Soft X-ray FEL Seeding Studies for LCLS-II

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FUture of SEeded free Electron lasers

(FUSEE) Workshop, December 2019

Trieste, Italy

Overview

Seeding goals for LCLS-II:

Produce fully coherent, narrowband, stable, and tunable pulses

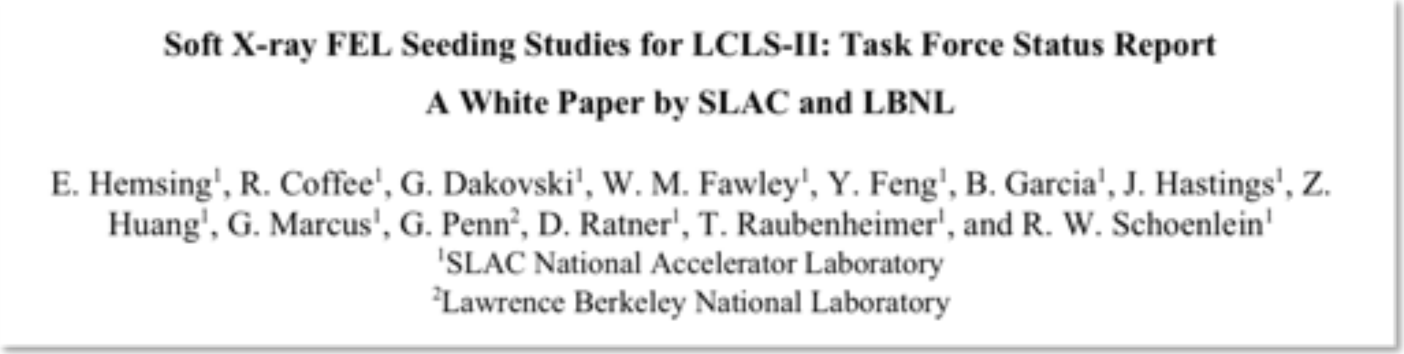
- Precision control of the central wavelength
  - Targets: C (284 eV), N (410 eV), O (543 eV), (Cu 933 eV)
- Transform-limited control of coherent bandwidth/pulse duration.
  - 10 $\mathrm{fs}_{\mathrm{FWHM}}$ ⇔ 180 $\mathrm{meV}_{\mathrm{FWHM}}$ (60 fs ⇔ 30 meV)
- Customizable phase properties
  - Phase-locked multi pulse/Multi color

Outline of Talk

- **Soft X-ray Self-Seeding (SXRSS)**
  - LCLS results
  - LCLS-II studies
- **Echo Enables Harmonic Generation**
  - LCLS-II studies

For more detail…

SLAC-TN-19-001 (2019)



Soft X-ray FEL Seeding Studies for LCLS-II: Task Force Status Report

A White Paper by SLAC and LBNL

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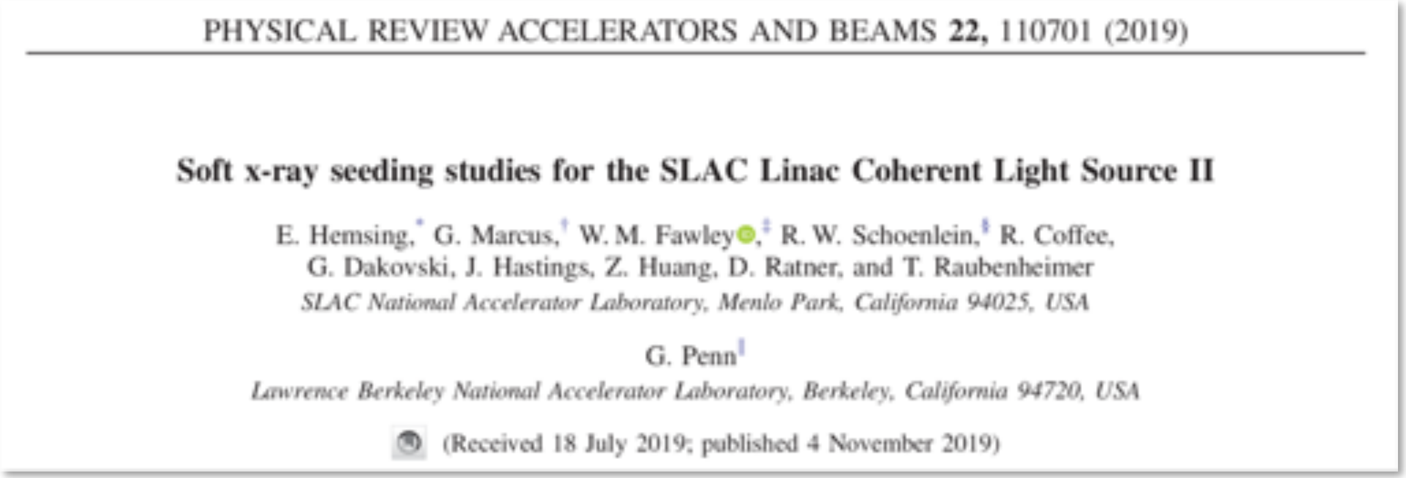

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 110701 (2019)

Soft x-ray seeding studies for the SLAC Linac Coherent Light Source II

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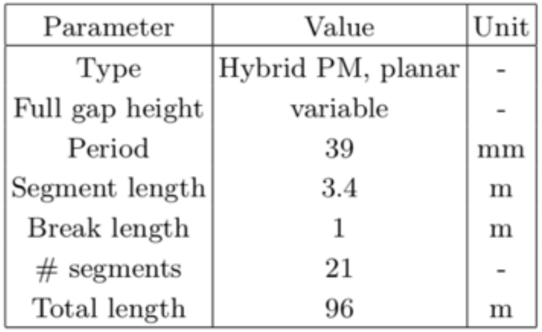
LCLS-II Accelerators and Undulators

Two sources: MHz rate SCRF linac and 120 Hz Cu LCLS-I linac

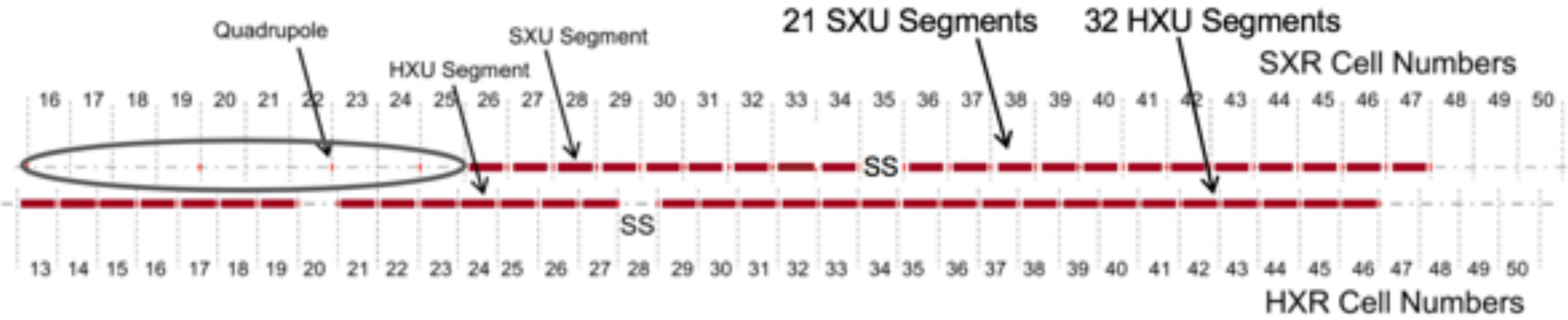
Hard and Soft X-ray undulators can operate simultaneously in any mode

SCRF beam destination controlled with fast (μs) magnetic deflector



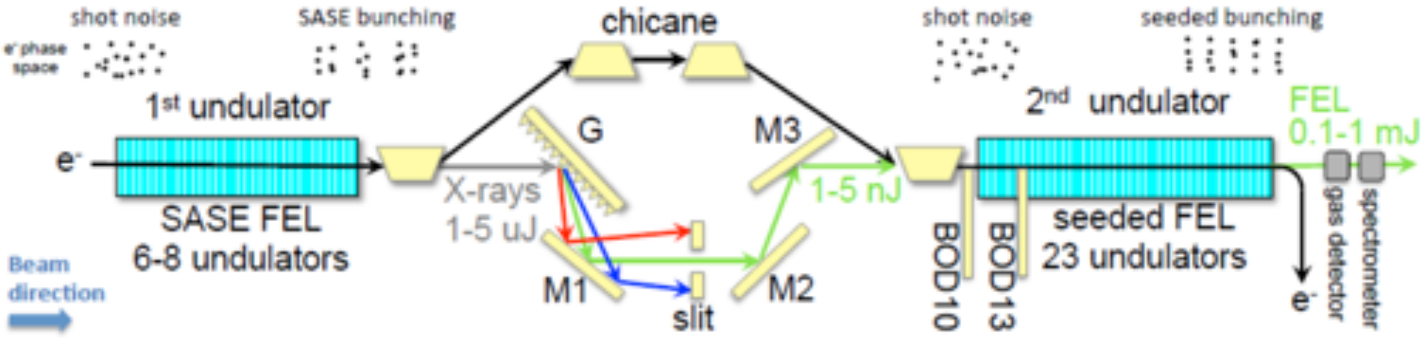
Parameter	Value	Unit
Type	Hybrid PM, planar	-
Full gap height	variable	-
Period	39	mm
Segment length	3.4	m
Break length	1	m
# segments	21	-
Total length	96	m

TABLE II. Parameters of the LCLS-II soft x-ray undulators.

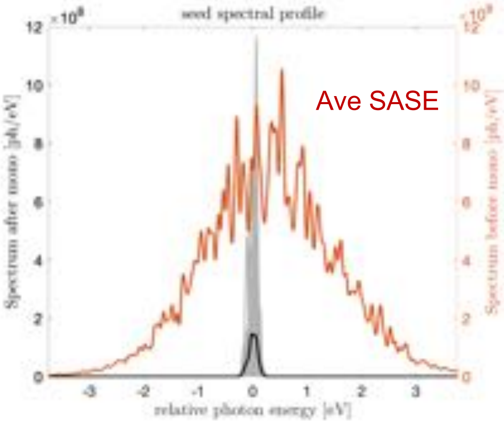


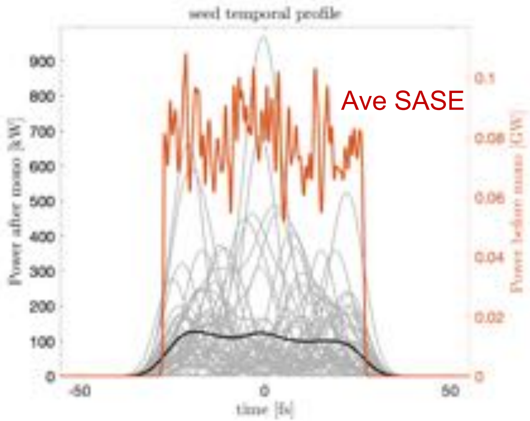
LCLS/LCLS-II SXR Self-Seeding System

D. Ratner, et al., Phys. Rev. Lett. 114, 054801 (2015).



- VLS grating, R_T, R_S disperse and focus x-rays
- M1 and slit for λ selectivity
- M2 and M3 reimage x-rays
- R = 5,000 (FWHM, nominal)
- ~2% efficiency (not including BW reduction)

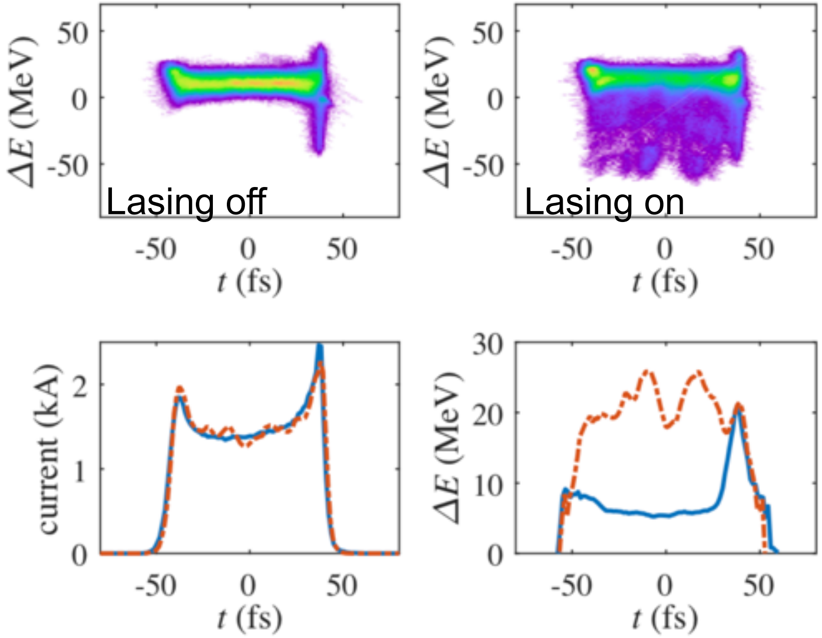




LCLS SXRSS beam setup

- LPS at the dump
- E = 4.1-4.75 GeV
- E_γ = 0.9-1 keV
- Q = 140 pC, horn truncation
- ρ=1.1x10^{-3} (L_g=1.9m)

- Relatively flat LPS in the core at entrance to undulator section
- I ~ 1 kA, fairly flat in the core

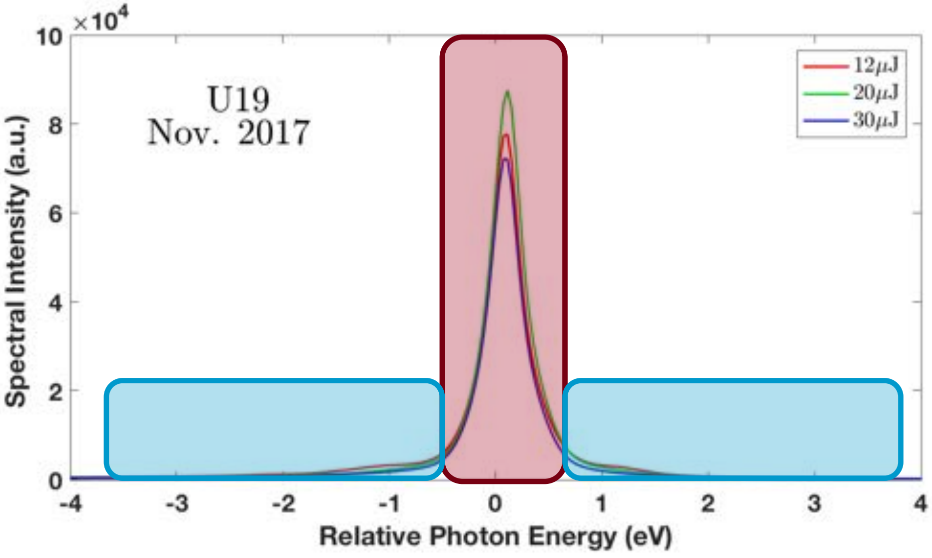


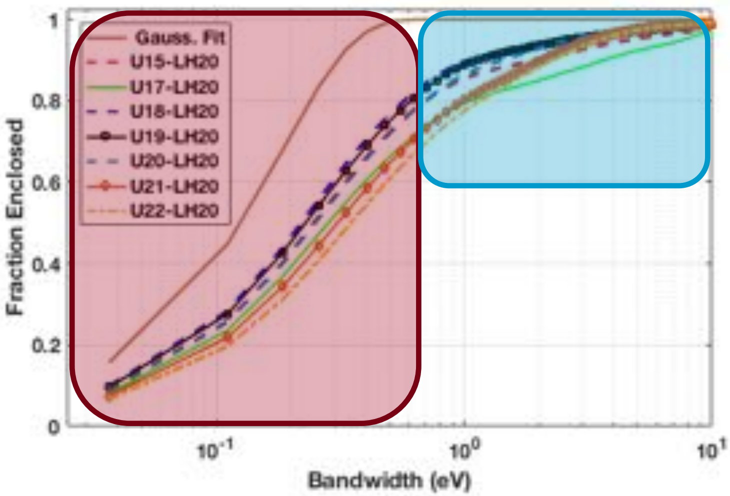
Best seeding results from horn truncation, LH optimization, and taking time to **linearize** the LPS **at the entrance to the seeded undulator**

Measured the spectrum at various locations along the seeded undulator before saturation (U13 – U19)

- Quantify pedestal growth as a function of z

Recent LCLS SXRSS experimental results





G. Marcus, et al., PRAB 22, 080702 (2019)

- Averaged spectrum shows
  - 300 meV fwhm
  - Spectral brightness
    - 2-5x higher than SASE
    - 50x higher than monochomatized SASE
  - Stable frequency $\langle \Delta\lambda/\lambda \rangle \leq 2\times10^{-5}$

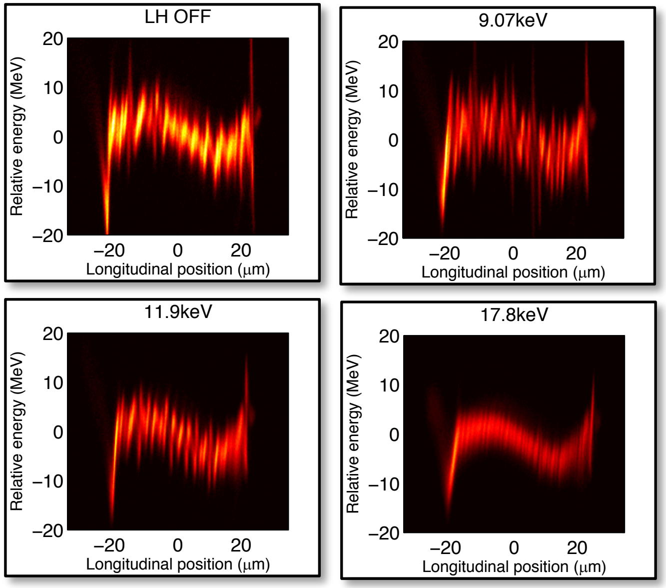
- Pulse energy still found at a relatively large bandwidth: ***Pedestal***
  - Grows approaching saturation
  - Can potentially be problematic to some users w/o a downstream mono
  - Caused by
    - e-beam structures (MBI)
    - SASE growth

LCLS SXRSS: Laser Heater Impact

Laser heater has strong control over spectral pedestal

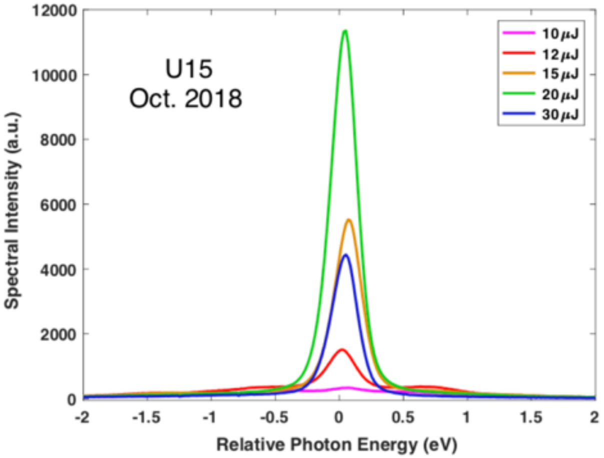
- Low heater -> broad and large pedestal
- **Goldilocks zone: suppress MBI but not FEL gain**
- High heater -> energy spread too big

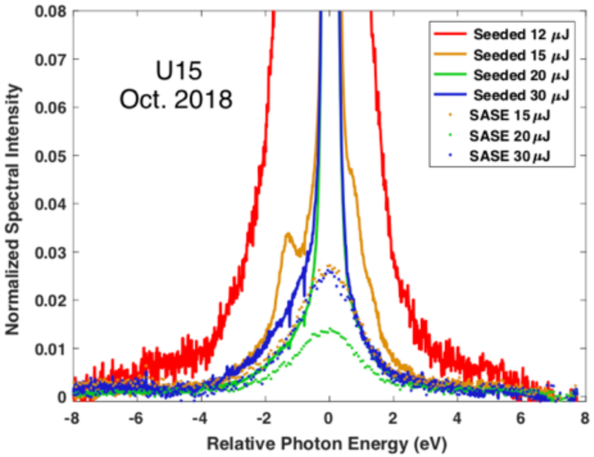
Observation of *MBI* at 4 GeV with X-band Transverse Deflector



D. Ratner et al., PRST-AB 18, 030704 (2015)

G. Marcus, et al., in preparation





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

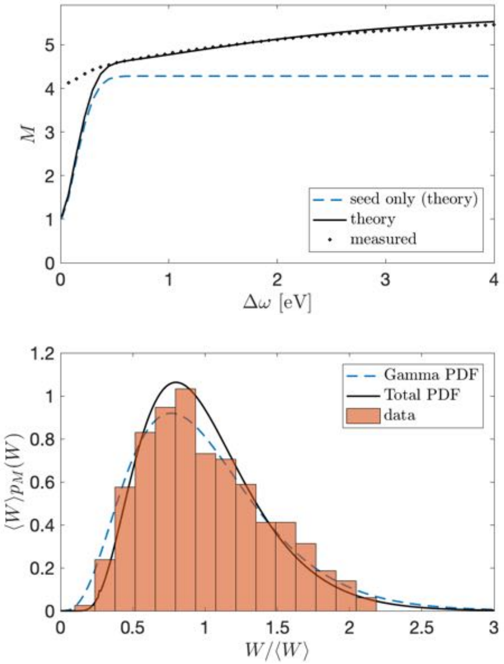
Z. Zhang et al., PRAB 19, 050701 (2016)

Stability and Statistical behavior of SXRSS

SASE and MBI both impact the statistics of the seeded spectrum

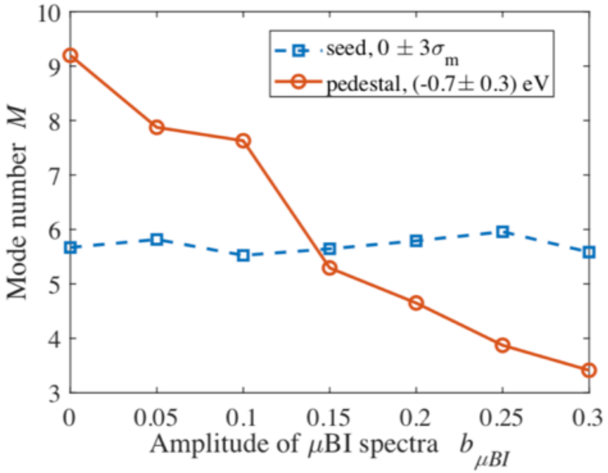
- Seeding with **multiple** coherent **modes allows SASE to grow** between spikes
- SASE pedestal follows **SASE statistics**

- MBI structures in beam frequency-mix with seed and produce **sidebands**
- MBI-driven pedestal follows **seed statistics** (not uBI statistics)



EH, et al., Accepted to PRAB (2019)

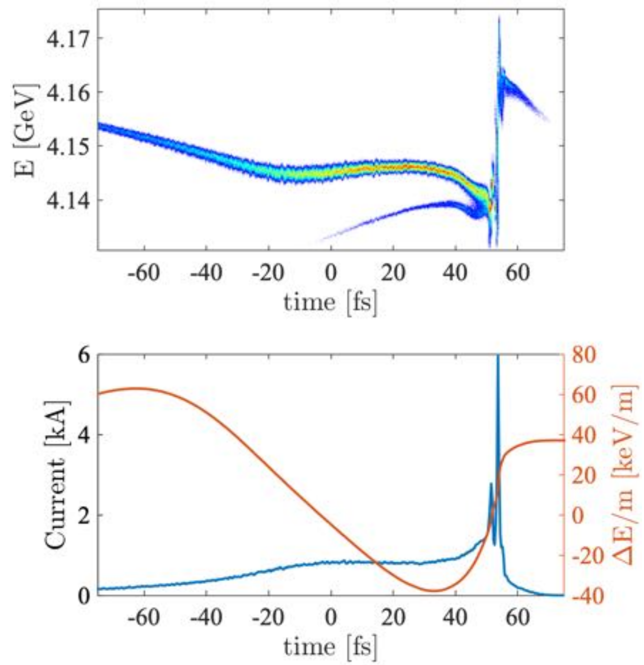
$$M = \frac{1}{\sigma_{\mathcal{E}}^2}$$



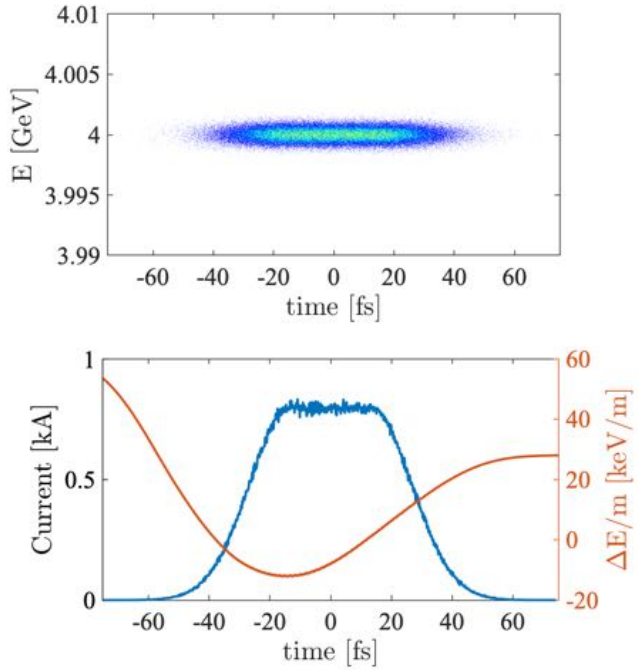
Z. Zhang, et al., Submitted to PRAB (2019)

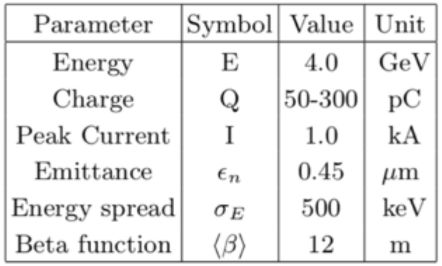
LCLS-II Beams for Simulation

Start to end (S2E)



Ideal beam



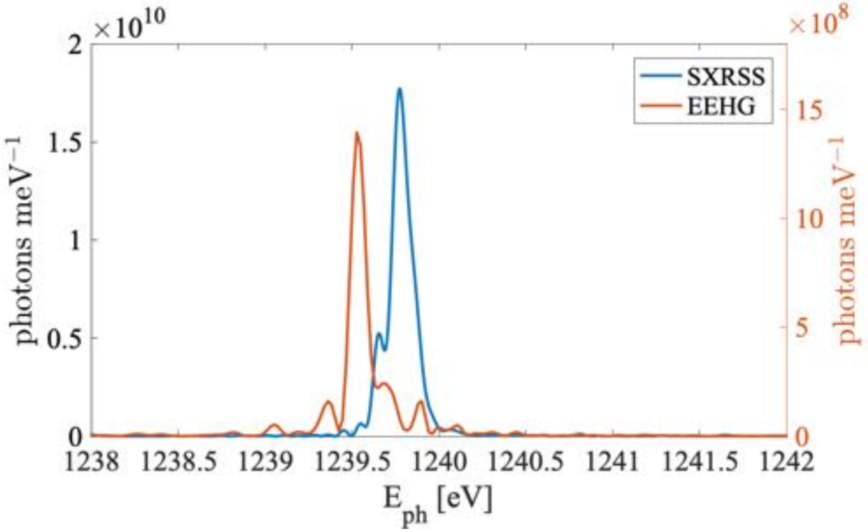


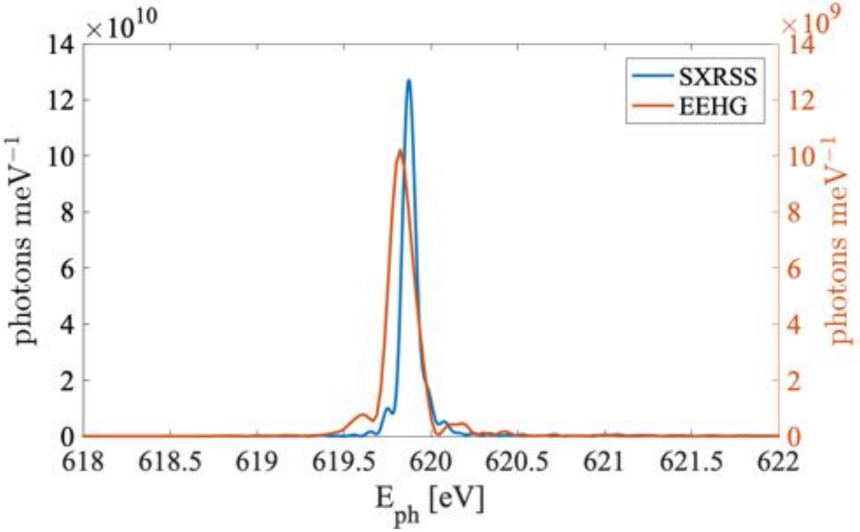
Parameter	Symbol	Value	Unit
Energy	E	4.0	GeV
Charge	Q	50-300	pC
Peak Current	I	1.0	kA
Emittance	ϵ_n	0.45	μm
Energy spread	σ_E	500	keV
Beta function	$\langle\beta\rangle$	12	m

TABLE I. Parameters of the LCLS-II e-beam for generating soft x-rays.

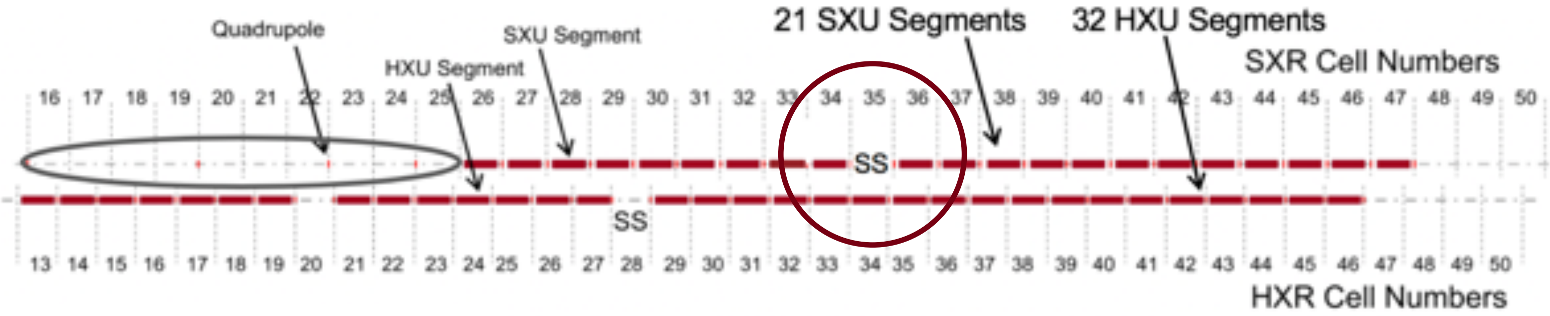
LCLS-II seeded spectra with IDEAL beams

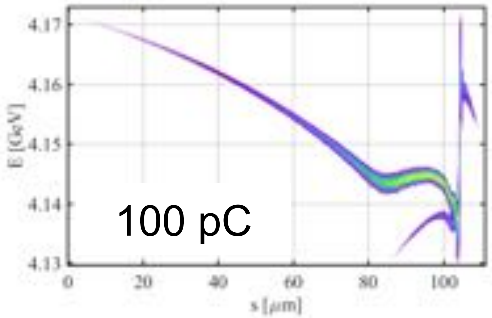
- Up to 1-10 GW power (standard tapering)
- Peak ph/meV
  - SXRSS = 20-40x SASE
  - EEHG = 1.4-2.5x SASE
- Bandwidth (fwhm)
  - SXRSS = 90-130 meV
  - EEHG = 125-180 meV
- Fraction of power in FWHM
  - SXRSS = 60%
  - EEHG = 60-70%

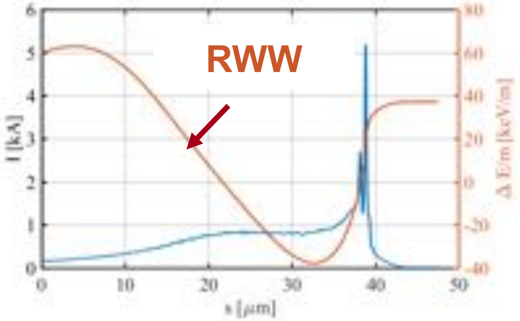


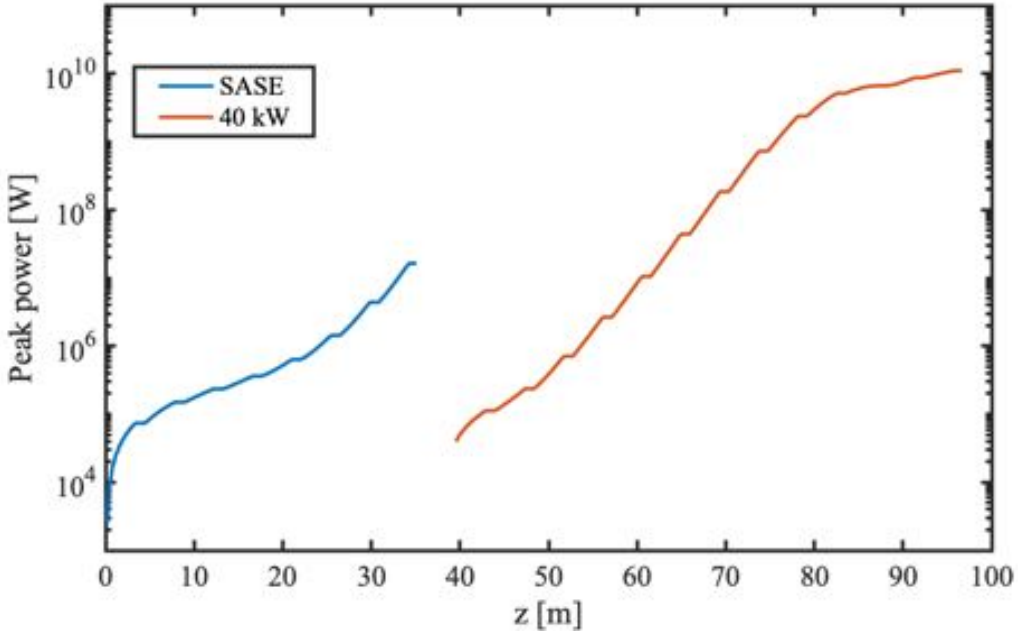


SXRSS at LCLS-II with S2E beam, IDEAL SEED

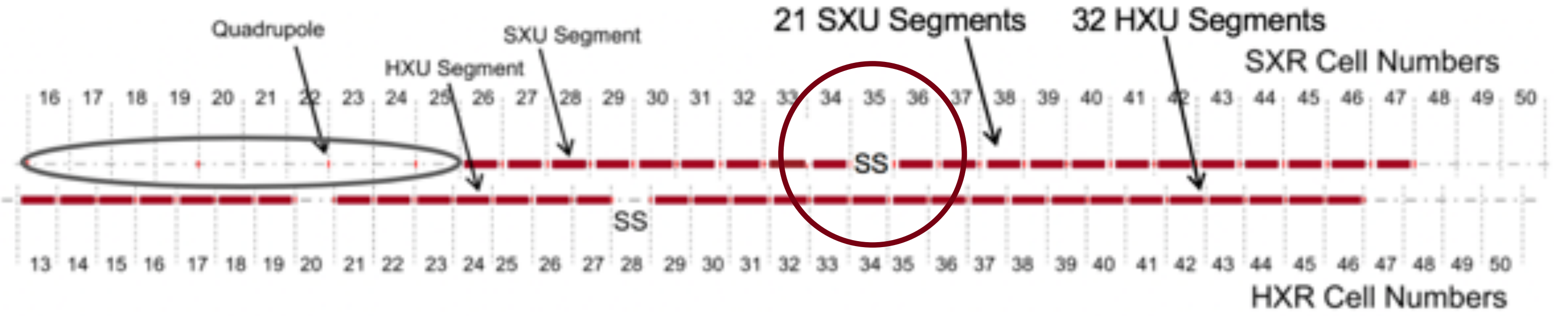


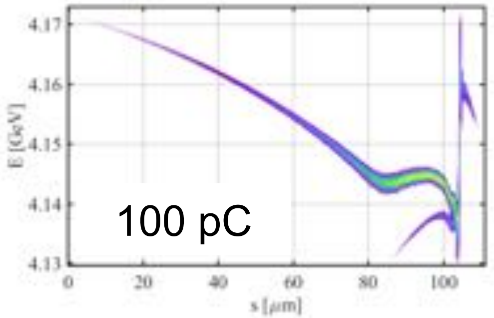


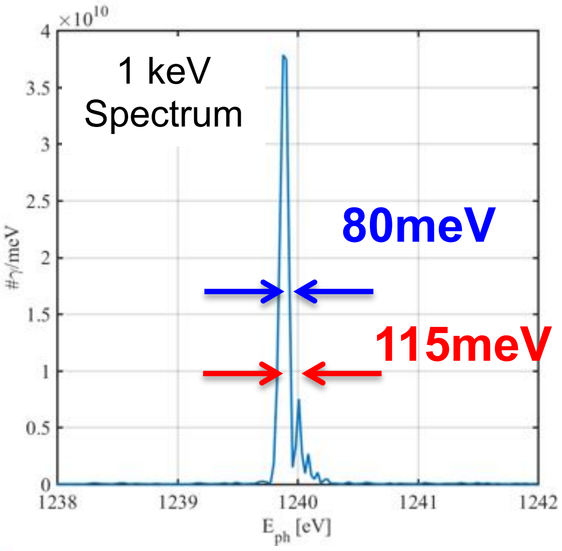




SXRSS at LCLS-II with S2E beam, IDEAL SEED

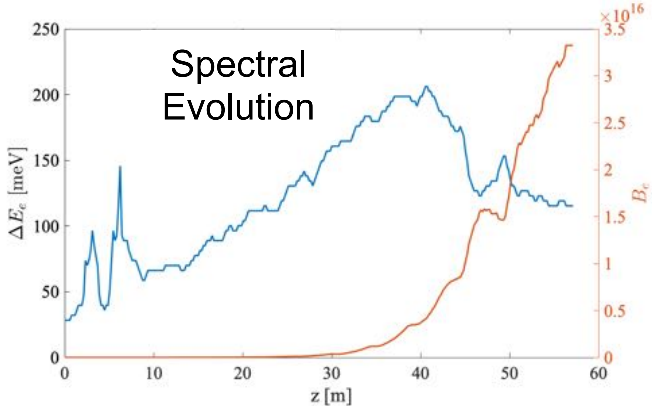


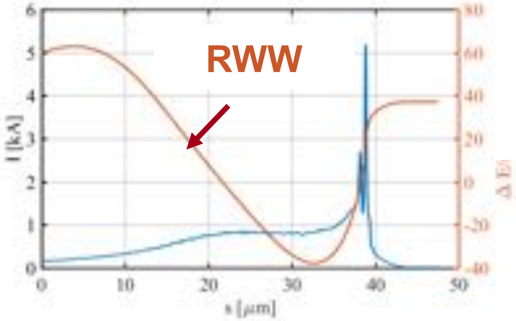

100 pC


1 keV Spectrum

80meV

115meV

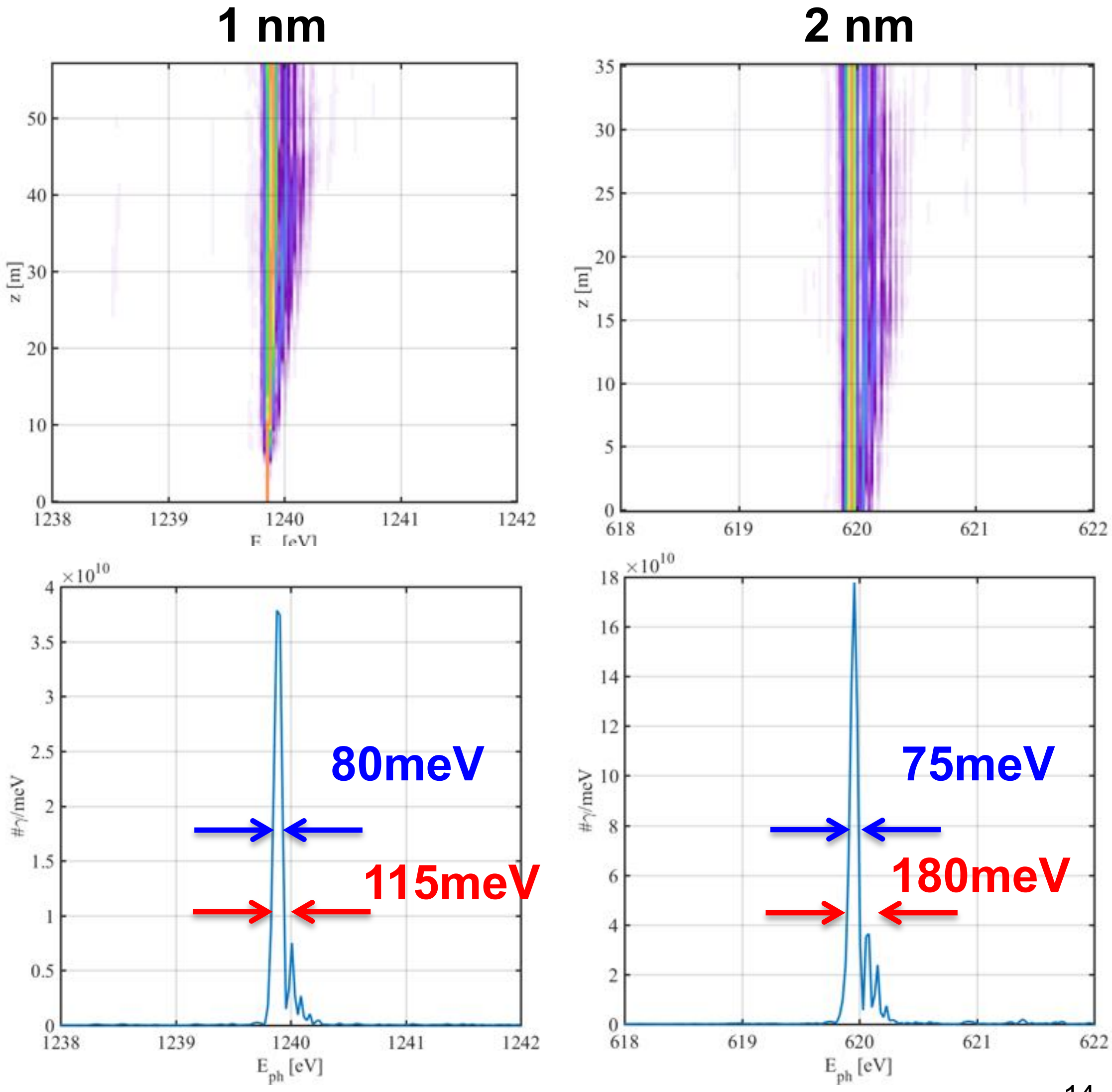

Spectral Evolution


RWW

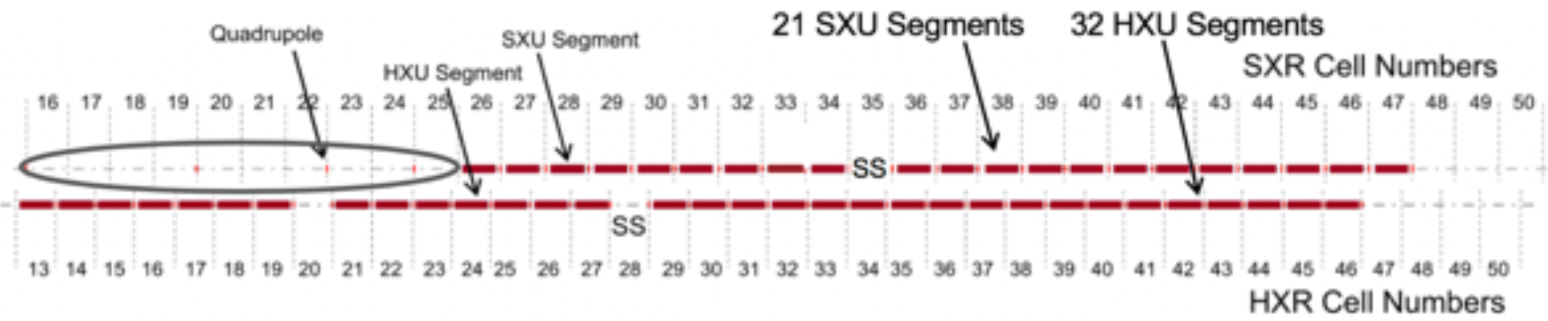
Resistive Wall Wake (RWW) from undulator chamber limits minimum bandwidth to >**70 meV (<25 fs)**

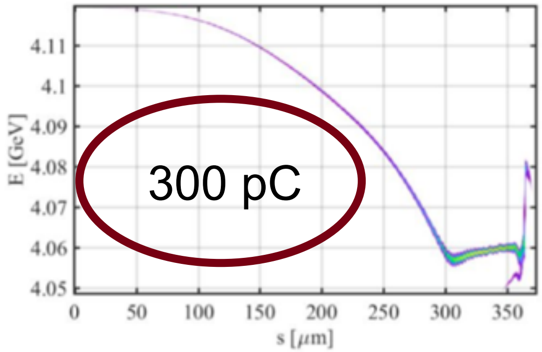
SXRSS at LCLS-II with S2E beam, IDEAL SEED

- ~2.5x transform limit (spike)
- 100 pC, 1 kA, 4GeV
- Shorter beam experiences reduced RWW nonlinearity
    - Strong splitting not present
- FWHM and “FWHM-equivalent”

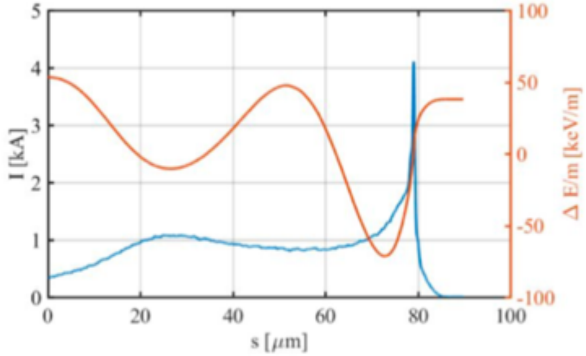


SXRSS at LCLS-II with S2E beam, IDEAL SEED





300 pC



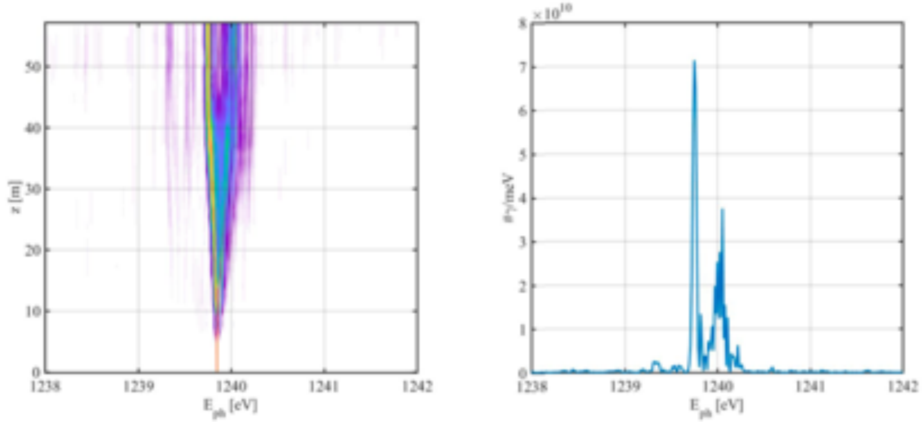


Figure 9. 300 pC LCLS-II beam SXRSS. Left: Normalized spectral evolution along the undulator. Right: Spectrum at the end of the undulator.

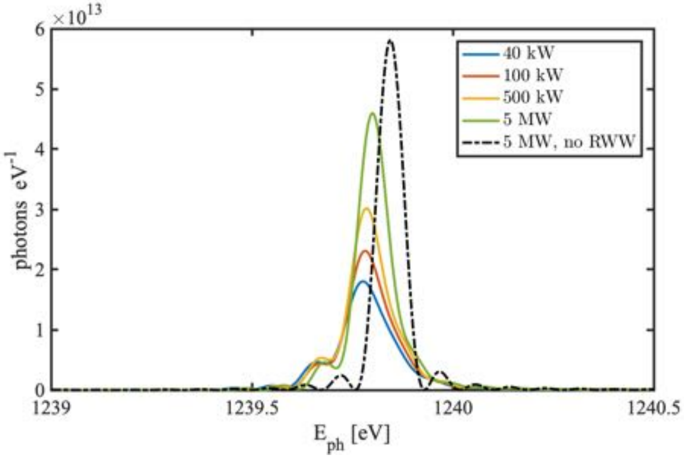
2 nm case very similar

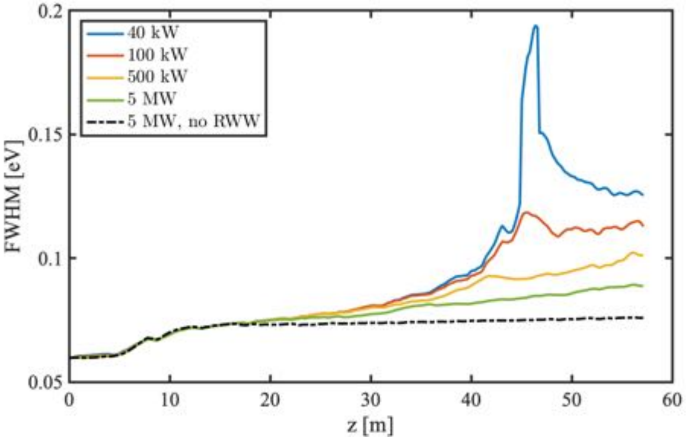
Q: Can we outrun the resistive wall wake?

Increase seed power to saturate sooner?

A: Not easily. Requires significant seed power and redesign of system.

- Peak photons/eV improves by 2.5 for seed increase from 40 kW to 5 MW
- Time-bandwidth product improves from 1.5 to 1.16.
- Getting BW<100 meV would require significant effort;
    - larger vacuum chamber apertures (e.g., increase from 5 mm to 7 mm)
    - or a factor of 100 increase in the seed power.





Summary for SXRSS

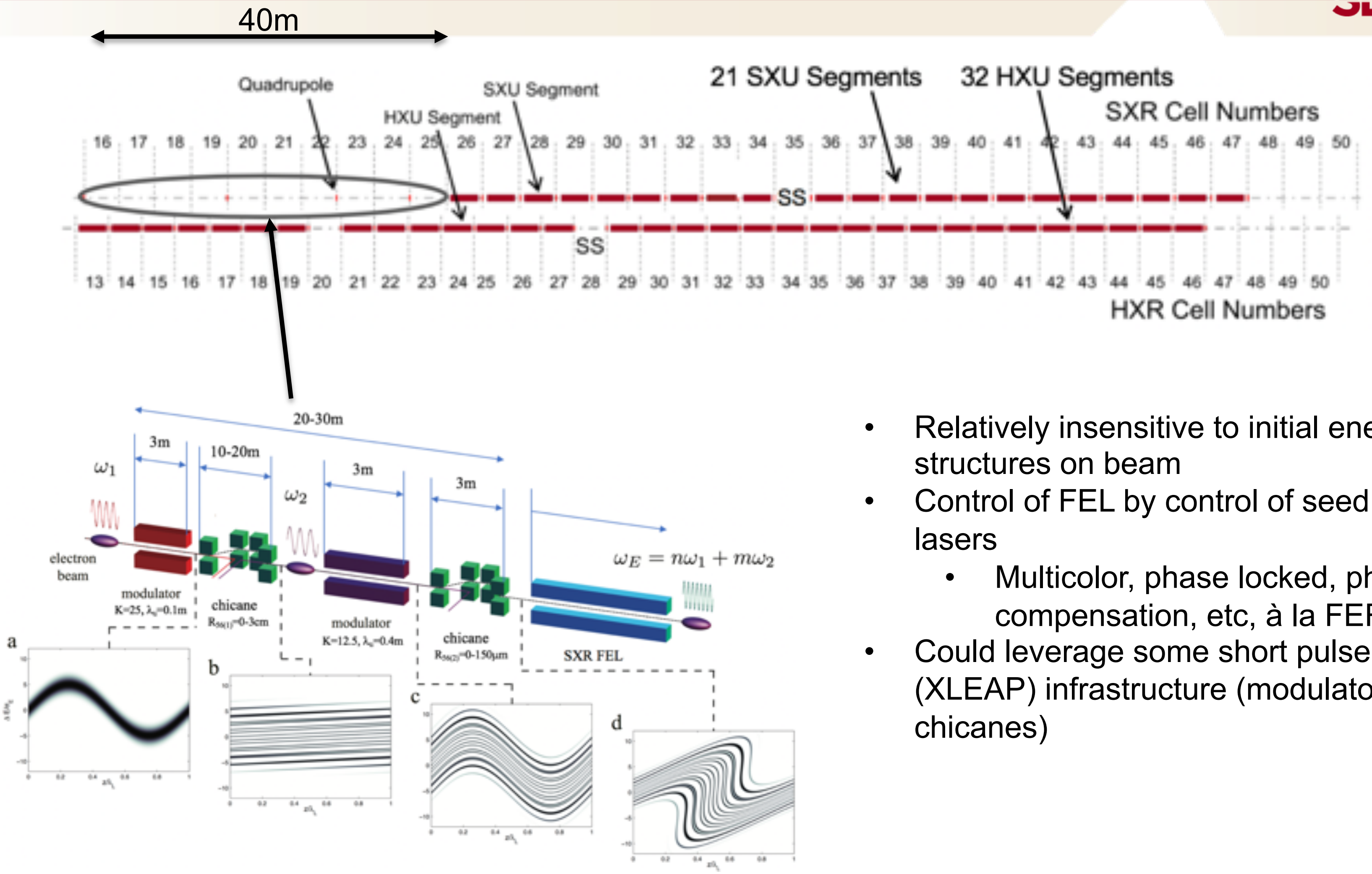
Three primary sources of spectral broadening with different spectral characteristics:

- MBI produces 0.3-5 micron structures in the e-beam that frequency-mix with the seed to produce a shot-to-shot varying spectral pedestal.
  - Pedestal grows at least linearly relative to the main seeded line prior to saturation
  - Pedestal can be controlled in part by LH; down to 10% of the seed energy at LCLS

- RWW in the undulator chamber introduces a nonlinear chirp that broadens spectrum.
  - For the 1 kA, 4 GeV e-beam at LCLS-II, this limits maximum linear portion of the e-beam to ~25 fs (R ~10,000 at 1 keV).
  - Difficult to outrun. An increase in the aperture from 5-mm to 7-mm would virtually eliminate this contribution

- SASE and saturation. Weak or nonuniform seed raises the relative SASE background.
  - At LCLS, SASE usually accounts for ~10% of the total output pulse energy in the linear gain regime. Deep in saturation and in the absence of optimized tapering, the relative SASE contribution continues to increase.

Echo Enabled Harmonic Generation (EEHG)

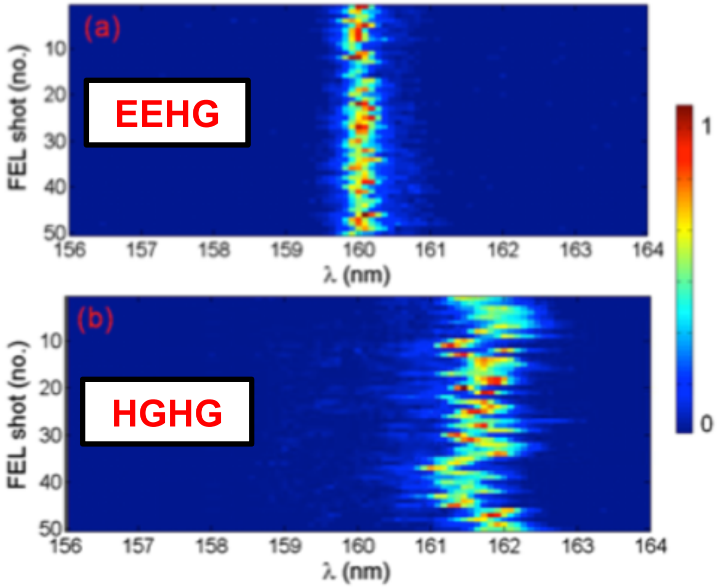


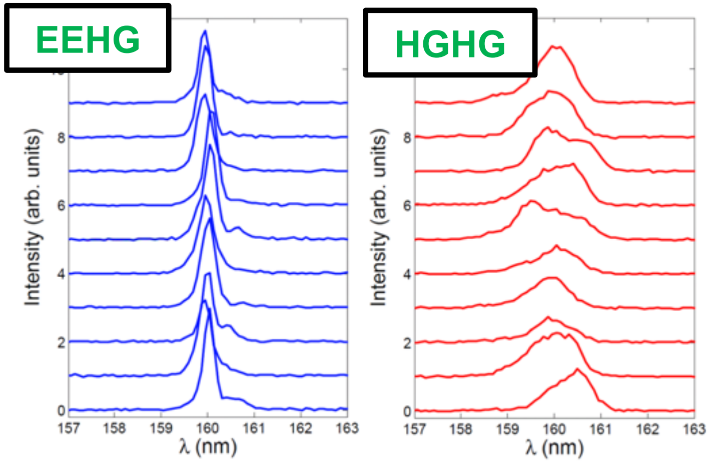
- Relatively insensitive to initial energy structures on beam
- Control of FEL by control of seed lasers
  - Multicolor, phase locked, phase compensation, etc, à la FERMI
- Could leverage some short pulse (XLEAP) infrastructure (modulators, chicanes)

G. Stupakov, PRL, 2009; D. Xiang, G. Stupakov, PRST-AB, 2009

EEHG: low sensitivity to initial phase space structure

- Linear electron beam chirp
    - EEHG spectral shift much less than HGHG
- Quadratic chirp
    - EEHG bandwidth much less than HGHG
- Reduced sensitivity of EEHG **stabilizes spectrum against <u>small</u> initial phase space structures** (eg., MBI)





E.H., et al, PRAB, 17, 070702 (2014), E.H., et al, PRAB, 20, 060702 (2017)

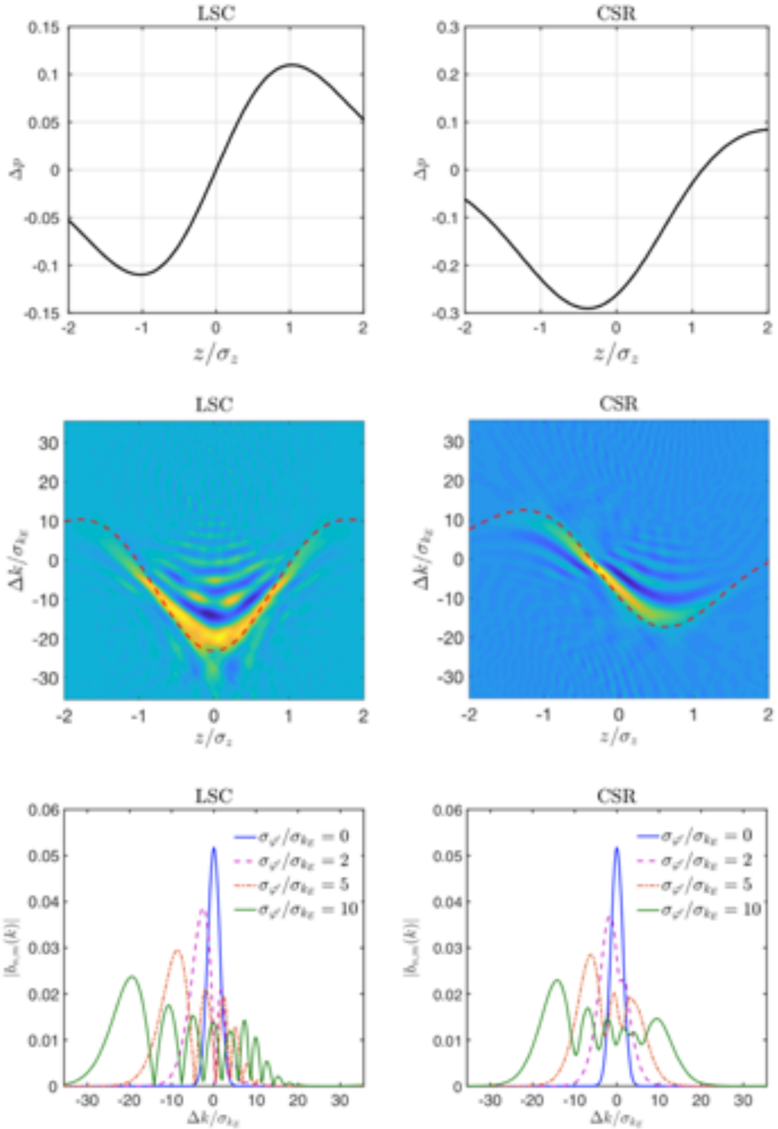
Wakefield effects on EEHG

- **EEHG much more sensitive to disturbances during laser manipulation**

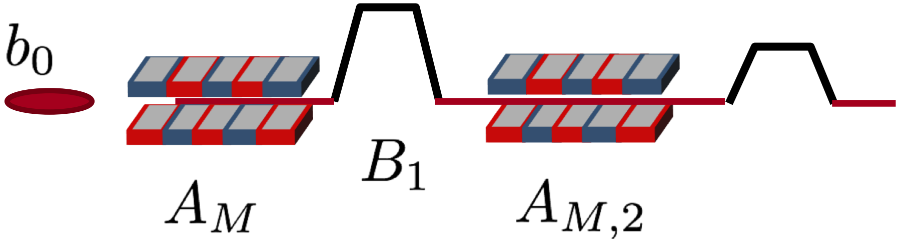
- Any **nonlinearity** introduced **in lasing core** by
  - Longitudinal space charge (LSC)
  - Coherent Synch. Rad. (CSR),
  - MBI,
  - Resistive wall wake (RWW)

broadens the spectrum and introduces spectral structure
  - Worst at high harmonics

- Mitigation is wake-dependent
  - LSC (small-K modulators)
  - CSR (gentle bends, longer flatter beams, shorter lasers)
  - MBI (small-K modulators, laser heater)
  - RWW (large vacuum apertures)



MBI growth in EEHG Seeding



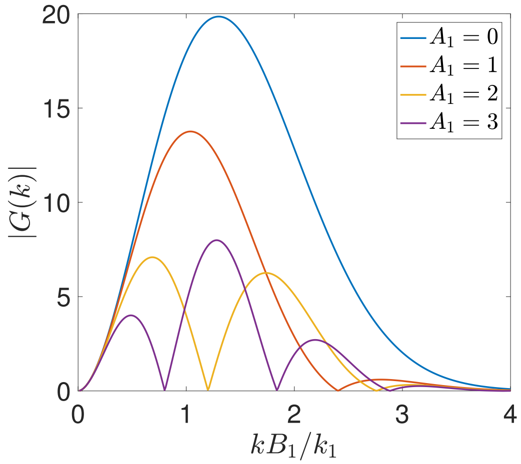
- **Initial** distortions can be suppressed by large chicane
- However, EEHG beamline can act like a cascaded MBI amplifier that **introduces distortions**
- **Modulators have large LSC impedance**
  - Bunching gain in first chicane

$$G(k_0) = -\frac{k_0 B_1}{2k_1 b_0} A_M(k_0) J_0\left(\frac{k_0 B_1}{k_1} A_1\right) e^{-\frac{1}{2}\left(\frac{k_0 B_1}{k_1}\right)^2}$$

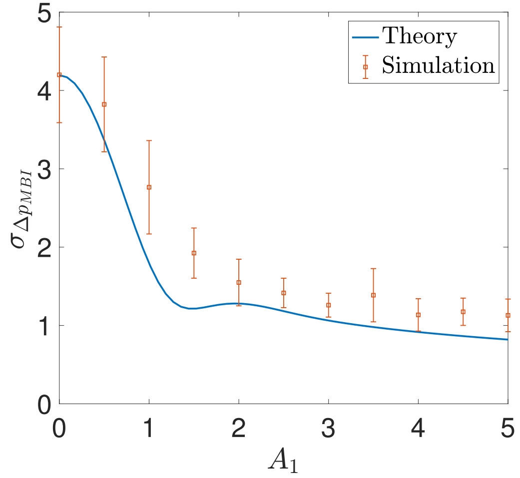
  - Induced energy spread on the beam

$$\sigma^2_{\Delta p_{MBI}} \approx \frac{k_1 \sigma_z}{(2\pi)^{3/2} B_1 A_1}\left(\frac{A_M A_{M,2}}{6 b_0}\right)^2$$

EH, PRAB 21, 050702 (2018)



Strong chicane and first laser modulation provide some MBI suppression



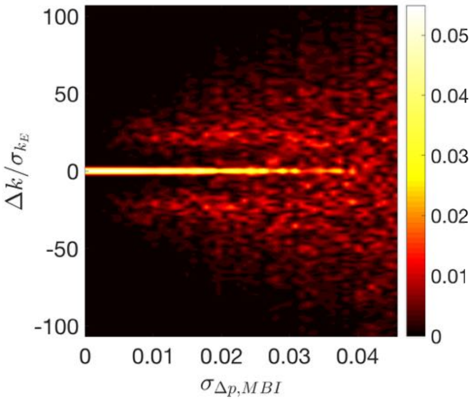
MBI growth in EEHG Seeding

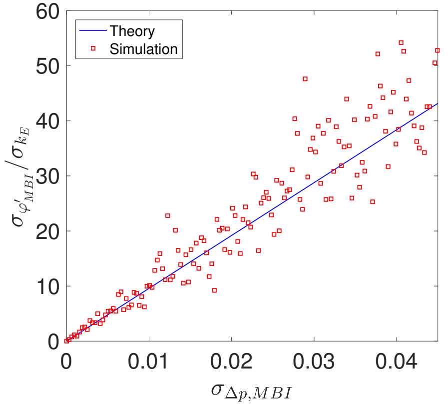
Induced energy spread on beam is well-correlated to final bunching reduction and spectrum bandwidth growth.

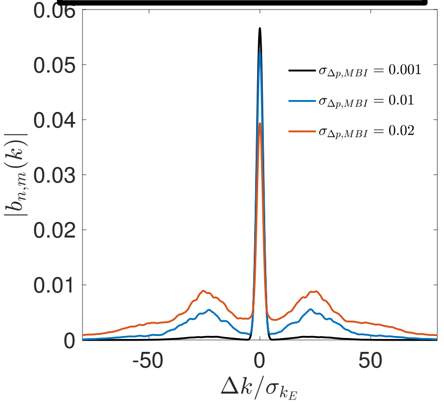
To maintain transform-limited bunching, the induced energy spread within the laser pulse length σ_L should satisfy;

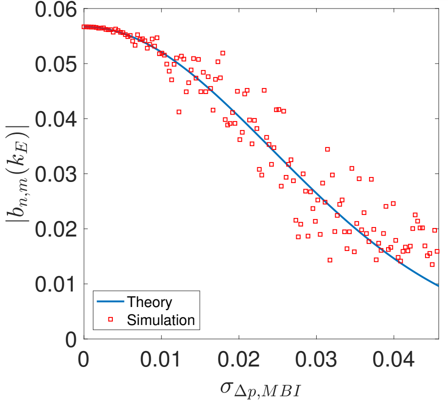
$$\sigma_{\Delta p_{MBI}} \lesssim \frac{h^{1/3}}{3k_2\sigma_L}$$

For LCLS-II, MBI-induced energy spread growth through a UV-based EEHG system needs to be <1% to produce near-transform limited pulses down to 1 nm.


bunching spectra


bandwidth growth


bunching spectra

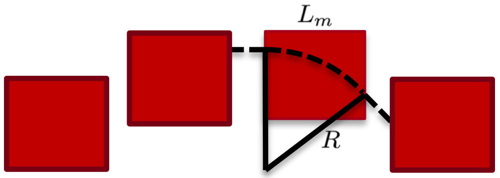

bunching reduction

Control of MBI critical to reach short wavelengths

CSR in strong EEHG chicane

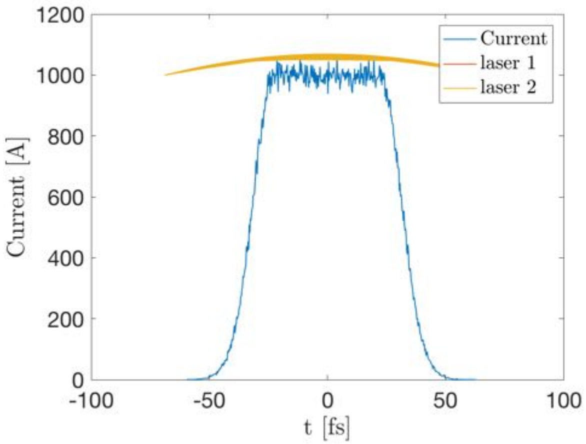
Steady-state energy modulation:

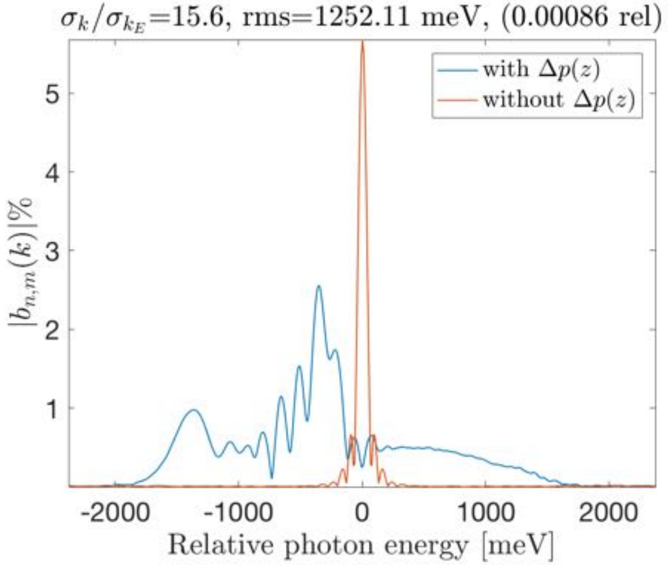
$$\Delta p_{CSR}(z) = -\frac{2L_m}{\sigma_\gamma I_A (3R^2)^{1/3}} \int_{-\infty}^{z} \frac{dz'}{(z-z')^{1/3}} \frac{dI(z')}{dz'}$$

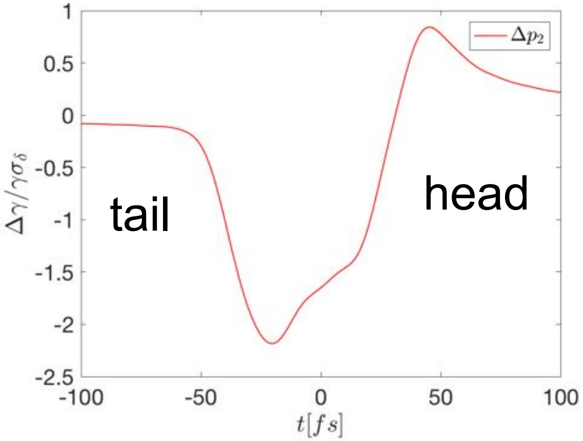


LCLS-II: EEHG to 2 nm

- Ideal 1 kA flattop 50 fs beam, 4 GeV
- Full laser temporal overlap
- **CSR wake destroys spectrum**
- **Largest impact from last two dipoles**



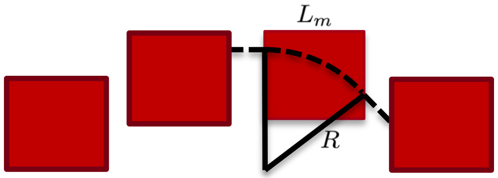




CSR in strong chicane

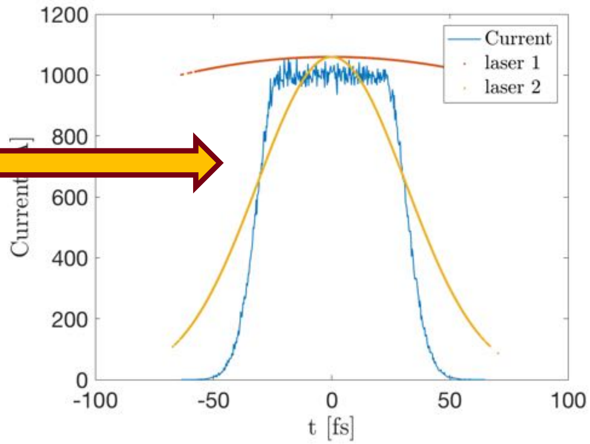
Steady-state energy modulation:

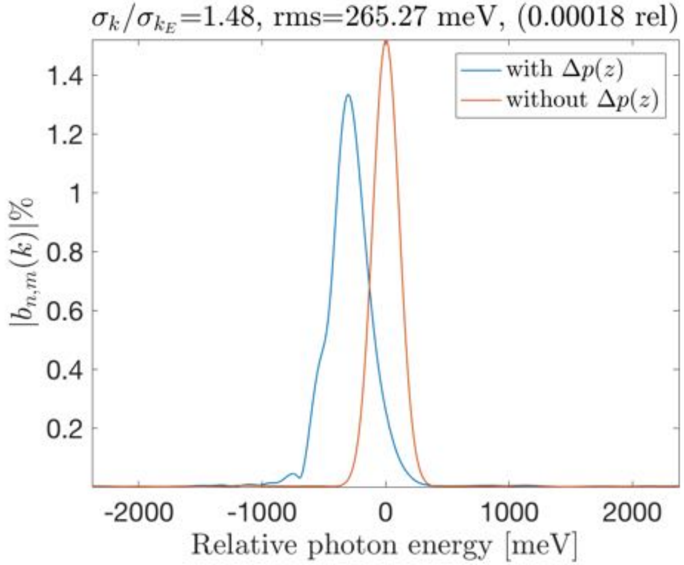
$$\Delta p_{CSR}(z) = -\frac{2L_m}{\sigma_\gamma I_A (3R^2)^{1/3}} \int_{-\infty}^{z} \frac{dz'}{(z-z')^{1/3}} \frac{dI(z')}{dz'}$$

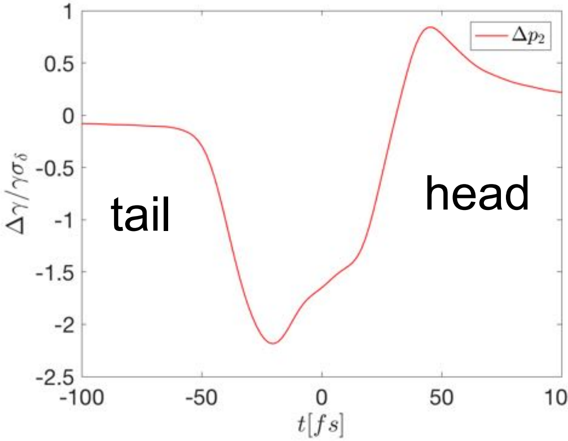


LCLS-II: EEHG to 2 nm

- Ideal 1 kA flattop 50 fs beam, 4 GeV
- **Short Laser 2 (60 fs fwhm)**
- Much better spectrum

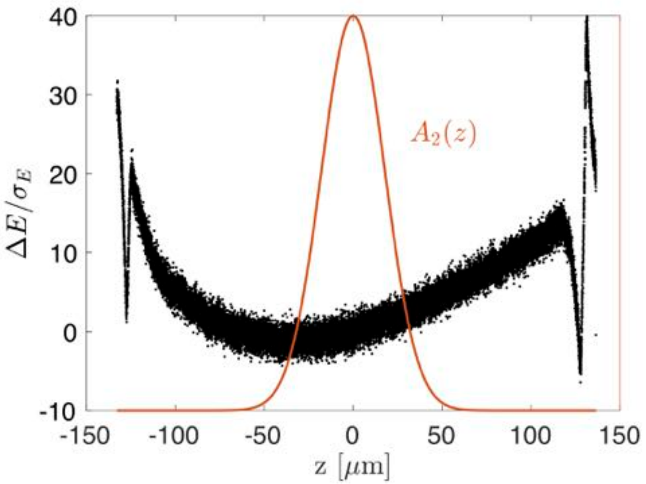






Minimizing the FEL bandwidth with EEHG

- **Nonlinear wakes of power N**, along with current horns and energy tails, can **preclude** using whole electron beam to reach **narrowest bandwidths**
- How short should the seed laser be?
  - Modulation intrinsically broadband if laser is *too short*
  - Modulation acquires bandwidth from nonlinearities if laser is *too long*
- For a given nonlinear energy chirp in beam (or in laser), the optimum laser pulse duration can be calculated analytically*



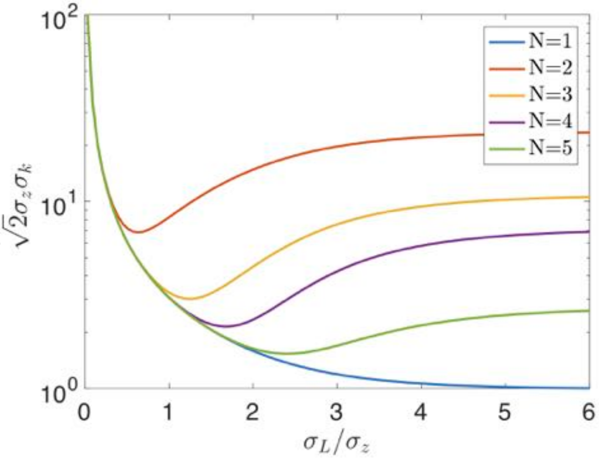
Example: Quadratic electron chirp

$$\Delta p(z) = \alpha z^2.$$

Optimal laser pulse length is

$$\sigma_L \approx \frac{h^{1/3}}{\sqrt{\alpha}}$$

Bunching bandwidth

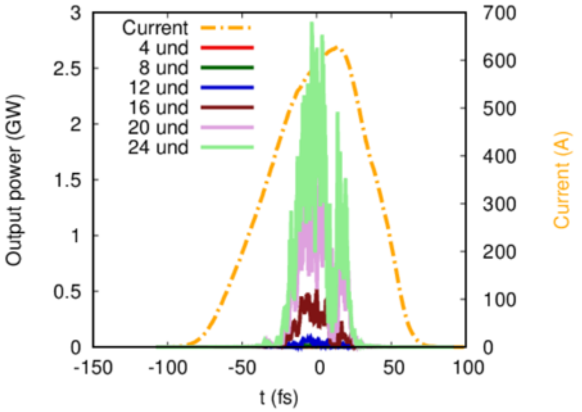


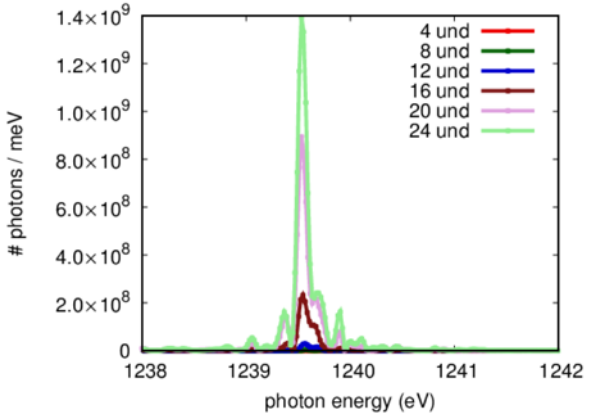
Laser 2 pulse length

*EH, Frontiers in Physics 7:35. (2019), doi: 10.3389/fphy.2019.00035

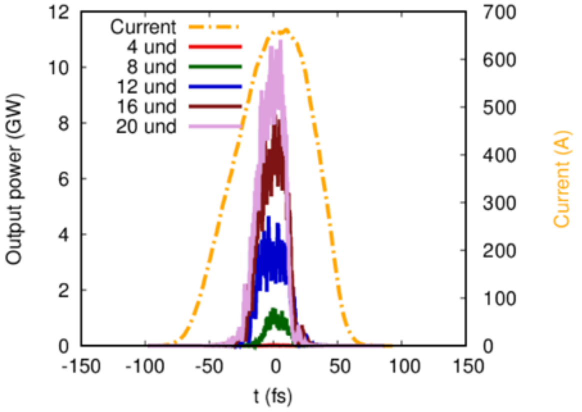
EEHG at LCLS-II with IDEAL beam

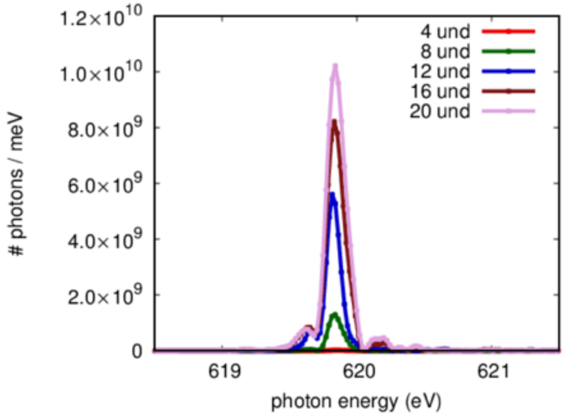
1 nm

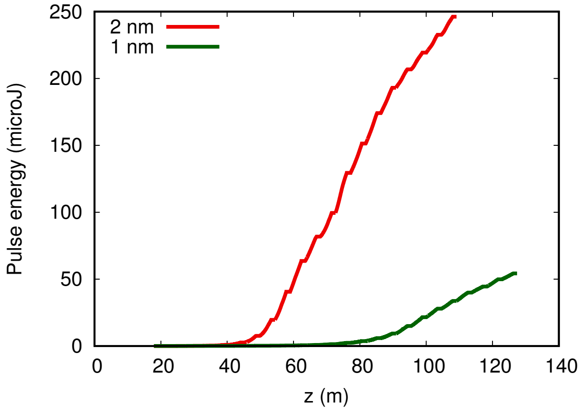




2 nm

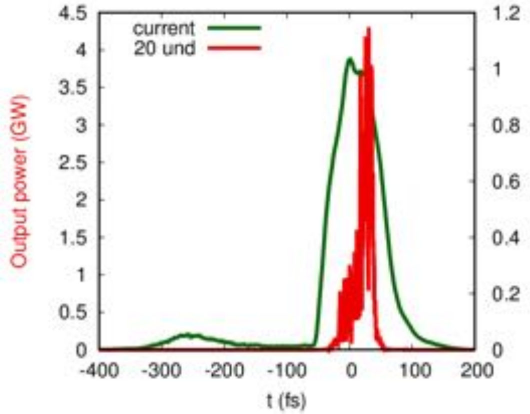


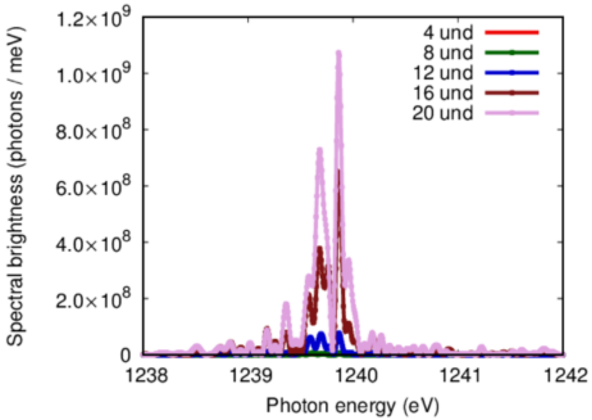




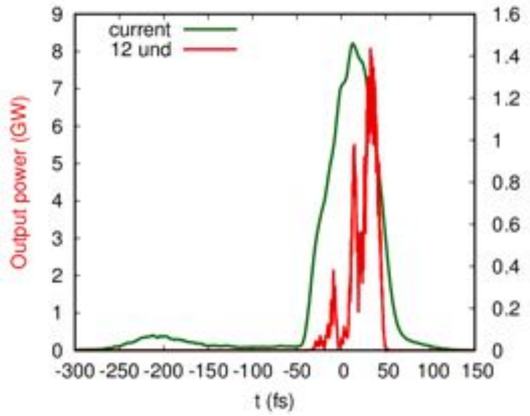
EEHG at LCLS-II start to end beam

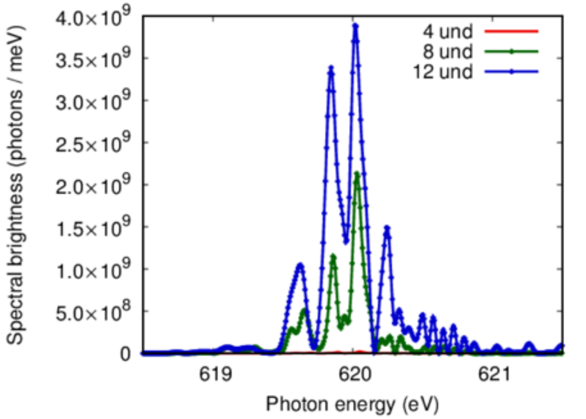
1 nm →

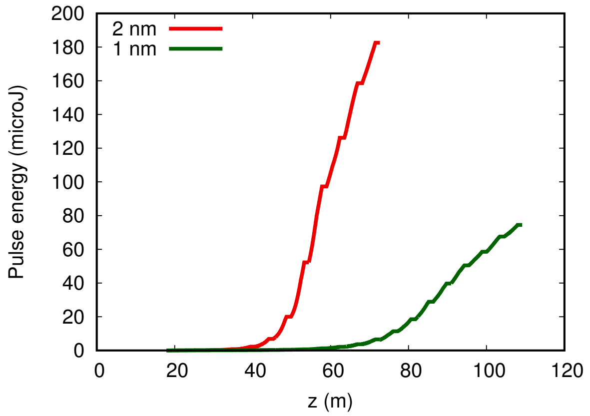




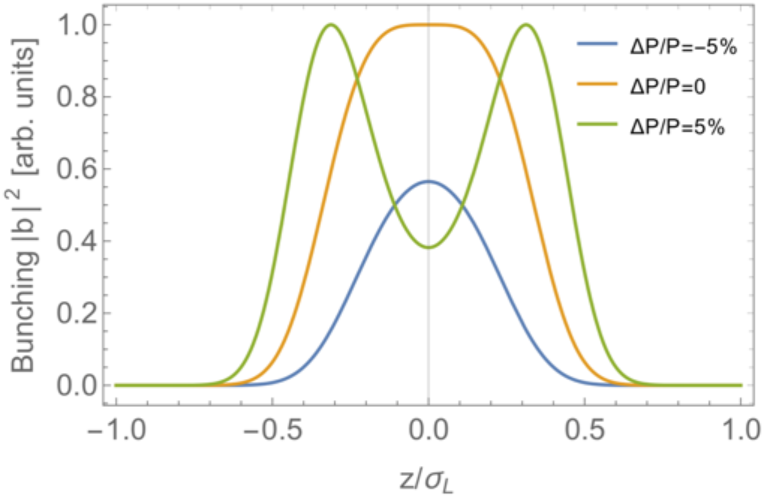
2 nm →

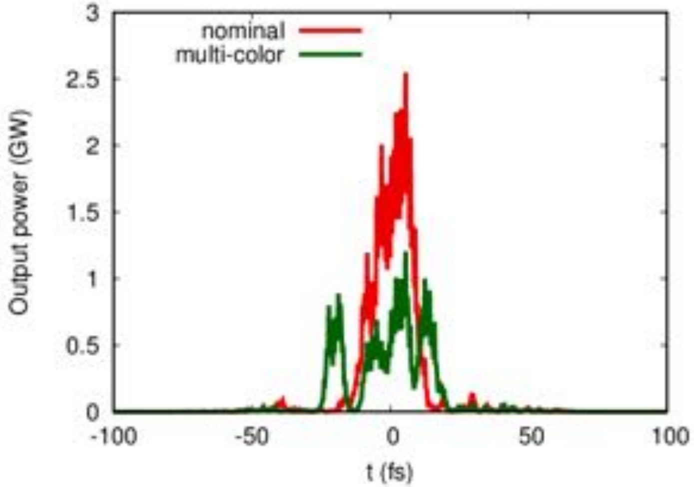


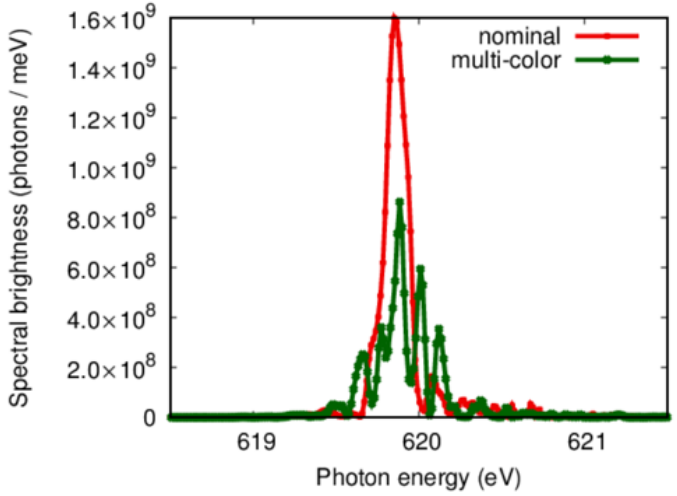




Custom Pulses with EEHG at LCLS-II







Multicolor FEL pulses produced by:

- Nearby harmonics (~1/h energy separation)
- Overmodulating with laser
- CSR wake

Summary for EEHG

EEHG works best at 2 nm wavelengths and longer with flat linear beams

- Stable intensity and central frequency expected (FERMI results)
- Somewhat tunable bandwidth, multicolor (FERMI results)

Several critical issues for optimal performance

- **Laser spectral phase:** Suppressed by the combination of harmonic compression and slippage in the modulator.
  - Not really a major issue.
- **MBI**: Strong EEHG modulators increase and cascade MBI effects during sensitive manipulation.
  - Small K modulators, and best suppression of initial MBI by the laser heater.
- **CSR**: wakes in the strong chicane produce nonlinearity that broadens spectrum
  - gentle bends, flatter current profiles, and short second laser pulses
- **ISR**: ‘Heating’ reduces bunching, particularly if it occurs in the strong chicane and second undulator.
  - Small second modulator K. Chicane bends not too short.
- **Intrabeam scattering (IBS):** increases the energy spread and reduces the bunching.
  - Favors a compact EEHG layout, in conflict with ISR requirements for large, weak magnets.
  - ~15% total bunching degradation from IBS and ISR at 1.2 keV.
- **Large amplitude e-beam energy structures:** Large energy chirps in the head or tail fold phase space and spoil the final FEL spectrum
  - Horn truncation

Summary of Seeding Options at LCLS-II

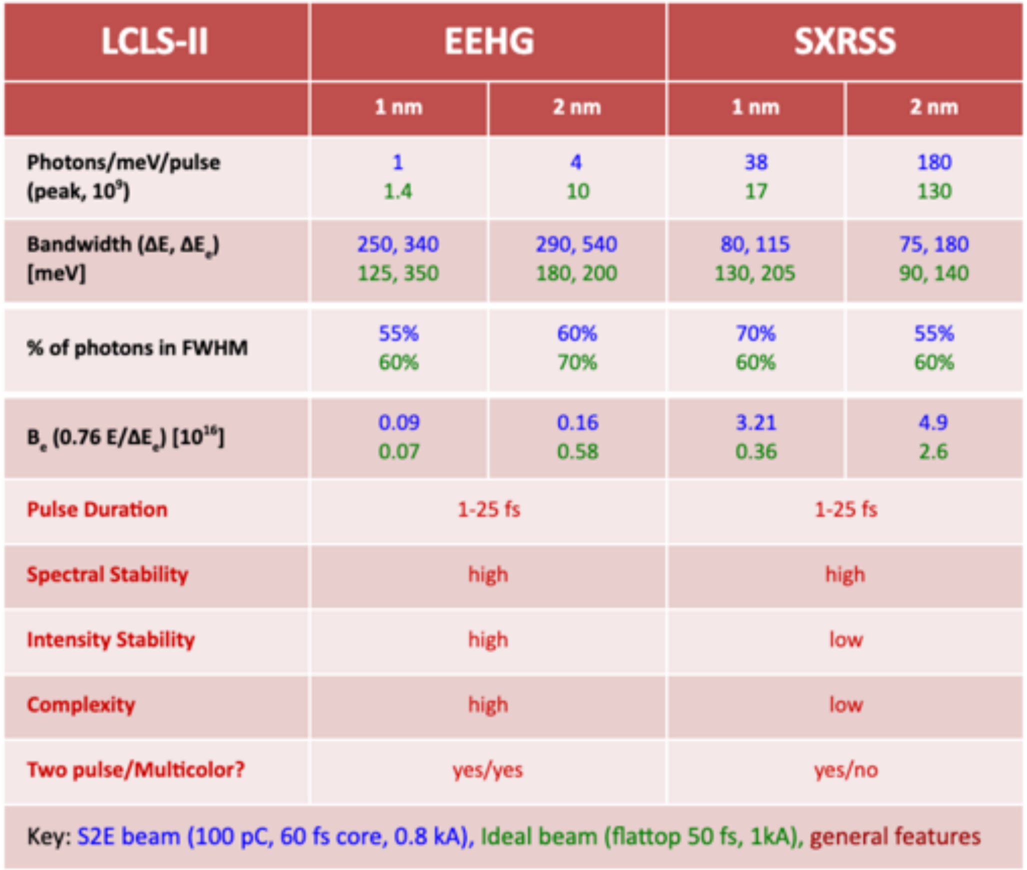
- EEHG and SXRSS are **promising** and **complementary**, but challenging for high brightness SXRs.
- **Flat and linear phase space** distributions best
  - Passive shaping and MBI control with laser heater
- RWW limits the maximum FTL pulse to ~25 fs (70 meV)

SXRSS

- 5-35 times higher spectral brightness
- Simplicity

EEHG

- Intensity stable
- multipulse and multicolor



LCLS-II	EEHG		SXRSS	
	1 nm	2 nm	1 nm	2 nm
Photons/meV/pulse (peak, 10^9)	1 1.4	4 10	38 17	180 130
Bandwidth (ΔE, ΔE_e) [meV]	250, 340 125, 350	290, 540 180, 200	80, 115 130, 205	75, 180 90, 140
% of photons in FWHM	55% 60%	60% 70%	70% 60%	55% 60%
B_e ($0.76\ E/\Delta E_e$) [10^{16}]	0.09 0.07	0.16 0.58	3.21 0.36	4.9 2.6
Pulse Duration	1-25 fs		1-25 fs	
Spectral Stability	high		high	
Intensity Stability	high		low	
Complexity	high		low	
Two pulse/Multicolor?	yes/yes		yes/no	

Key: S2E beam (100 pC, 60 fs core, 0.8 kA), Ideal beam (flattop 50 fs, 1kA), general features

Thanks to R. Coffee, G. Dakovski, W. M. Fawley, Y. Feng, J. Hastings, Z. Huang, G. Marcus, G. Penn, D. Ratner, T. Raubenheimer, R. W. Schoenlein, and Z. Zhang

Thanks for your attention!