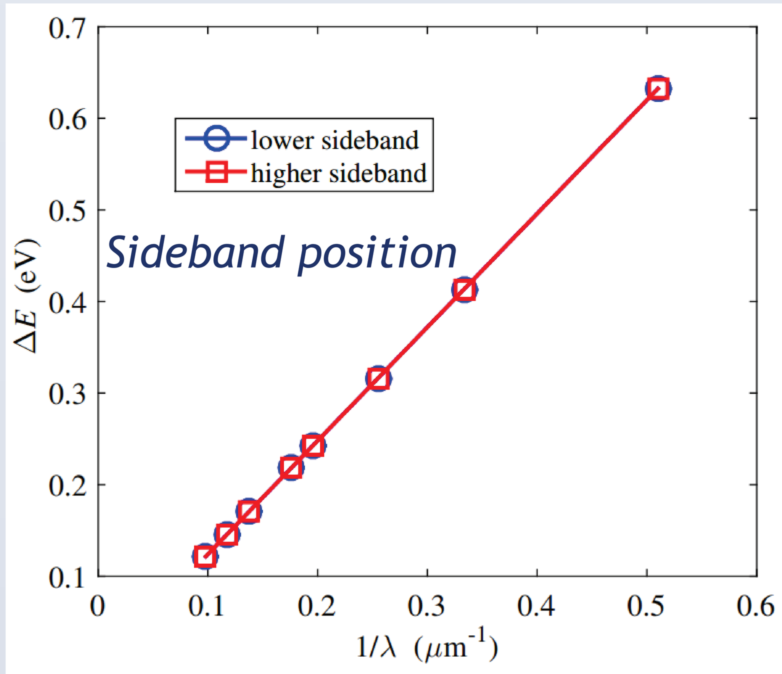
$$\frac{P_s(\hat{z})}{P_1(\hat{z})} = \frac{b_0^2}{9}\hat{z}^2 = \frac{(2k_u\rho z)^2}{9} b_0^2$$

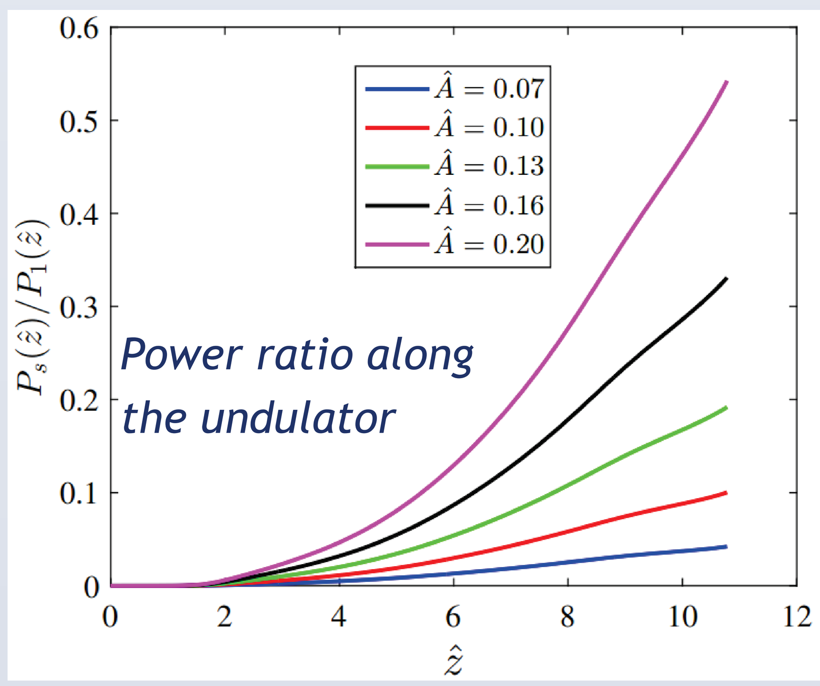
1D Simulation

Table 1: Simulation parameters in 1-D FEL code

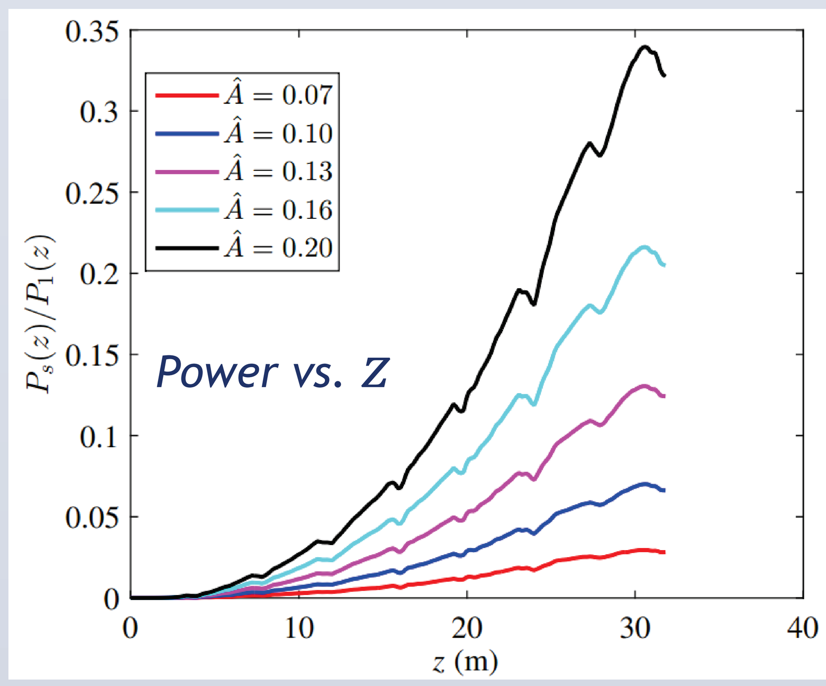
Parameter	Value	Unit
Beam energy E	3.48	GeV
Slice energy spread	0	MeV
Normalized emittance ϵ_N	0.9	μm
Current I	1.4	kA
Average β	30	m
Undulator period λ_u	3	cm
FEL parameter ρ	8.6×10^{-4}	
Gain length L_G	1.6	m
Seeding wavelength λ_r	2.29	nm
Seeding power	20	kW
Energy modulation wavelength	2-10	μm
Energy modulation amplitude	0.1-0.6	MeV

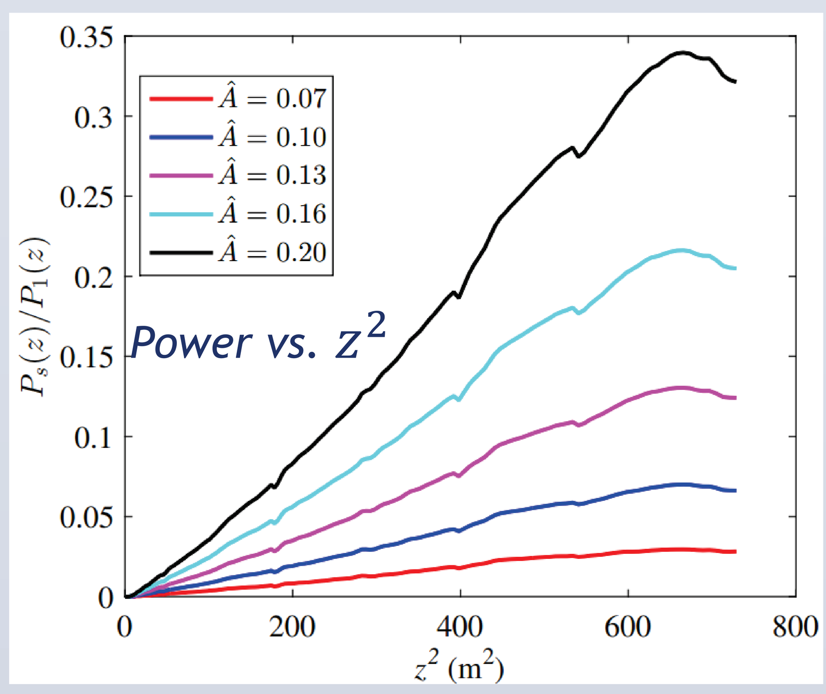






Genesis Simulation





Summary

- ❑ Both energy and density modulation can induce sidebands in a seeded FEL.
- ❑ A simple 1D theory is developed to estimate the sideband content and agrees well with simulations.
- ❑ The power ratio of the sidebands to the seeded signal grows quadratically with the modulation amplitude and undulator length before FEL saturation.
- ❑ Further work includes detailed comparison with the experimental observations and developing methods to produce a more uniform electron beam in the longitudinal phase space.

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