FEL Seeding
Requirements and Development at LCLS

5-Way Collaboration Meeting

Pohang

Oct 2016

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Motivation - Soft X-ray FEL (external) Seeding

Control of Longitudinal Coherence - Spectral Amplitude (and phase)

- X-ray spectroscopy (resonant scattering) probe of excited-state dynamics
  Control time resolution & bandwidth – tailored to science requirements
  10 fs_{FWHM} ⇔ 180 meV_{FWHM} (60 fs ⇔ 30 meV)
- Ultrafast Spectroscopy ⇒ sub-femtosecond pulses, large coherent BW
- High Resolution Spectroscopy (XANES, XES, RIXS, XPS…..)
  ΔE <<100 meV (>>10,000 res. power at 1 keV)
- Nonlinear X-ray Science – (X-ray pump/probe, wave-mixing, etc.)
- Range of interest: **C** (284 eV), **N** (410 eV), **O** (543 eV), transition-metal L-edges (Cu 933 eV)

Potential Practical Benefits

- High average spectral flux (ph/s/meV)
- Timing synchronization (seed laser vs. linac/FEL contribution to time jitter)
- Spectral stability, amplitude stability, tunability

What is the projected performance (BW, stability, pedestal, mono effects etc.)?
Can some of these objectives be met through other approaches (eSASE, iSASE, self-seeding etc.)?

Objectives

What are the most promising external seeding schemes to reach 1 nm (2 nm)?

- What are the key requirements on the laser?
- What are the key requirements on the e-beam?

What are the seeding limitations imposed by SCRF e-beam (ΔE, μBI etc.)?

- Achievable narrow BW (resolving power)
- Achievable short pulse duration
- Pedestal (e.g. as % of pulse energy)
- Implications for external seeding schemes at 1 nm (2 nm) (sensitivity of particular schemes)
- Implications for self-seeding at 1 nm (2 nm)

What specific R&D steps are needed to better understand these limitations?

- Simulations
- Experiments
- Development of new/better models

External Seeding Task Force

Erik Hemsing (Lead) , Gregg Penn (LBL), Daniel Ratner, Zhirong Huang, Tor Raubenheimer, Bob Schoenlein, Jerry Hastings, Gabe Marcus, Georgi Dakovski, Ryan Coffee

Identify all seeding schemes for LCLS-II SXR, evaluate science impact and technical status

Simulations at 1-2 nm, experiments at FERMI 4-6 nm, validate & modify codes as needed

Evaluate schemes based on:

- Scientific Impact, Technical Feasibility, R&D Requirements, Risk etc.

Down select external seeding scheme, develop design for LCLS-II, assess development required to reach 1 nm

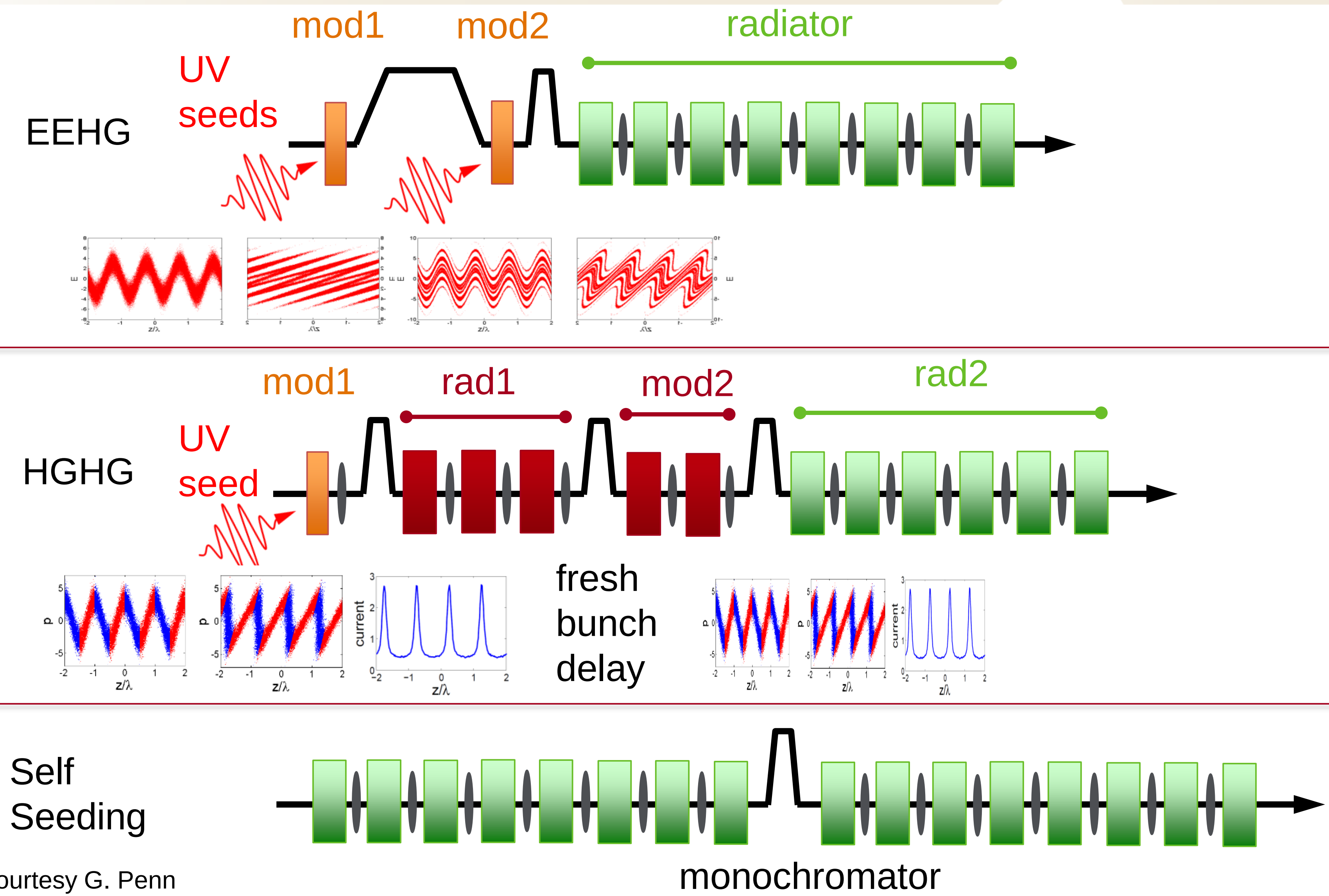
Subcommittees

- FEL & Beam Physics
  - Hemsing, Ratner, Huang, Raubenheimer
  - Study and compare beam/FEL physics issues of different techniques. Challenges/benefits. Beam and infrastructure requirements, beamline layout. Identify & set timetable for critical expts.
- Numerical Simulations and Modeling
  - Marcus, Penn, (+ Bill Fawley, Bryant Garcia)
  - Validate & modify existing/new codes (Puffin, old/new Genesis, Ginger etc). Track LCLS-II design changes w/ best IMPACT results. Modeling and benchmarking with self-seeding and FERMI. Complex beam/optics x-port/x-forms.
- Laser Physics and Science Drivers
  - Coffee, Dakovski, Schoenlein, Hastings
  - Identify and target key scientific opportunities, new applications/techniques. Laser system and controls demands/development. Identify physical space, hardware and infrastructure. Identify & set timetable for critical expts.

Leading Seeding Techniques

- Direct Seeding - High Harmonic Generation (HHG) – [State Of The Art: 38 nm]
  - FEL amplification of low power EM input, usu. harmonic of 800nm generated in noble gas
  - **Proof of principle demonstrated. Path to SXRs unclear.**
  - Limited to >20nm by 10^{-6} conversion efficiency. Seed must exceed shot noise in beam.
- High Gain Harmonic Generation (HGHG) – [4 nm, 65^{th} harm from 260nm]
  - Harmonic density bunching. Limited to <15^{th} harmonic in single stage
  - Cascade multiple stages w/fresh beam to reach soft x-rays. **Demonstrated and in use**
- Echo-Enabled Harmonic Generation (EEHG) – [32 nm, 75^{th} harm from 2.4um]
  - Harmonic density bunching. Small energy modulations required. Reach soft x-rays from UV lasers in single stage. **Proof of principle demonstrated. Tests @ SXRs upcoming.**
  - Highly nonlinear phase space manipulation and preservation challenging.
- Self Seeding (HXRSS & SXRSS)
  - Monochromatized FEL seeds itself. **Demonstrated and in use.**
  - Damage & rep rate limits. Pedestal/wakefields contribute
- **Combinations?** (HGHG+EEHG, Self-Seeding +?, etc)
  - **In development**

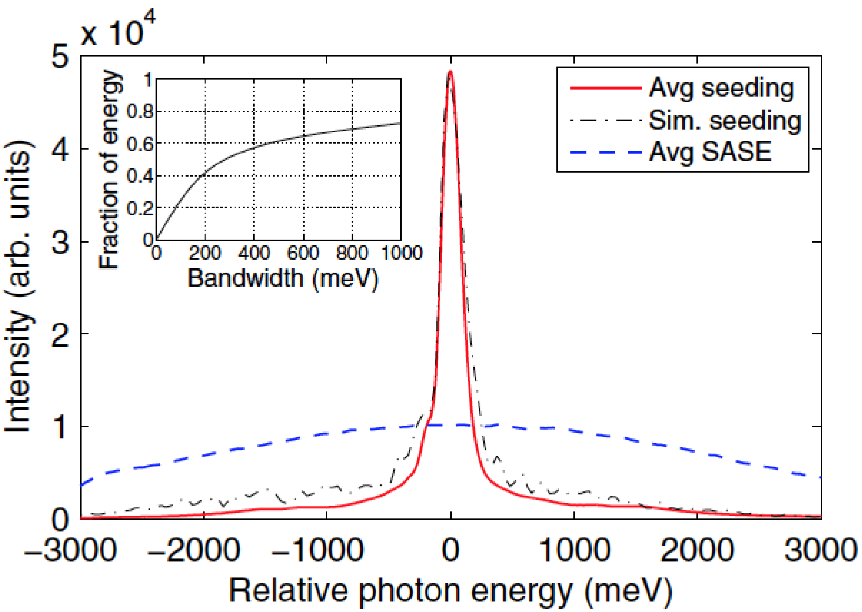
Seeding schemes and layouts

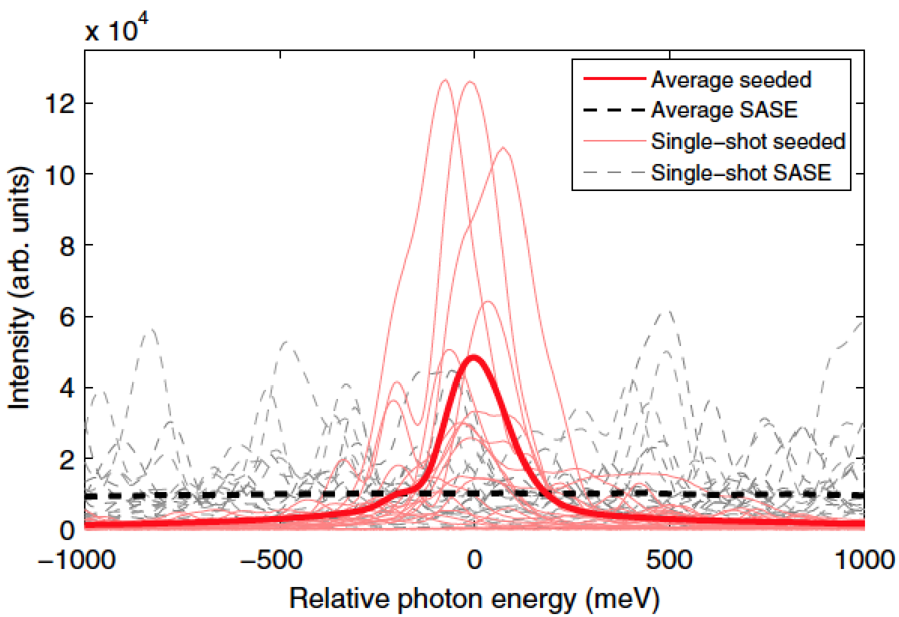


Courtesy G. Penn

LCLS SXRSS

- @ 930 eV, 50 fs, ~ 3x transform-limited
- Energy structure on beam (MBI, wakefields) can reduce spectral brightness
- Challenges moving forward: Intensity stability, high rep rate, resolving power vs x-form limit tunability,…



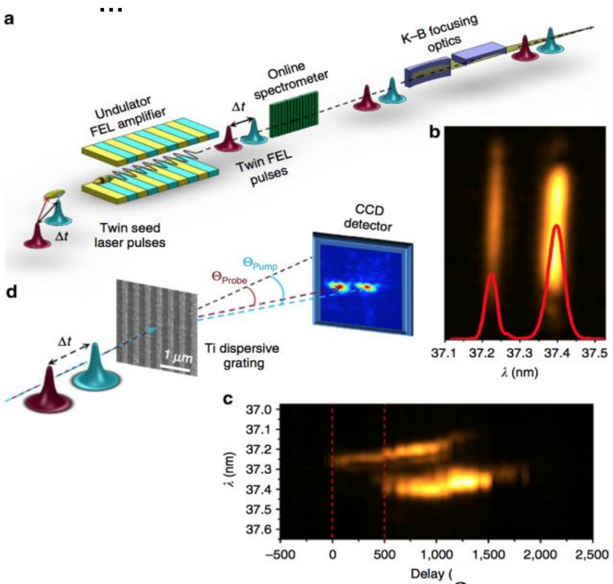


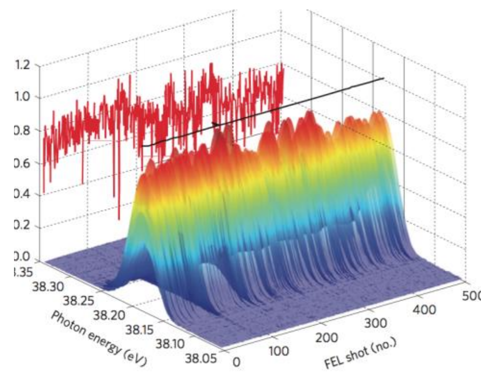
*D. Ratner, et al, *Phys. Rev. Lett.* **114**, 054801 (2015)

Some recent external seeding experiments/operations

HGHG@ FERMI

E. Allaria, et. al., Nature Photonics 6, 699–704 (2012)
E. Allaria, et. al., Nature Photonics 7, 913–918 (2013)
…





EEHG @ SINAP

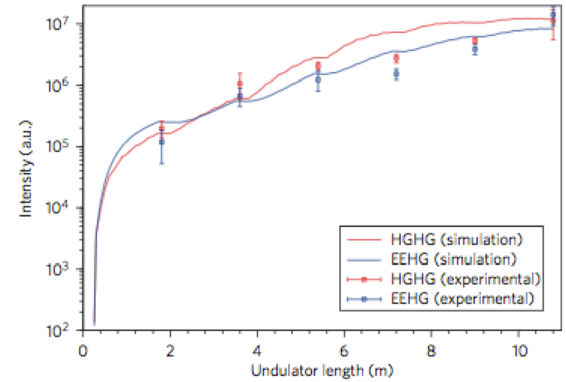
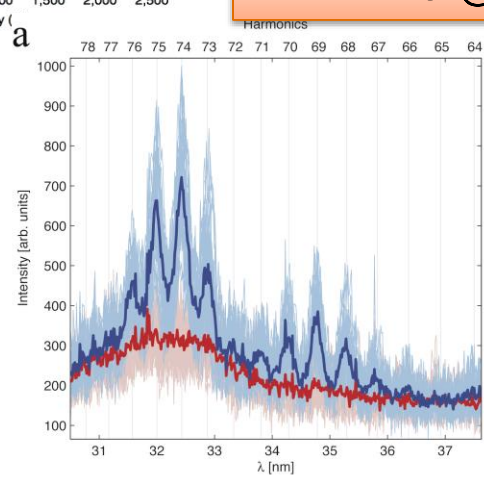
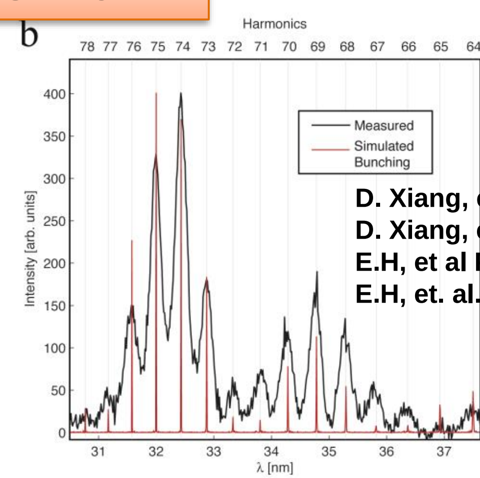


Figure 5 | Gain curves of the EEHG and HGHG FEL at SDUV-FEL. Intensity is measured with a calibrated CCD at the end of the radiator (red open squares, HGHG; blue open squares, EEHG). Error bars correspond to the peak-to-peak intensity statistics of 100 measurements. Simulation results are shown as a red line (HGHG) and a blue line (EEHG).

Z. T. Zhao, et. al., Nature Photonics 6, 360–363 (2012)

EEHG @ SLAC





D. Xiang, et. al., PRL 105, 114801 (2010)
D. Xiang, et. al., PRL 108, 024802 (2012)
E.H, et al PRST-AB 17, 070702 (2014)
E.H, et. al., Nat. Photon. 10, 512–515 (2016)

EEHG stability and control

Echo less sensitive to chirps

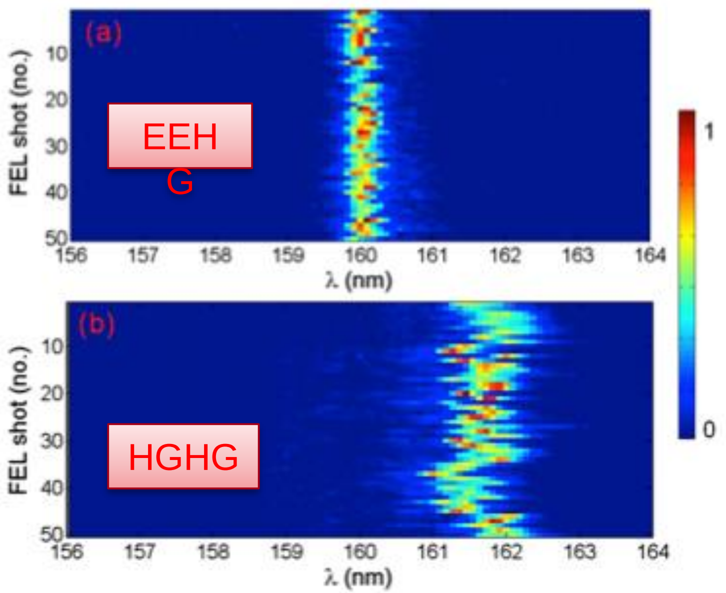
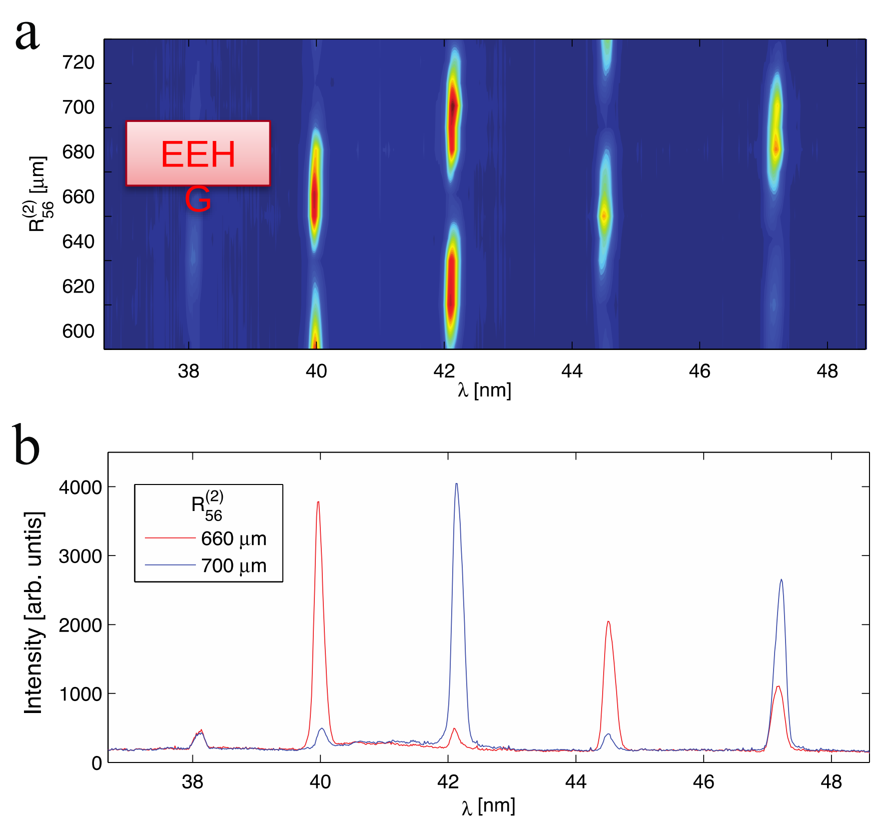


FIG. 7. Fifty consecutive radiation spectra for EEHG (a) and HGHG (b) with a chirped beam. Note, the central wavelength of HGHG signal is shifted by the linear chirp and the bandwidth of the HGHG signal is increased by the nonlinear chirp, while those for EEHG are essentially unaffected.

E. H, et al PRST-AB 17, 070702 (2014)

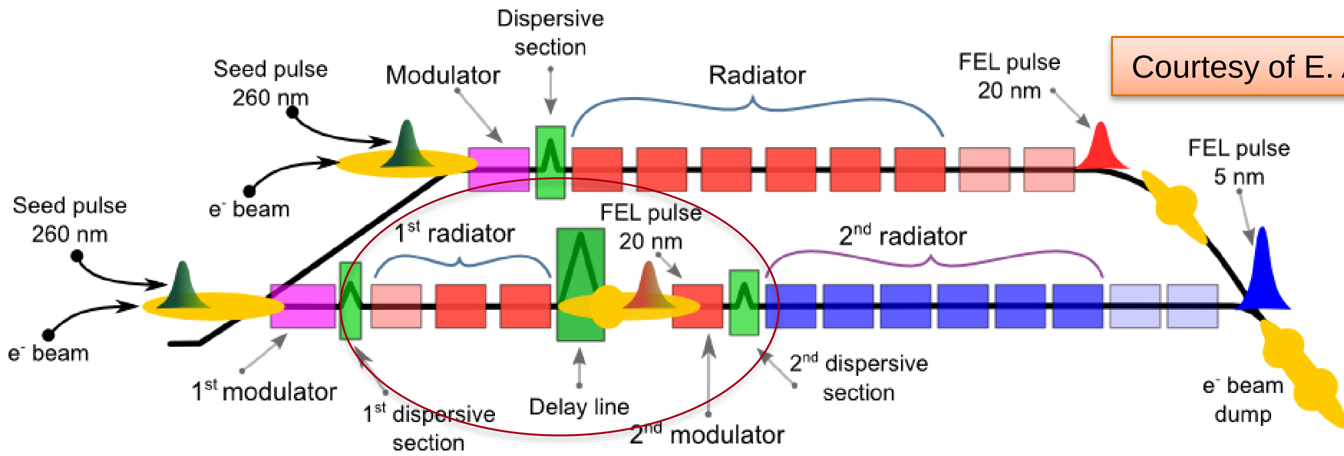
Select/suppress individual harmonics



E.H, et. al., Nature Photonics 10, 512–515 (2016)

Upcoming Experiments: Echo @ FERMI (2018)

SLAC



- Offers one-to-one comparison with cascaded HGHG at 4-6 nm
- Superior performance could mean permanent shift to EEHG

- A proper **seed injection** system needs to be designed.
- Present **delay-line** has a “*moderate*” R56 (~1 mm) and the vacuum chamber already has ports to accommodate the laser injection.
- A **new undulator** in required for the second modulator.
- More careful **studies** need to be done for considering implication of the FERMI layout:
  - Distance between mod1 and mod2;
  - Maximum available R56;
- Undulators from the **1st stage radiator** of FEL-2 can be **moved to FEL-1** extending FEL-1 capabilities.

EEHG vs HGHG?

SLAC

- Cascaded HGHG demonstrated and in use at FERMI using fresh bunch
  - Excellent control demonstrated in single stage – harder in two stage
  - ~40 fs maximum pulse duration @4nm
- EEHG is **single stage**. Pulse lengths up to full e-beam
- FEL **temporal properties** are **determined** by the second **seed pulse**.
- EEHG is **less sensitive** to **energy spread**.
- **Effects** of **phase space distortion** on the FEL spectral properties are significantly **reduced**.
- Potentially EEHG can generate **bunching** at very **high harmonics** (~100).

- All these possibilities have been **demonstrated** with recent experiments at SLAC and SINAP **but** only **at long wavelength**.
- An **experiment** at the **few nm** wavelength is **necessary** before adopting this solution for a user facility.

- Courtesy E. Allaria

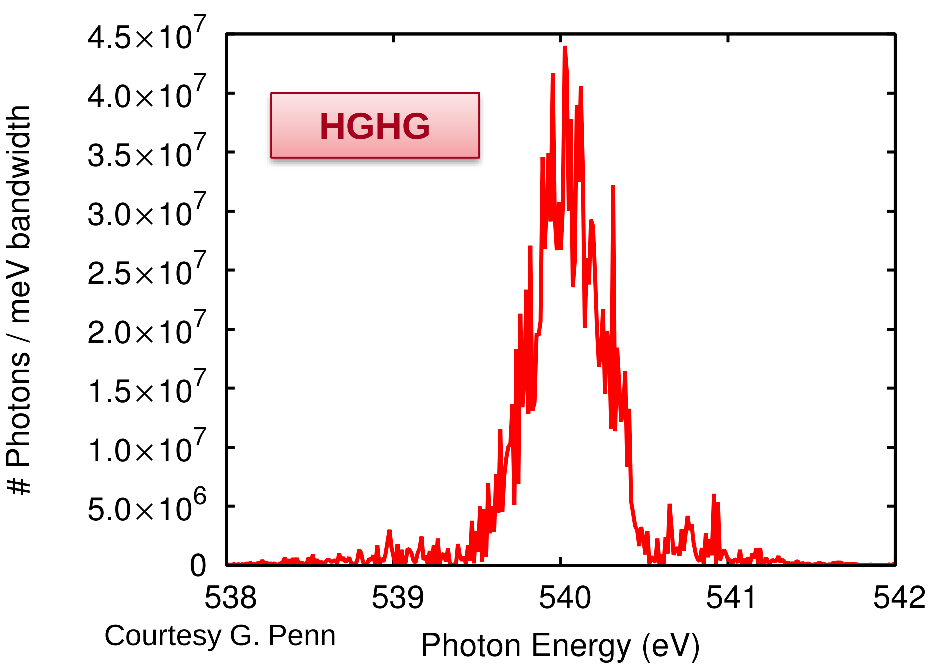
LCLS-II Simulations

2-stage HGHG

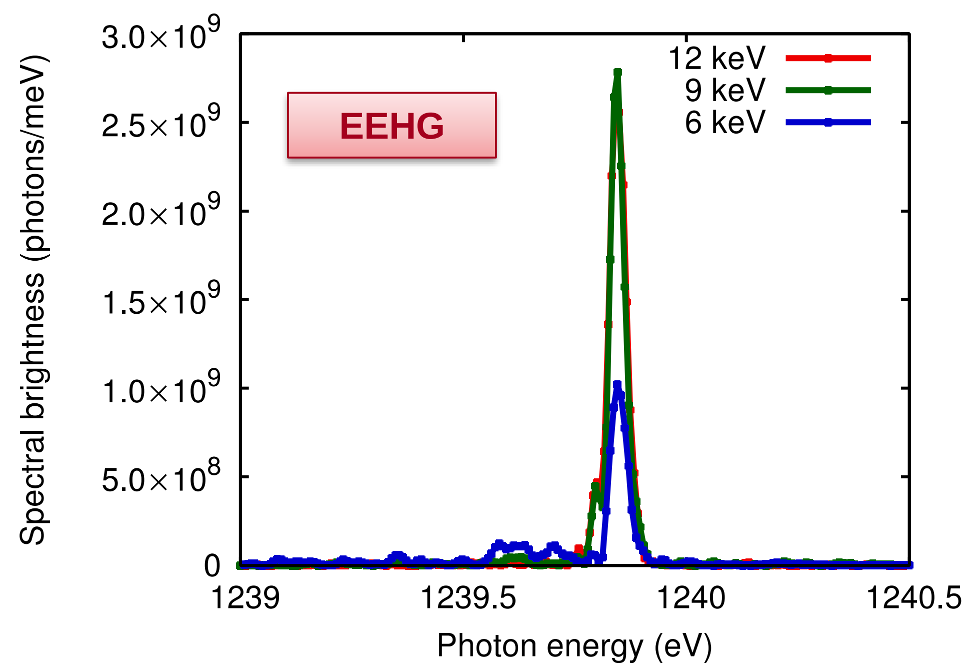
- only for short pulses?
- good results down to ~4 nm @ FERMI
- LCLS-II simulations look good at 540 eV
- 1 keV is challenging, **definitely incoherent**

EEHG

- good output power, control over pulse length
- somewhat sensitive to microbunching and wakefields
- 1keV seems to work: 20-40 meV FWHM, 1.5-2 × transform limit

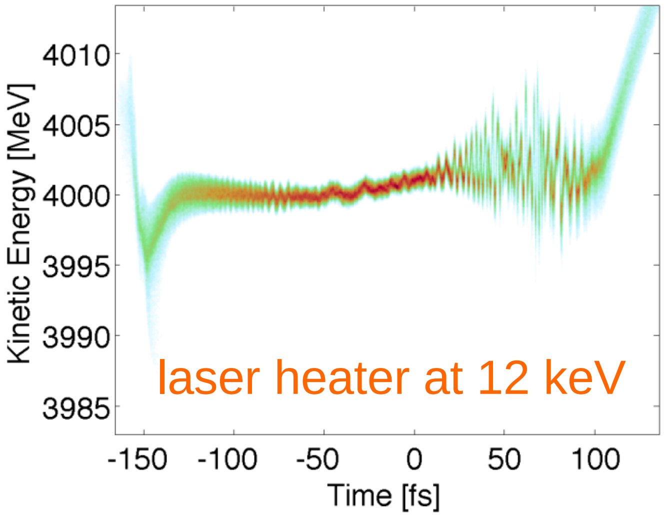


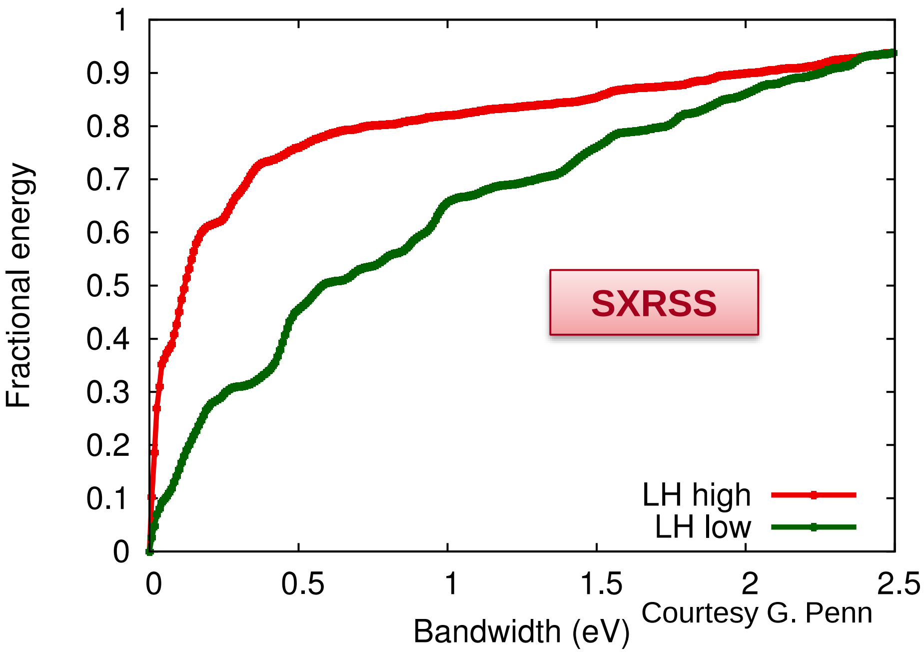
Courtesy G. Penn



Sensitivity of seeding schemes to microbunching

- Continue to track LCLS-II design changes, best IMPACT results
- Vary laser heater to select different microbunching levels
- Different photon energies
- Look at self-seeding, EEHG, HGHG





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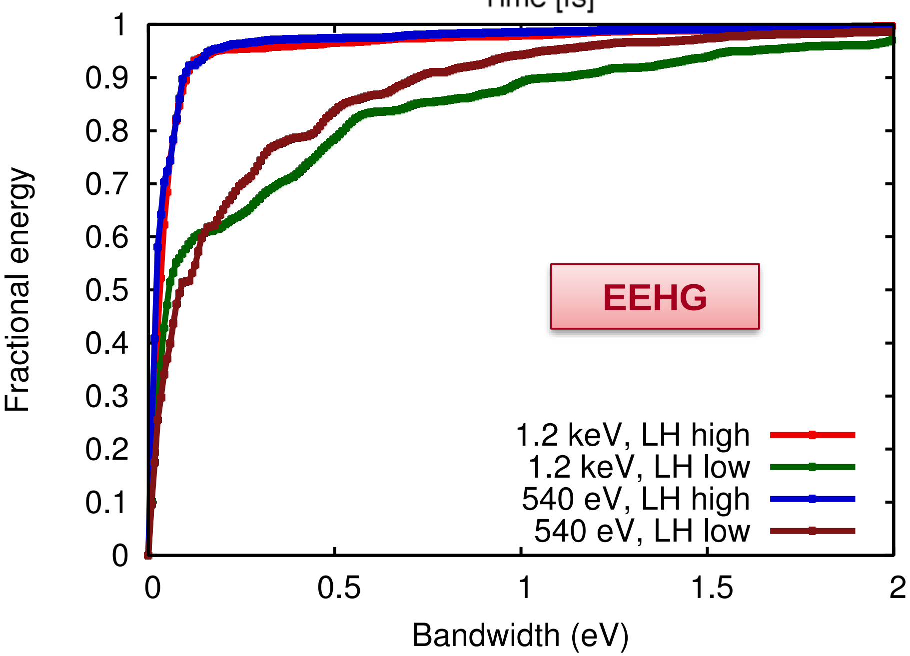
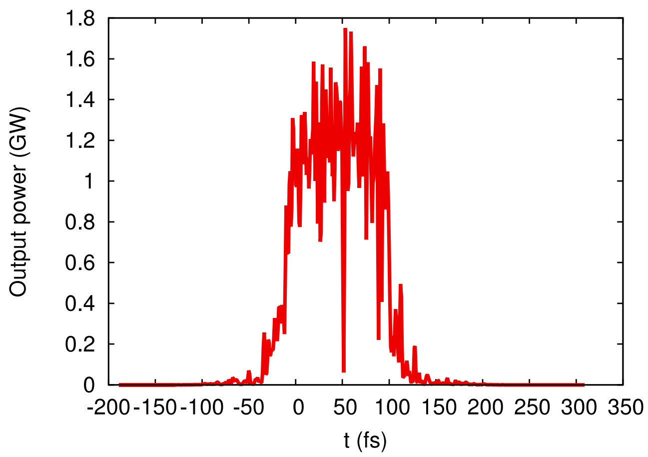


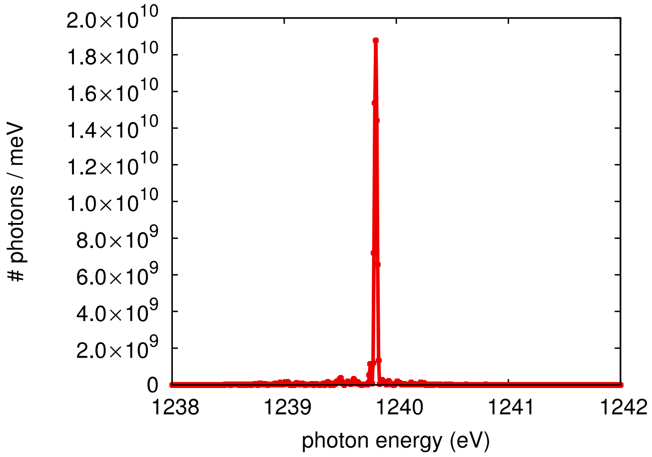
Sensitivity of seeding to laser phase errors

Ex (G. Penn): 400 fs FWHM seed lasers using an idealized e-beam

- 140 uJ after 70 m

minimal impact for 10^{-9} rad um^2 quadratic phase errors





- Dedicated analytic/simulation studies: effects, control, scaling
- Coordinate with efforts at LCLS x-ray characterization and timing sync (Coffee)

Summary

- Seeded FEL R&D highly active and rapidly advancing
- Offers distinct opportunities to address science cases for tunability/stability in SXRs, particularly for high rep rate
- SLAC leading the way in EEHG R&D
- Collaborations between SLAC and international institutions for preliminary experiments (FERMI, SINAP) and collaboration (U. Strathclyde, Daresbury, Shanghai Jiao Tong U., etc…)
- Develop optimal approach that also leaves the greatest flexibility **-- *we won't really know all the answers until we do experiments and try to implement. Design a system that has sufficient flexibility to modify and to integrate with other modes of operation***

Outlook and timeline