Beams by Design and FEL Seeding

Erik Hemsing

SLAC National Accelerator Laboratory

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

The Need To Seed

Soft X-ray Science Drivers

Range of interest: C (284 eV), N (410 eV), O (543 eV), transition-metal L-edges (Cu 933 eV)

- X-ray spectroscopy (resonant scattering) probe of excited-state dynamics with tunable transform limited pulses
- 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.)

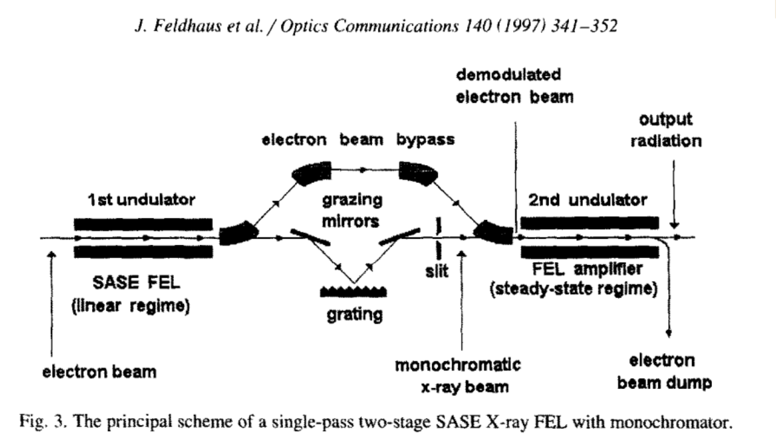
Potential Features

- Narrow line-widths near transform limit (high temporal coherence)
  - Tunable transform-limited time/bw trade off (10-60 fs, 180-30 meV)
- High spectral density (ph/meV) with good background contrast (minimal pedestal)
- Spectral & amplitude stability
  - Central frequency control
  - Customizable pulse shaping
- Multicolor operations
- Higher order transverse modes with new photon degrees of freedom

Leading Seeding Techniques

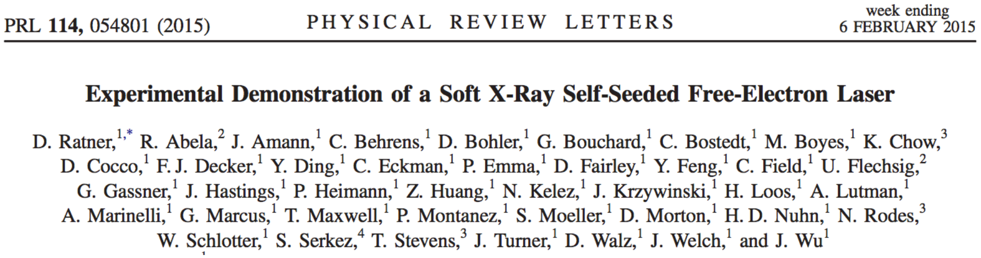
- Direct Seeding - High Harmonic Generation (HHG) – [State Of The Art: 38 nm]
  - FEL amplification of low power EM input, usu. harmonic of 800nm generated in noble gas
  - Limited to >20nm by 10^{-6} conversion efficiency. Seed must exceed shot noise in beam (>100kW).
- High Gain Harmonic Generation (HGHG) – [4 nm, 65th harm from 260nm]
  - Harmonic density bunching. Limited to <15th 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, 75th harm from 2.4um]
  - Harmonic density bunching. Small energy modulations required. Reach soft x-rays from UV lasers in single stage? **Experiments 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 (SXRs).
- **Combinations?** (HGHG+EEHG, Self-Seeding +?, etc)

Soft x-ray self seeding (SXRSS)



J. Feldhaus et al. / Optics Communications 140 (1997) 341–352

Fig. 3. The principal scheme of a single-pass two-stage SASE X-ray FEL with monochromator.

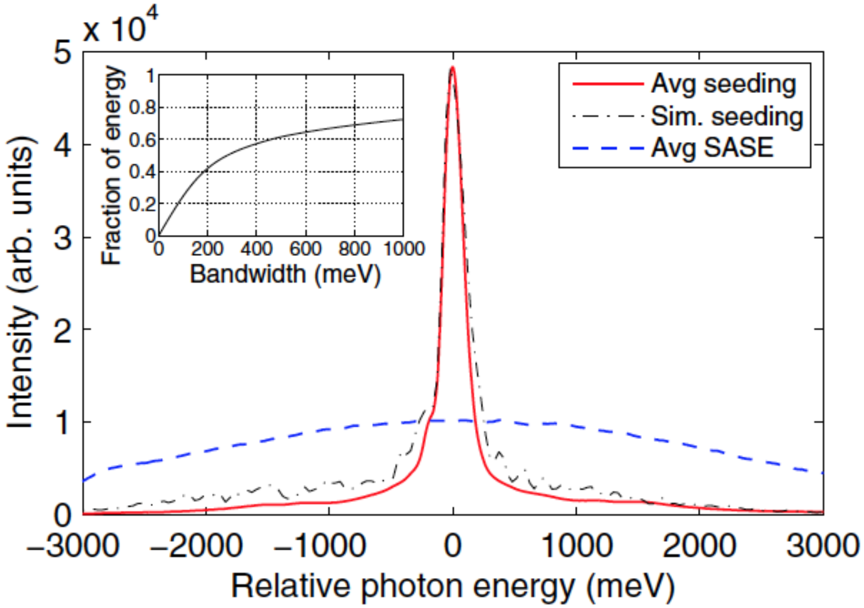


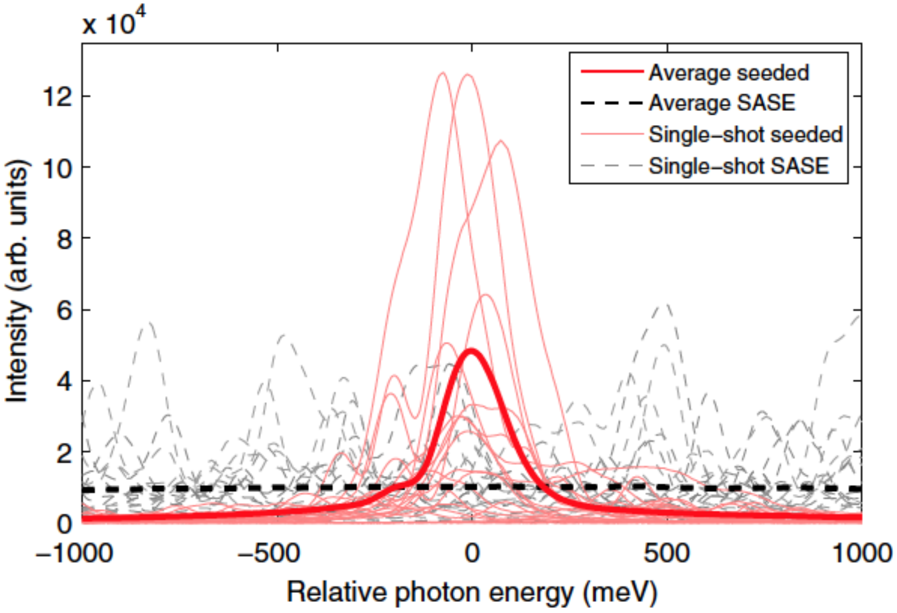
PRL 114, 054801 (2015) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2015

Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser

D. Ratner,[1,*] R. Abela,[2] J. Amann,[1] C. Behrens,[1] D. Bohler,[1] G. Bouchard,[1] C. Bostedt,[1] M. Boyes,[1] K. Chow,[3] D. Cocco,[1] F. J. Decker,[1] Y. Ding,[1] C. Eckman,[1] P. Emma,[1] D. Fairley,[1] Y. Feng,[1] C. Field,[1] U. Flechsig,[2] G. Gassner,[1] J. Hastings,[1] P. Heimann,[1] Z. Huang,[1] N. Kelez,[1] J. Krzywinski,[1] H. Loos,[1] A. Lutman,[1] A. Marinelli,[1] G. Marcus,[1] T. Maxwell,[1] P. Montanez,[1] S. Moeller,[1] D. Morton,[1] H. D. Nuhn,[1] N. Rodes,[3] W. Schlotter,[1] S. Serkez,[4] T. Stevens,[3] J. Turner,[1] D. Walz,[1] J. Welch,[1] and J. Wu[1]

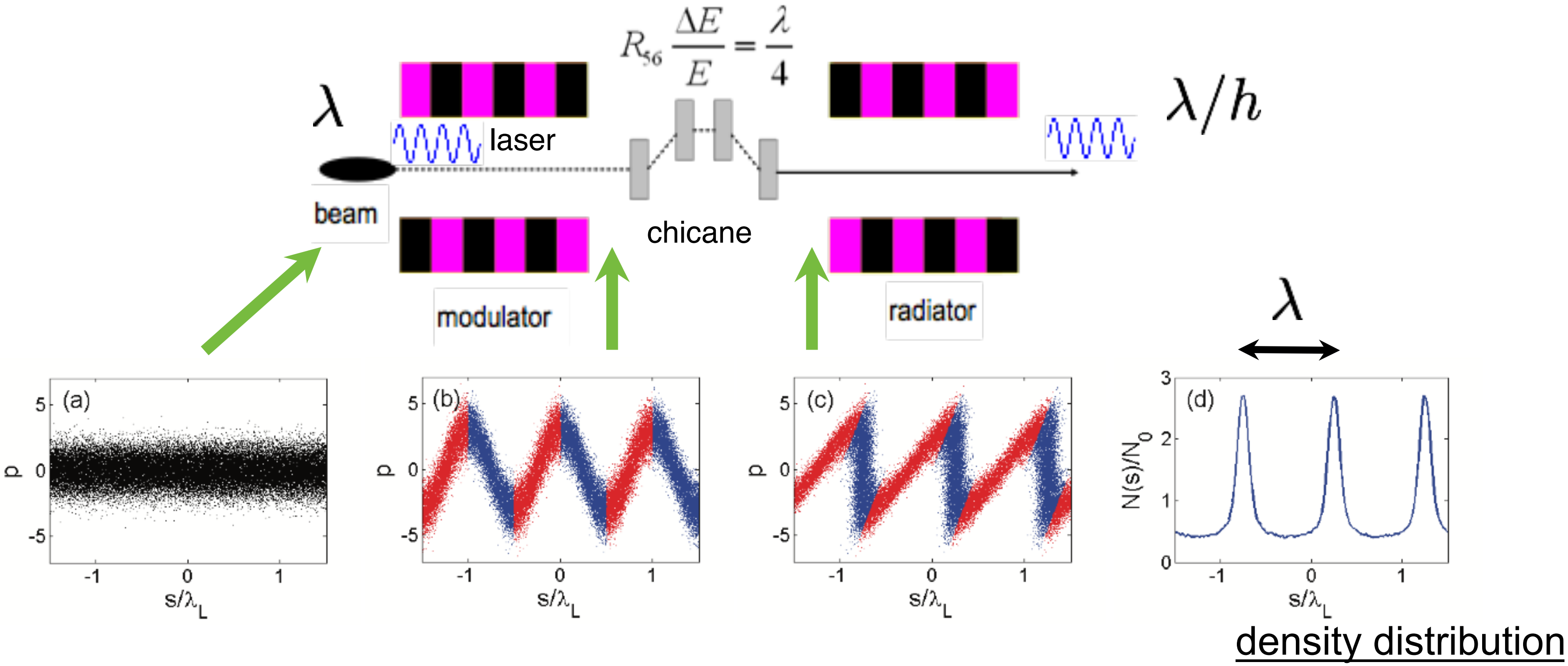
LCLS: 930 eV, 50 fs, ~ x3 transform-limited



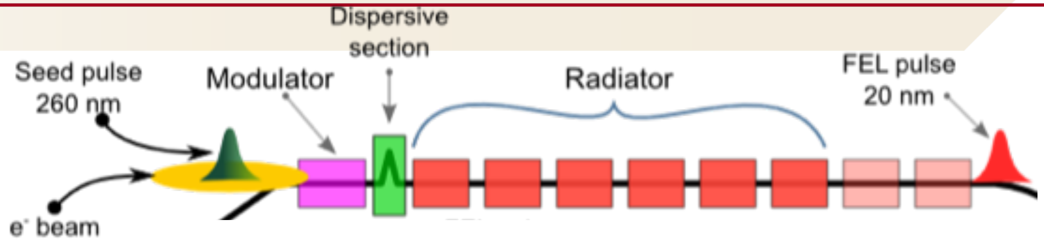


High Gain Harmonic Generation (HGHG)

- Laser generates energy modulation in electron beam phase space
- Energy modulation converted to density modulation in dispersive section (chicane)
- Coherent radiation at wavelength amplified to saturation in FEL

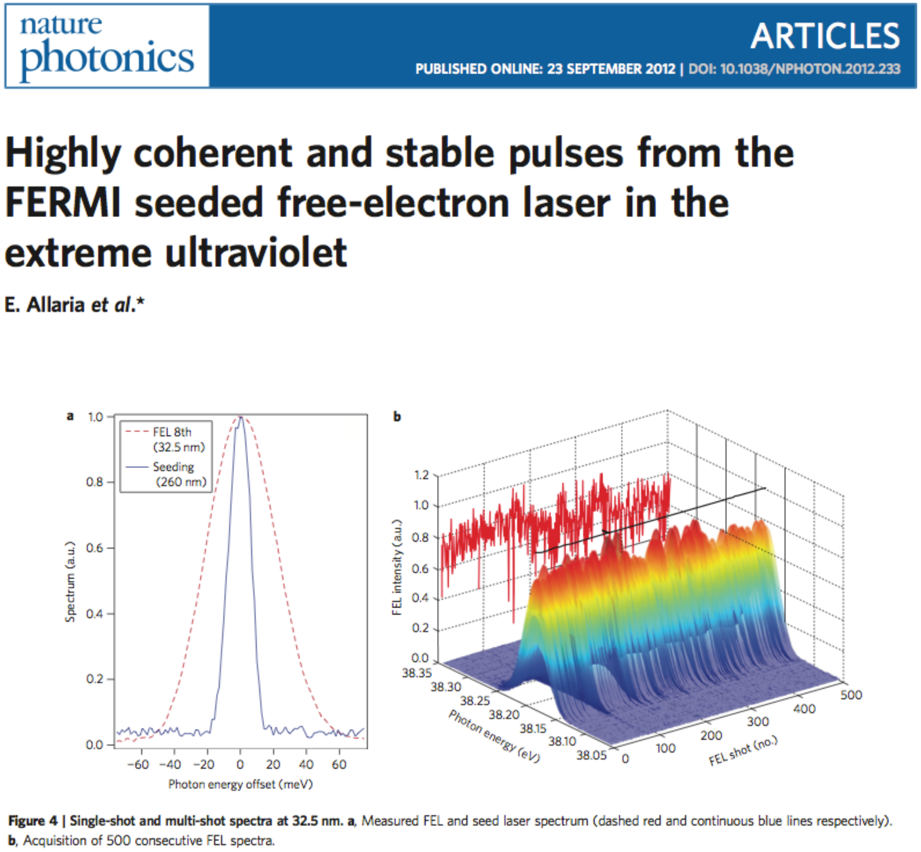


HGHG-based FEL pulse control @ FERMI



HGHG seeding provides significant control over FEL output, eg:

- **stable central wavelength and power**
- **narrow bandwidth**
- **multicolor operations (two harmonics, or two different seeds with different wavelengths)**
- ***phase-locked pulses***
- ***FEL chirp compensation by laser shaping***
- ***chirped pulse amplification, etc.***

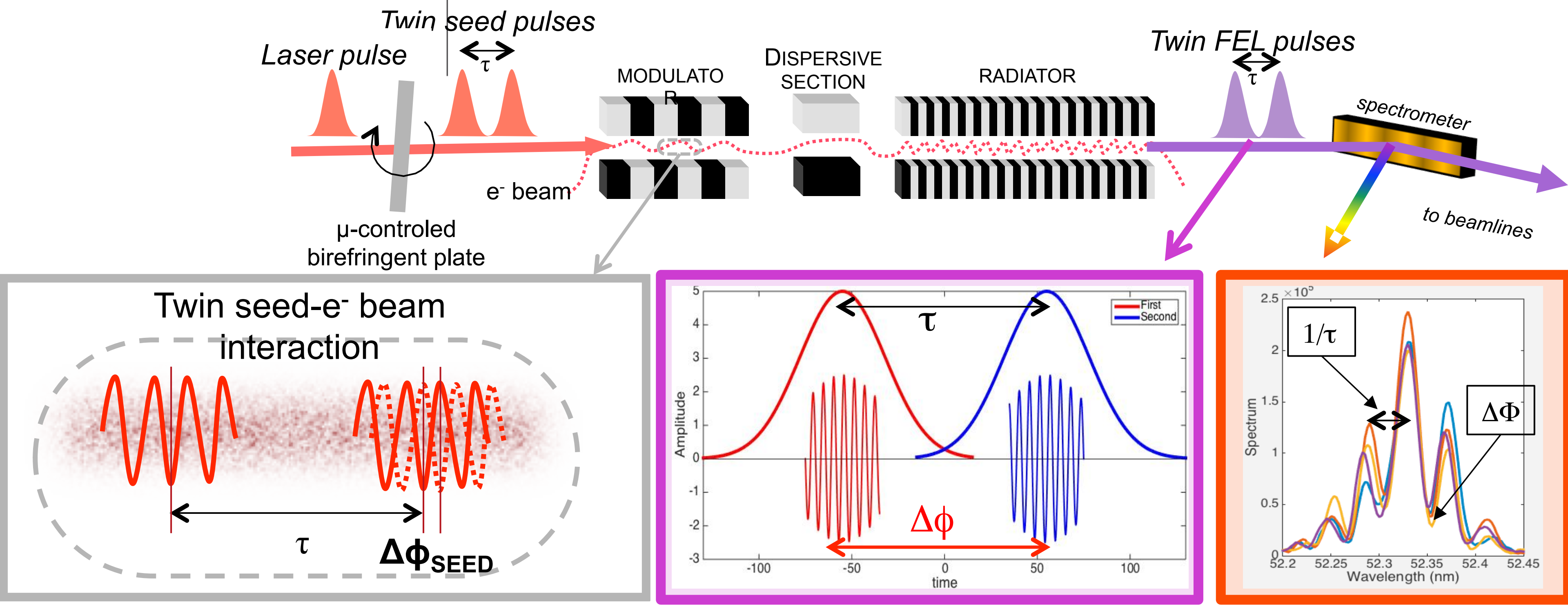

nature photonics ARTICLES
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

E. Allaria *et al.**

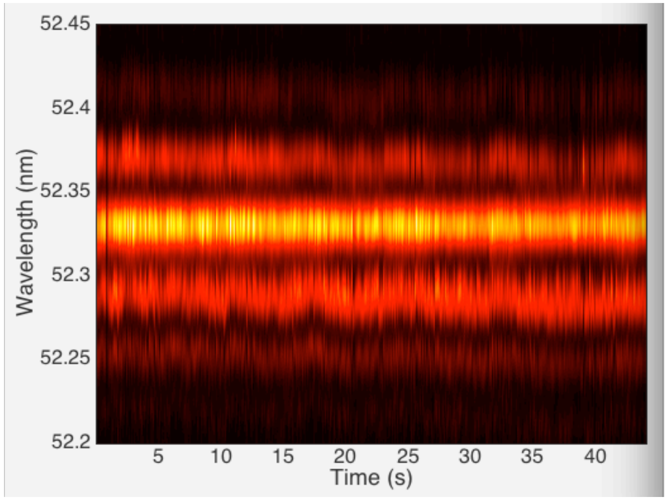
Figure 4 | Single-shot and multi-shot spectra at 32.5 nm. a, Measured FEL and seed laser spectrum (dashed red and continuous blue lines respectively). **b**, Acquisition of 500 consecutive FEL spectra.

Phase-locked FEL pulses



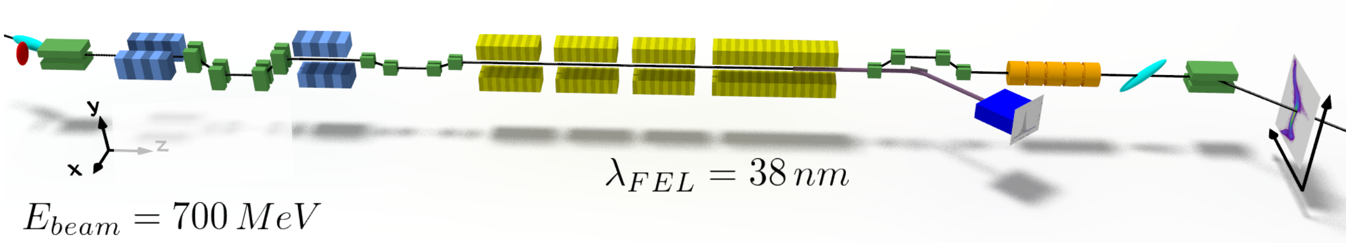
Two seed lasers can control the **relative time** between **two FEL** pulses. A fine tuning allows to **control** the **relative phase** between the two **output FEL pulses**.

Interference between two **coherent** and **phase-locked** pulses is evident in the spectral domain.



Courtesy E. Allaria. From D. Gauthier et al. PRL 116, 2, 024801 (2016)

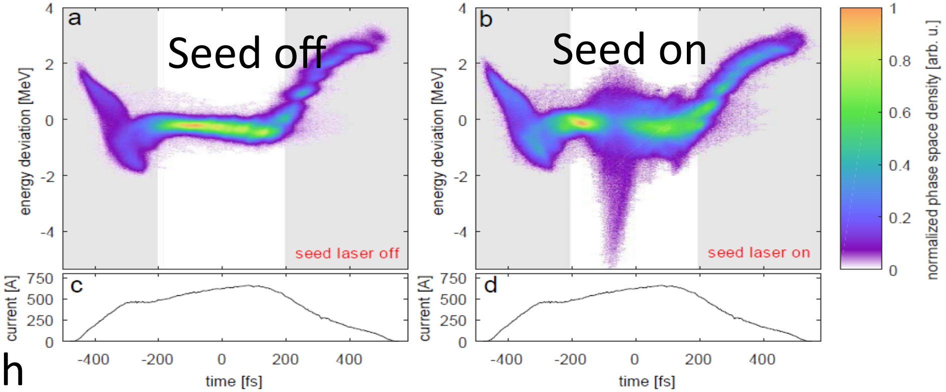
sFLASH – TDS analysis of HGHG seeded FEL



$\lambda_{FEL} = 38\,nm$

$E_{beam} = 700\,MeV$

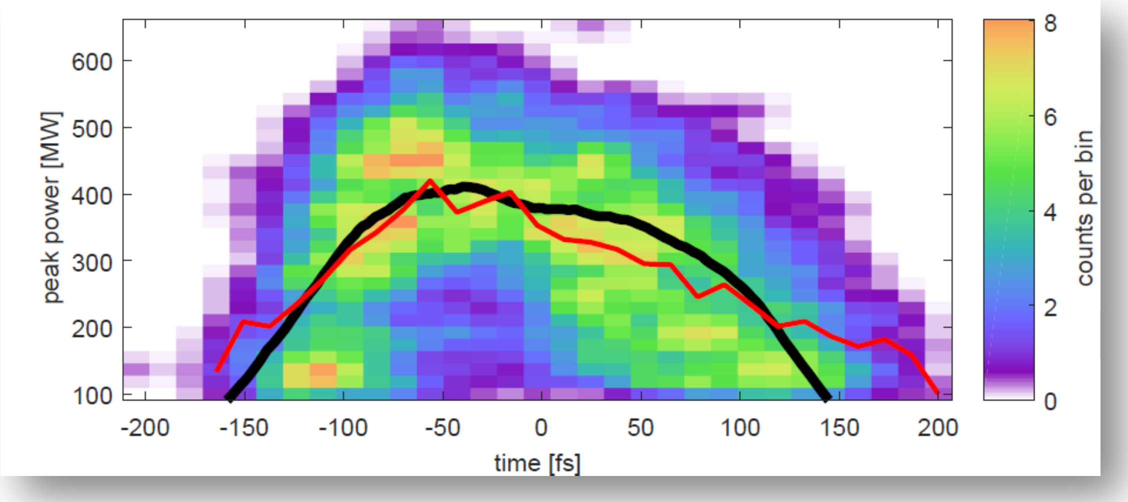
$\lambda_{seed} = 266\,nm$



FEL performance along the e-bunch

Red: experiment

Black: theoretical prediction

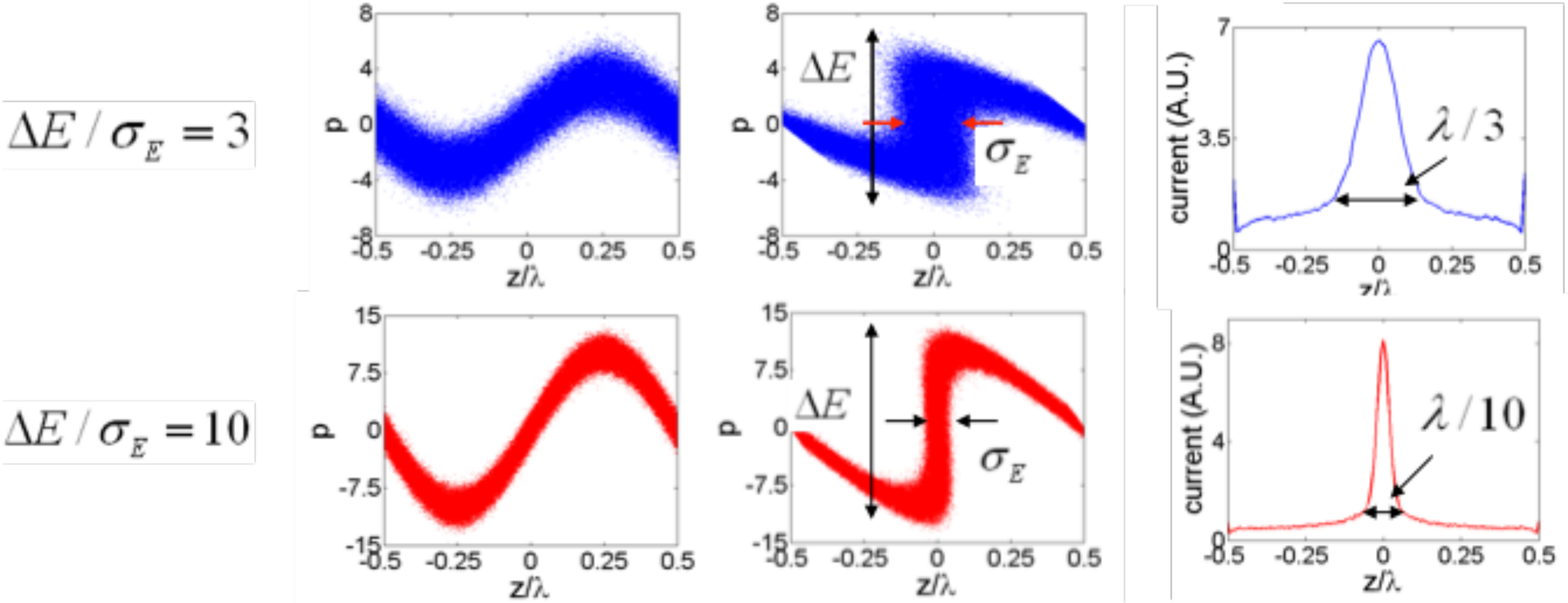


Courtesy J. Boedewadt.

T. Plath et al., accepted at Scientific Reports

Limitations on single stage HGHG

- **Low up-frequency conversion efficiency:** $\Delta E / \sigma_E \approx n$


$\Delta E / \sigma_E = 3$

$\Delta E / \sigma_E = 10$

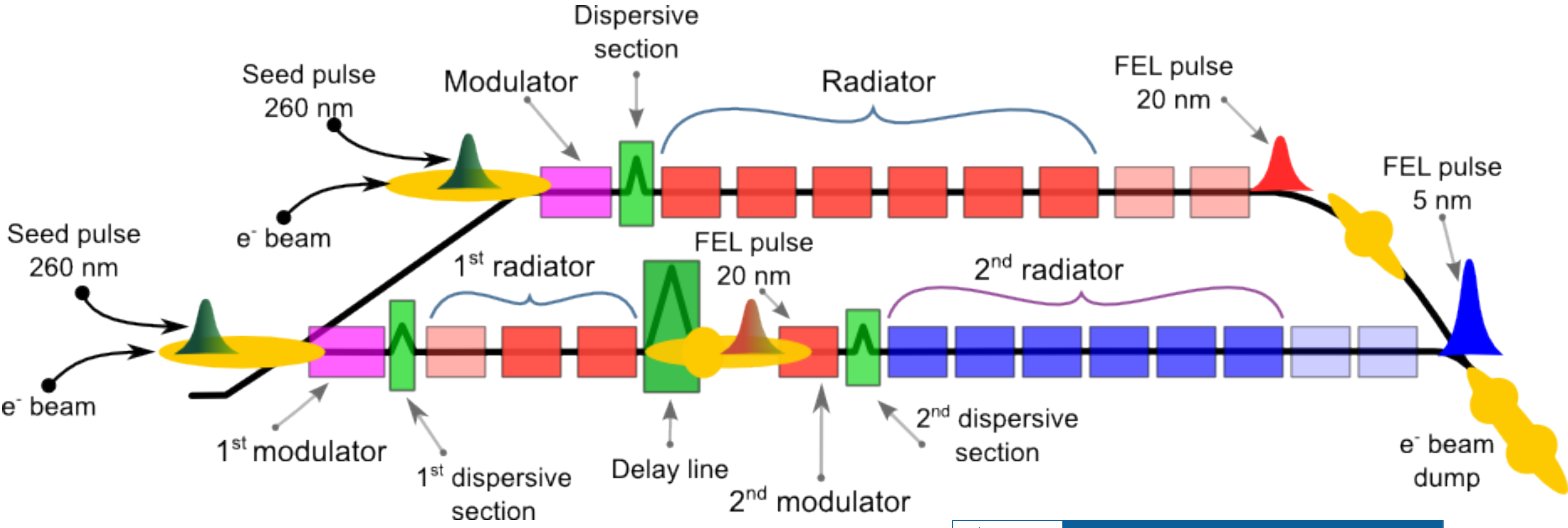
Modulator exit **Chicane exit** **Current distribution**

- **Outcome: Bunching (large ΔE) OR Gain (small ΔE)**
- **But seeded FEL wants: Bunching AND Gain**

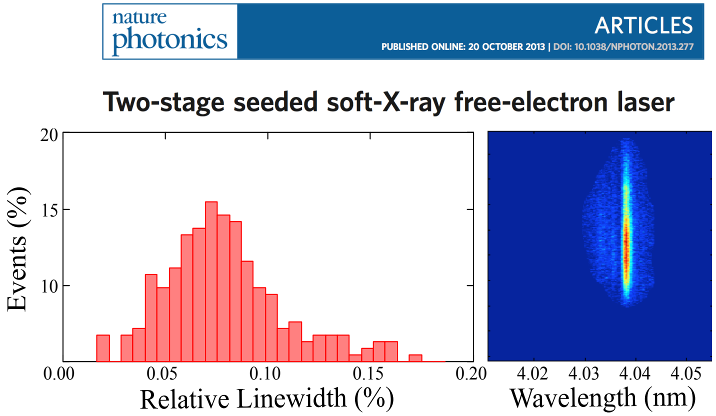
(Slide courtesy D. Xiang)

FERMI FELs: FEL-1 & FEL-2

FEL-1, based on a **single** stage **high gain harmonic generation** scheme seeded by a **UV laser**, covers the spectral range from **100 nm** down to **20 nm**.



FEL-2, in order to be able to reach the wavelength range from **20 nm** to **~4 nm** starting from a **seed laser** in the **UV**, is based on a **double cascade** of harmonic generation.


nature photonics

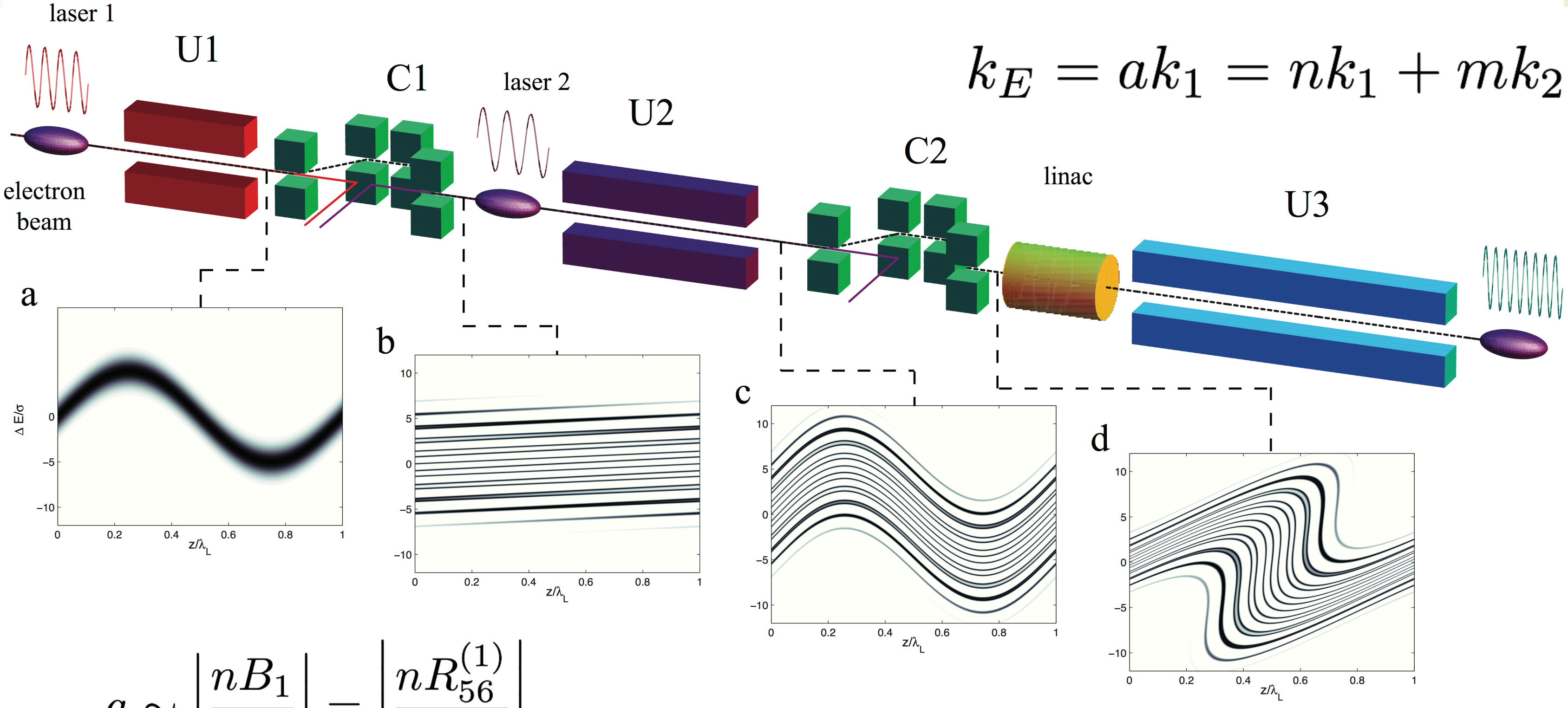
ARTICLES

PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.277

Two-stage seeded soft-X-ray free-electron laser

Courtesy E. Allaria.

Echo-Enabled Harmonic Generation (EEHG)



$$k_E = ak_1 = nk_1 + mk_2$$

$$a \sim \left|\frac{nB_1}{B_2}\right| = \left|\frac{nR_{56}^{(1)}}{R_{56}^{(2)}}\right|$$

Advantages

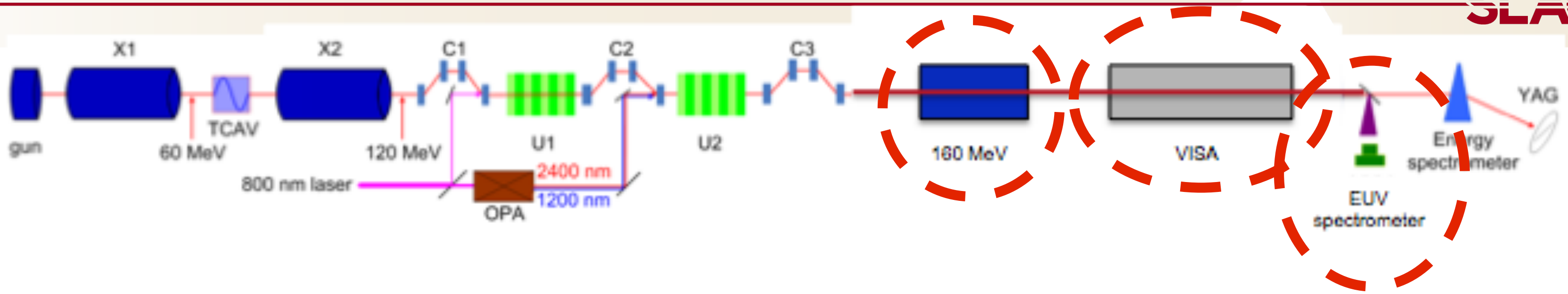
- Only small energy modulation needed
- UV laser converted to soft x-rays in single stage
- Tunable through dispersion
- Relatively insensitive to e-beam phase space distortions

Challenges

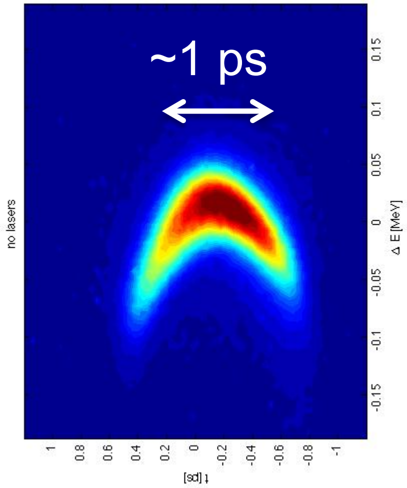
- Preservation of fine phase space correlations
- Sensitive to intrabeam scattering, diffusion, and laser quality

G. Stupakov, PRL 102, 074801 (2009)
D. Xiang and G. Stupakov, 12, 030702 (2009)

EEHG layout at Next Linear Collider Test Accelerator (NLCTA) SLAC



- 120 MeV,~1ps, <50pC typical
- S-Band Gun, 2 X-band linacs
- ~1ps 800nm/2.4um lasers
- Post EEHG linac for 160-192 MeV
- 2m VISA undulator (110 periods K=1.26).
- UV-EUV spectrometers

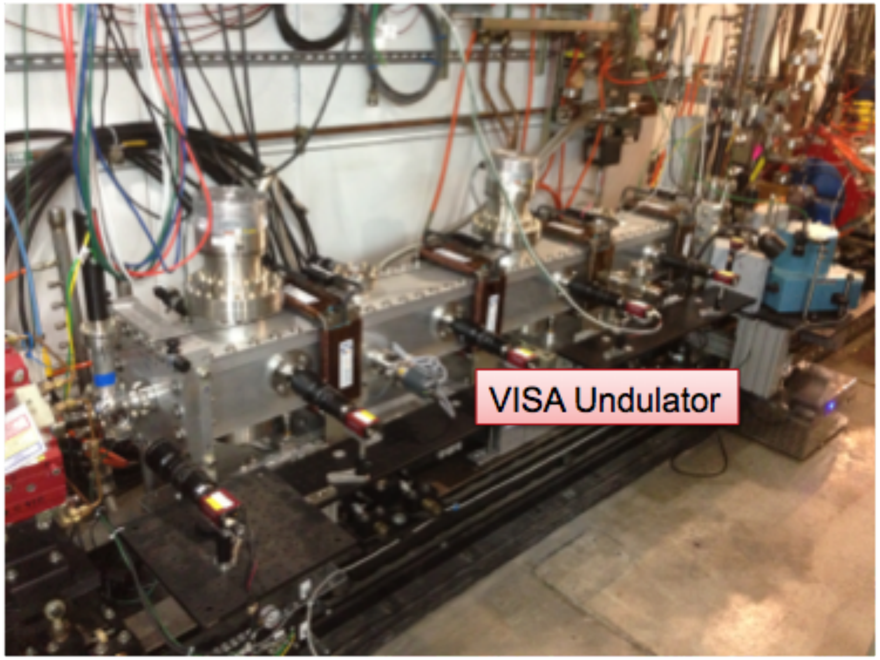


1-2keV slice energy spread

No linearizer

VISA: 117 nm w/190MeV

- 4th und harmonic emission for Echo-75 @ 32nm

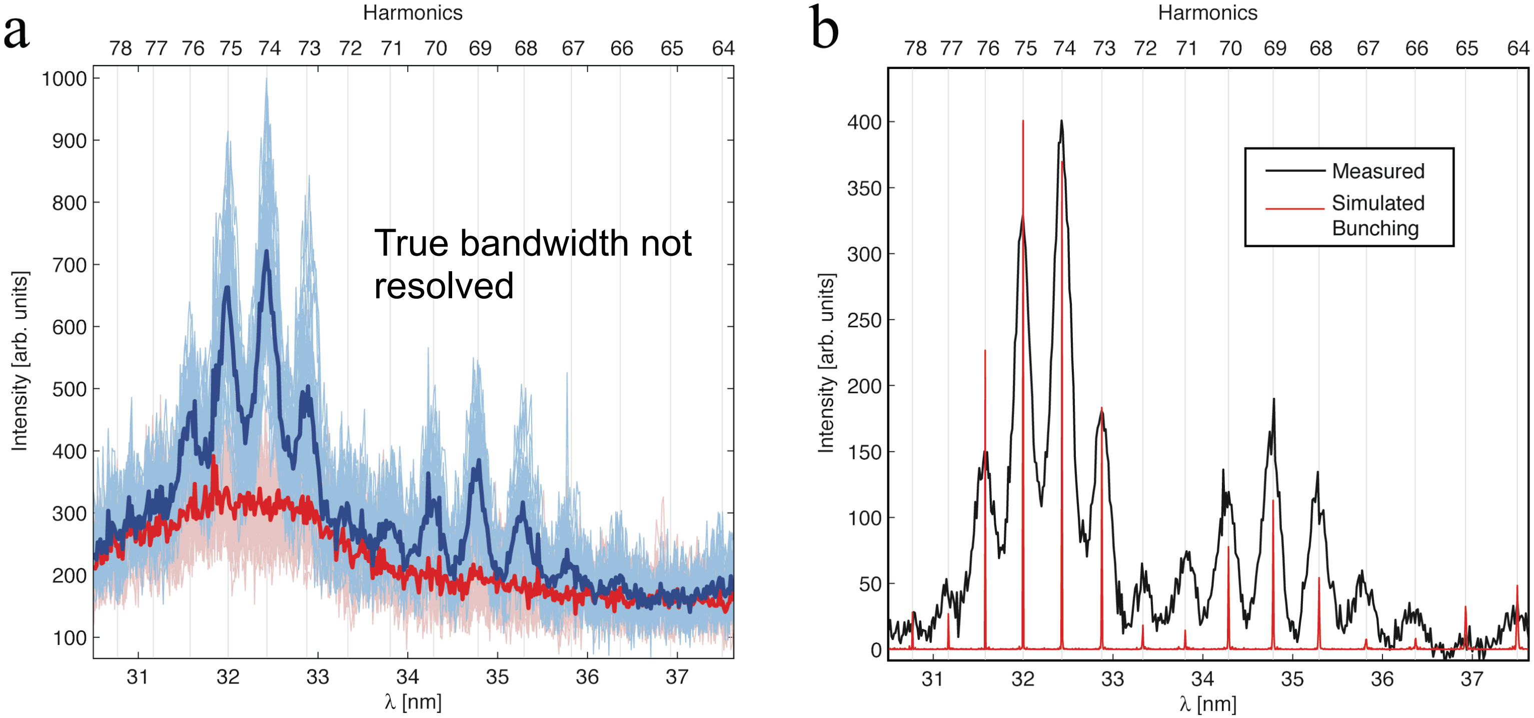


Echo at 75th harmonic

- 2400 nm to 32nm
- 190 MeV
- Results in agreement with theoretical expectations

$$h \simeq \frac{\lambda_2}{\lambda_1}\frac{nR_{56}^{(1)}}{R_{56}^{(2)}}$$

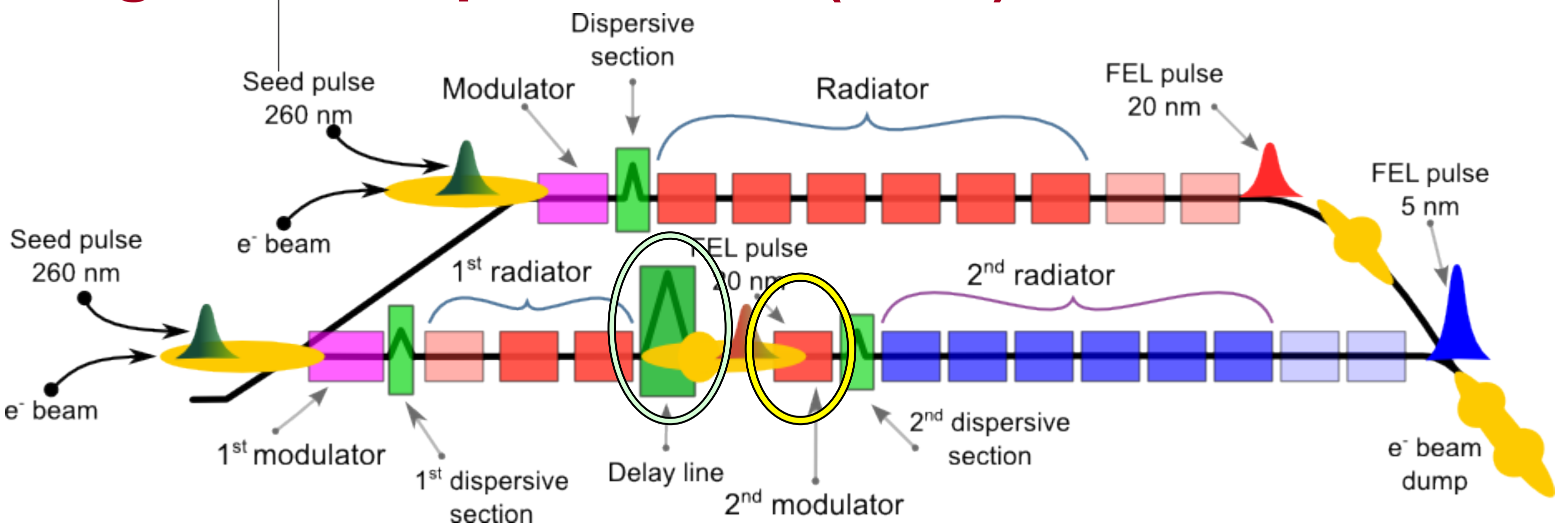
ΔE_1	ΔE_2	$R_{56}^{(1)}$	$R_{56}^{(2)}$
60 keV	100 keV	12.5 mm	484 um



True bandwidth not resolved

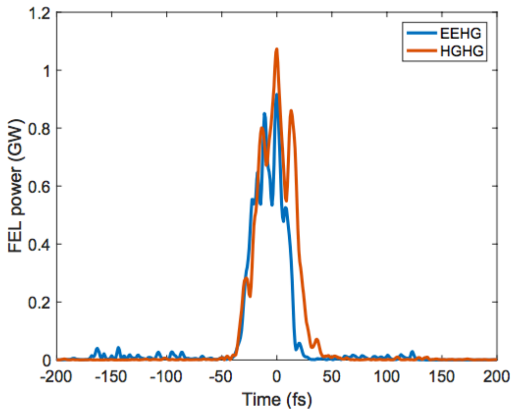
E.H. et al. NATURE PHOTONICS | VOL 10 | AUGUST 2016

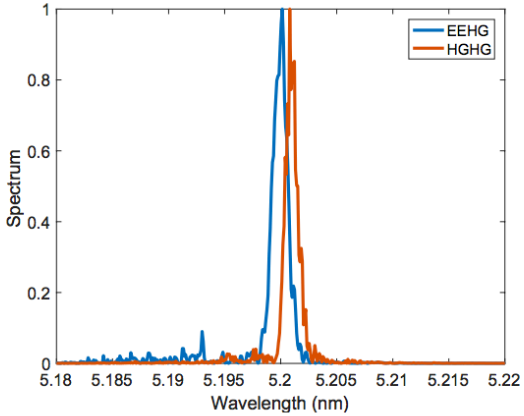
Upcoming EEHG expts: FERMI (2018)



Reconfigure cascaded HGHG (FEL2) line for EEHG to <10nm

- Undulator for 2nd modulator.
- Second seed laser for 2nd modulator.
- Injection chamber for seed and diagnostic.
- Increase dispersion on delay line R56 > 2 mm.





Similar performance expected with EEHG at n=-2. However EEHG provides:

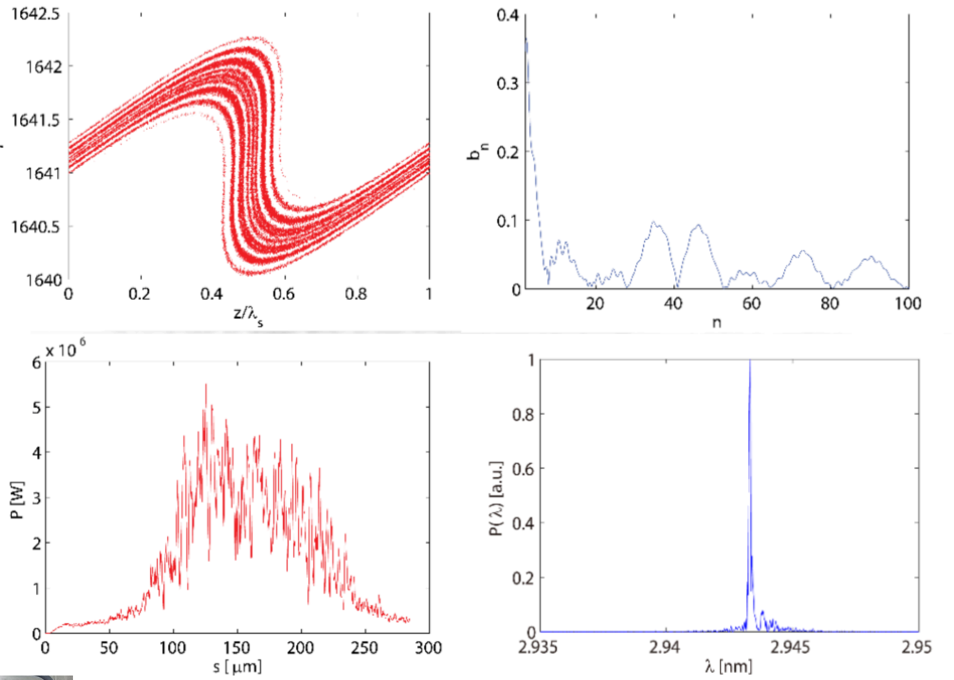
- Reduced sensitivity to energy spread (increased MBI suppression w/laser heater)
- Possibility of double-pulse operation at short wavelengths
- Two colors

Courtesy E. Allaria. See P. R. Ribic et al. Photonics 2017, 4, 19; doi:10.3390/photonics4010019)

Upcoming EEHG expts: SXFEL test facility (2018)

- Test bed for the key technologies of XFEL and principles for seeded FELs
- Originally designed for two-stage cascaded HGHG
- With minor modification, it is well suited for a variety of seeded FEL schemes

Start-to-end simulation results for the 90th harmonic



Courtesy C. Feng.

EEHG and HGHG Scaling

EEHG

Bunching factor

$$b_{n,m} = e^{-\xi_E^2/2} J_n(-\xi_E A_1) J_m(-a A_2 B_2)$$

Scaling parameter

$$\xi_E = nB_1 + aB_2$$

HGHG

Bunching factor

$$b_{a_H} = e^{-\xi_H^2/2} J_{a_H}(-\xi_H A_1)$$

Scaling parameter

$$\xi_H = a_H B_1$$

Both optimized by maximizing

$$\left| e^{-\xi^2/2} J_n(-\xi A_1) \right|$$

$$\xi_E \simeq \pm 1/2$$

$$\xi_H \simeq 1$$

Difference in optimal scaling parameters leads to difference in performance

Linear electron beam chirp – harmonic shift

$$p_0 = p + h_1 k_1 z$$

Linear beam chirp shifts harmonics according to scaling parameter

$$\frac{(\Delta a)_{EEHG}}{(\Delta a)_{HGHG}} \approx \frac{\xi_E}{\xi_H}.$$

Reduced sensitivity of EEHG to phase space distortions stabilizes central wavelength against jitter

Affects stability of EEHG vs cascaded HGHG

$$\frac{(\Delta a)_{EEHG}}{(\Delta a)_{C-HGHG}} \approx \frac{\xi_E}{a_H^{(2)} \xi_H}.$$

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

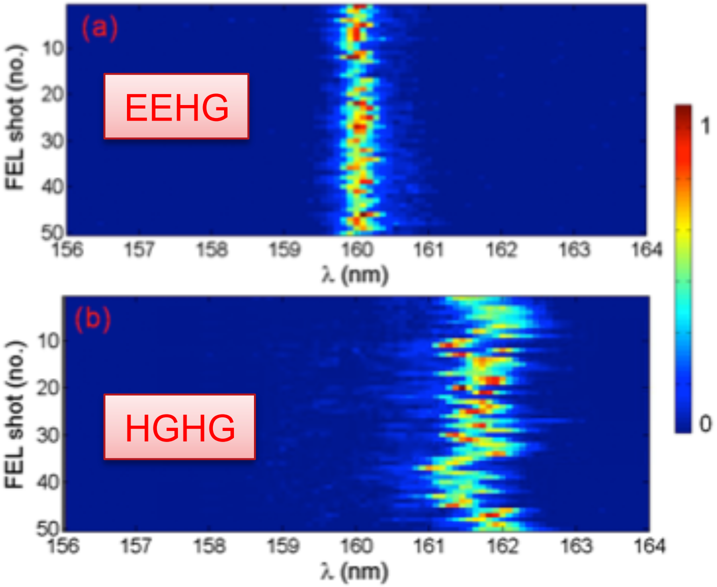


FIG. 7. Fifty consecutive radiation spectra for EEHG (a) and HGHG (b) with a chirped beam. Note, the central wavelength of HGHG signal is shifted by the linear chirp and the bandwidth of the HGHG signal is increased by the nonlinear chirp, while those for EEHG are essentially unaffected.

ξ can be negative in EEHG

Linear electron beam chirp - Bandwidth

$$p_0 = p + h_1 k_1 z$$

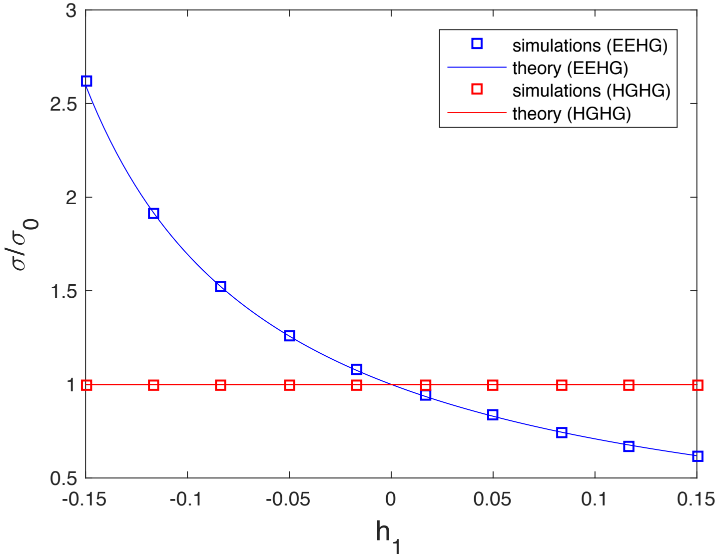
EEHG bandwidth has dependence on **linear chirp** due to stronger dispersion which changes bunch length:

$$(K = k_2/k_1)$$

$$(\sigma/\sigma_0)_{EEHG} = \frac{1}{1 + mKh_1B_1/a_E} \approx \frac{1}{1 + h_1B_1}$$

HGHG bandwidth does NOT depend on **linear chirp** because the frequency also shifts with the bunch length.

$$(\sigma/\sigma_0)_{HGHG} = 1$$



Typically for FELs the chirp is small enough that the bunch length does not change much, so this is usually negligible.

E. H, et al. Submitted to PR-AB

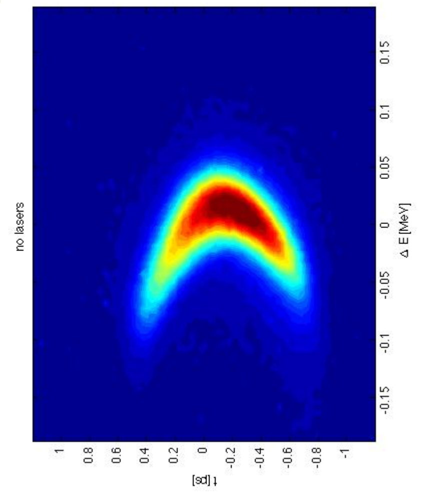
Quadratic electron beam chirp - Bandwidth

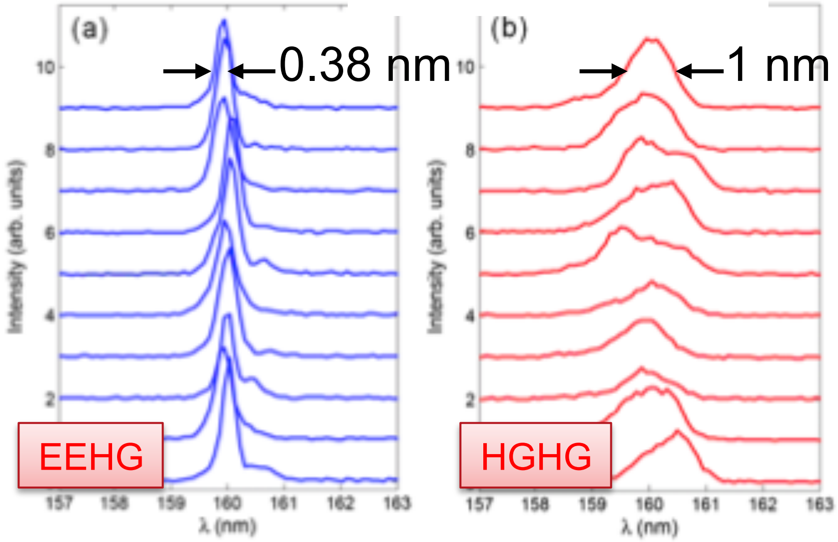
$$p_0 = p + h_2 k_1^2 z^2$$

Bandwidth scaling on pure **quadratic chirp is**:

$$\frac{(\sigma)_{EEHG}}{(\sigma)_{HGHG}} = \left| \frac{\xi_E}{\xi_H} \right|$$

- Non-linear curvature adds more bandwidth to HGHG by shifting wavelengths across the beam
- front is compressed, back is decompressed
- EEHG less sensitive

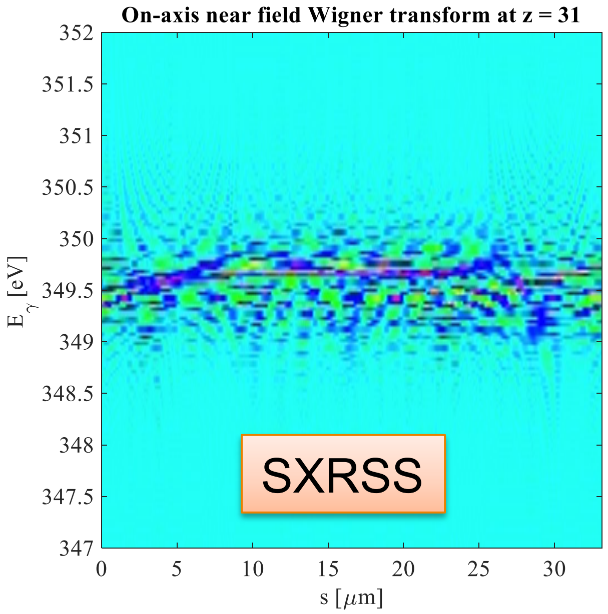




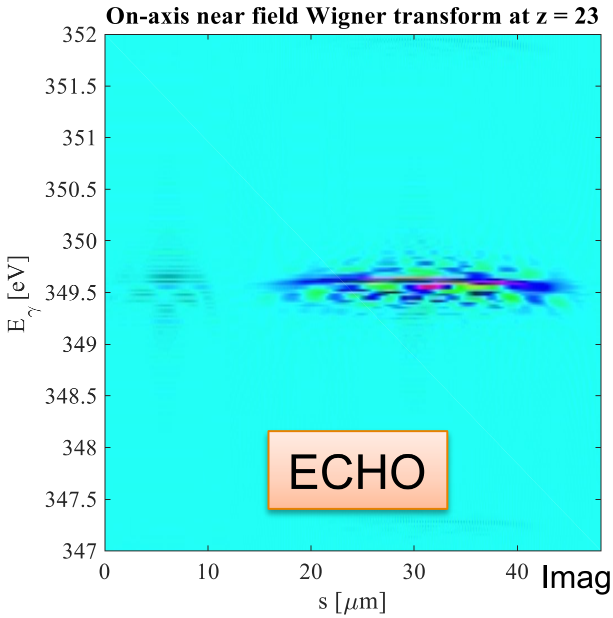
EEHG vs Self Seeding

Simulation comparison with LCLS SRXSS results. Echo seems more robust to MBI

- Spectral pedestal suppressed, narrower bandwidth
- Cascaded HGHG performs worst
- More dedicated simulation work needed



On-axis near field Wigner transform at z = 31



On-axis near field Wigner transform at z = 23

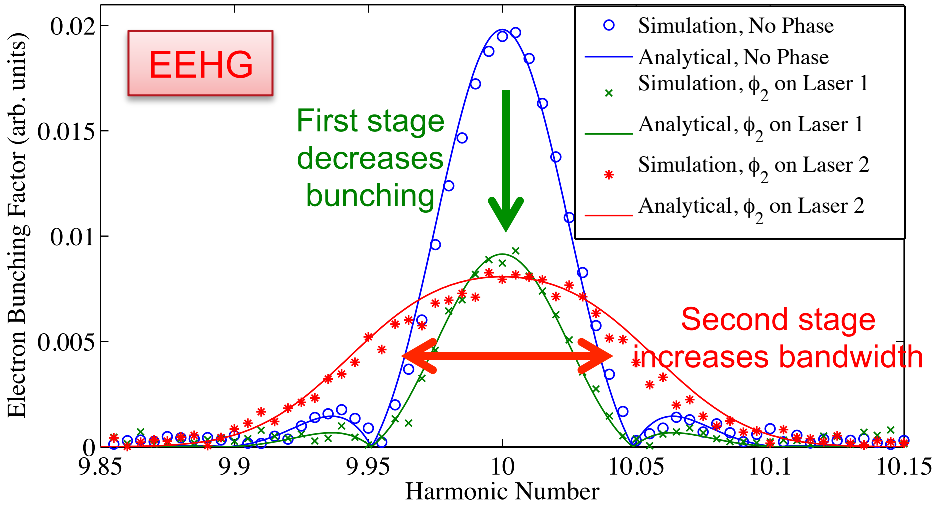
Image courtesy of G. Marcus

EEHG ***looks*** like a promising method to obtain a cleaner pulse with higher spectral brightness, ***but needs benchmarking with experiments.***

Laser Phase Errors in Harmonic Seeding

$$\tilde{E}(\omega) = e^{-\frac{(\omega-\omega_0)^2}{2\sigma_\omega^2} + i\left[\frac{\phi_2}{2}(\omega-\omega_0)^2 + \frac{\phi_3}{6}(\omega-\omega_0)^3 + \ldots\right]}$$

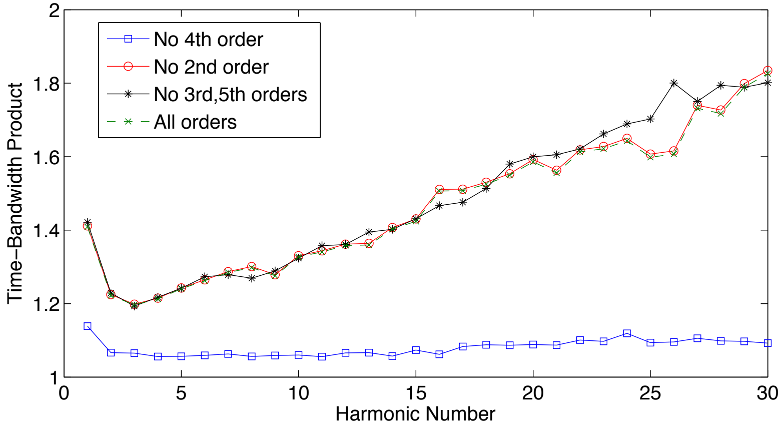
- Phase errors amplified by harmonic number. Time-bw product scales linearly or sub-linearly
- Dominated by even order phase terms
- New techniques needed for measuring and controlling UV laser phase (combine with FEL feedback)



EEHG

First stage decreases bunching

Second stage increases bandwidth



G. Stupakov, SLAC-PUB-14639, Nov 2011
G. Geloni, et al. arXiv:1111.1615, DESY-11-200 (2011)
D. Ratner, et al. PRST-AB 15, 030702 (2012)

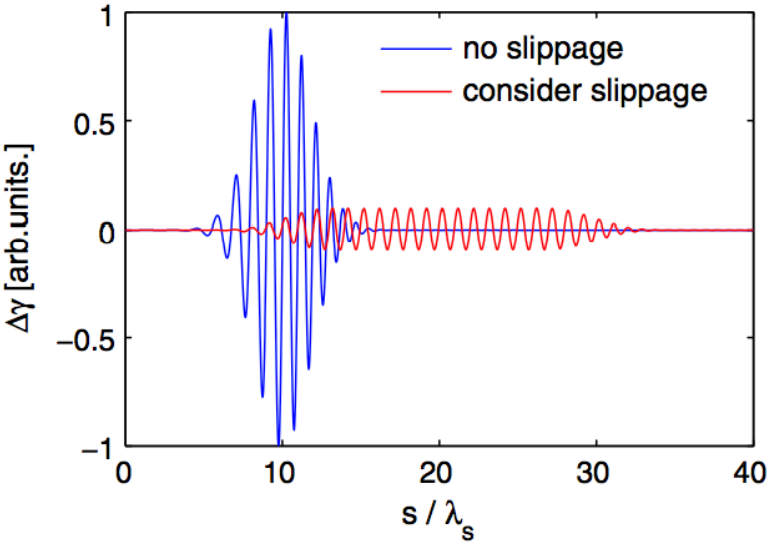
Spectral cleaning

Use lasers long and large compared to e-beam

- Reduce phase distortions both in time and transversely

Slippage boosted cleaning

- Use subharmonic modulator to lengthen slippage of laser through beam (like pSASE)
- Needs larger K, which can increase ISR, MBI



C. Feng, et al. PRST-AB 16, 060705 (2013)
G. Weng, et al. NIMA 737 (2014) 237-241

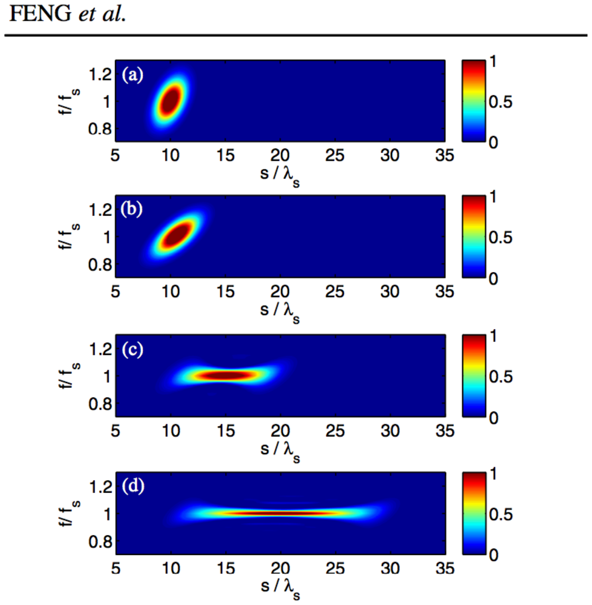
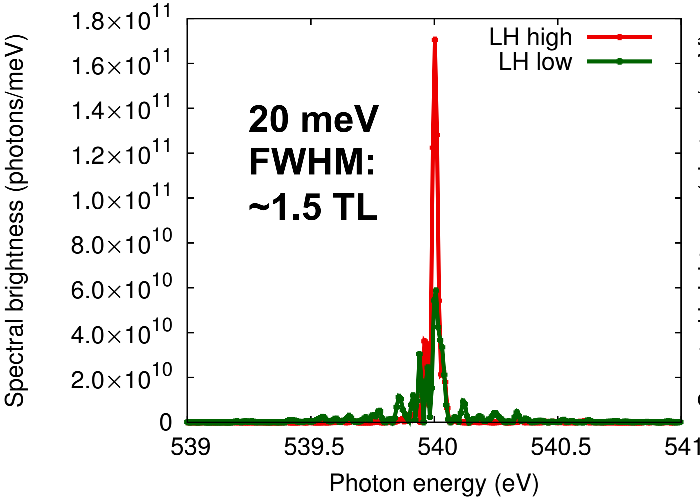


FIG. 3. Wigner distributions of the seed laser with FWHM pulse length of $3\lambda_s$ (a) and energy modulations (b)–(d) for different period numbers of the modulator ($N = 1, 10, 20$). The frequency chirp in the seed laser pulse is $\alpha = 0.16/\lambda_s{}^2$.

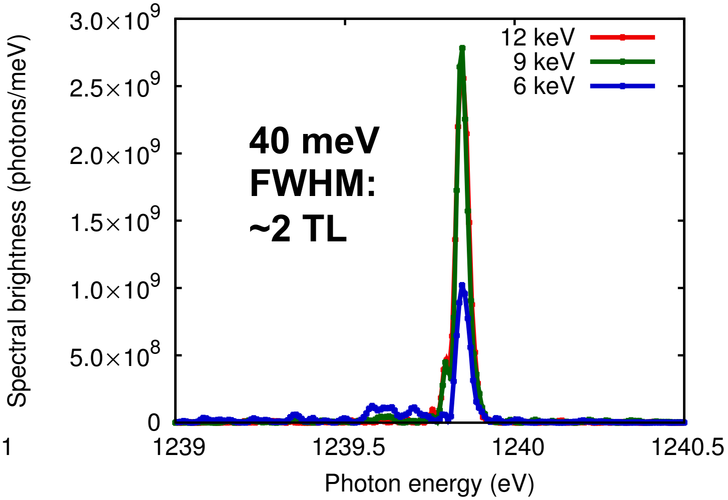
LCLS-II Studies

EEHG at 1-2 nm studies

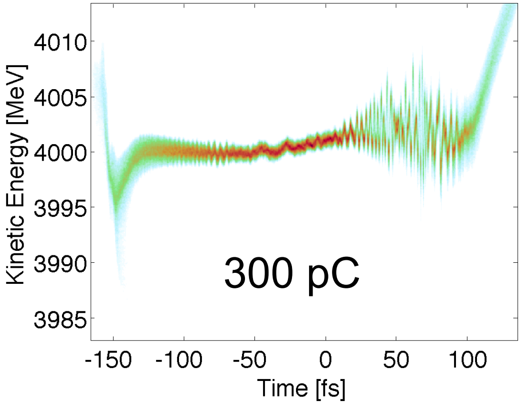
- S2E 4GeV beams (SC Linac)
- incl. wakefields, CSR, ISR
- Near transform limit pulses, depending on laser heater



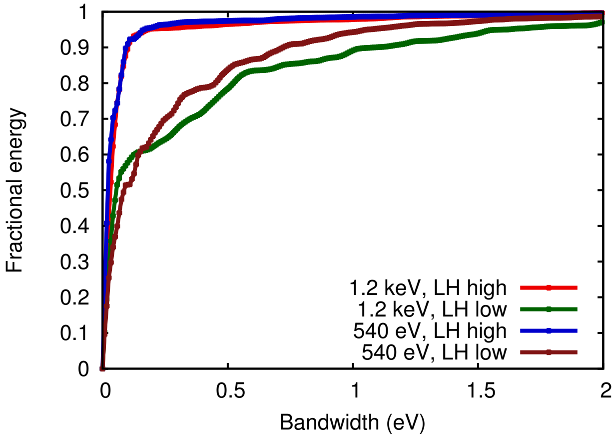
20 meV FWHM: ~1.5 TL



40 meV FWHM: ~2 TL



300 pC



Summary

- Seeding promising for designer FEL beams that are customized for new photon science opportunities
- Different schemes have different strengths/weaknesses. Solutions may depend on science drivers/users
- Echo 75 observed experimentally at long wavelengths. Results in good agreement with theory
- Upcoming experiments (FERMI, SXFEL, etc) will provide critical information for seeding at/near soft x-rays
- SLAC exploring most promising options for LCLS-II beyond baseline

- Thanks to contributors
- and **Thank You for your attention**

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