Echo Seeding Results

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Physics and Applications of High Brightness Beams

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

The Need to Seed

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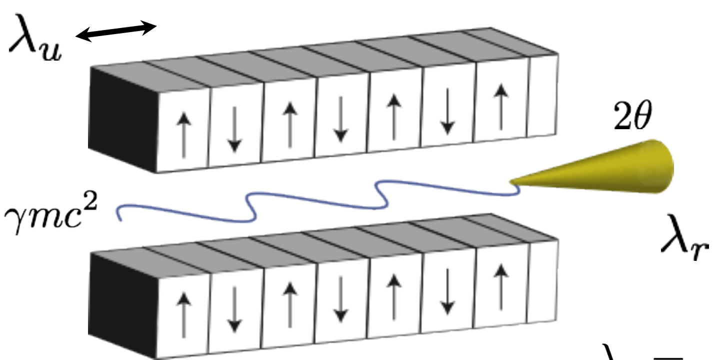
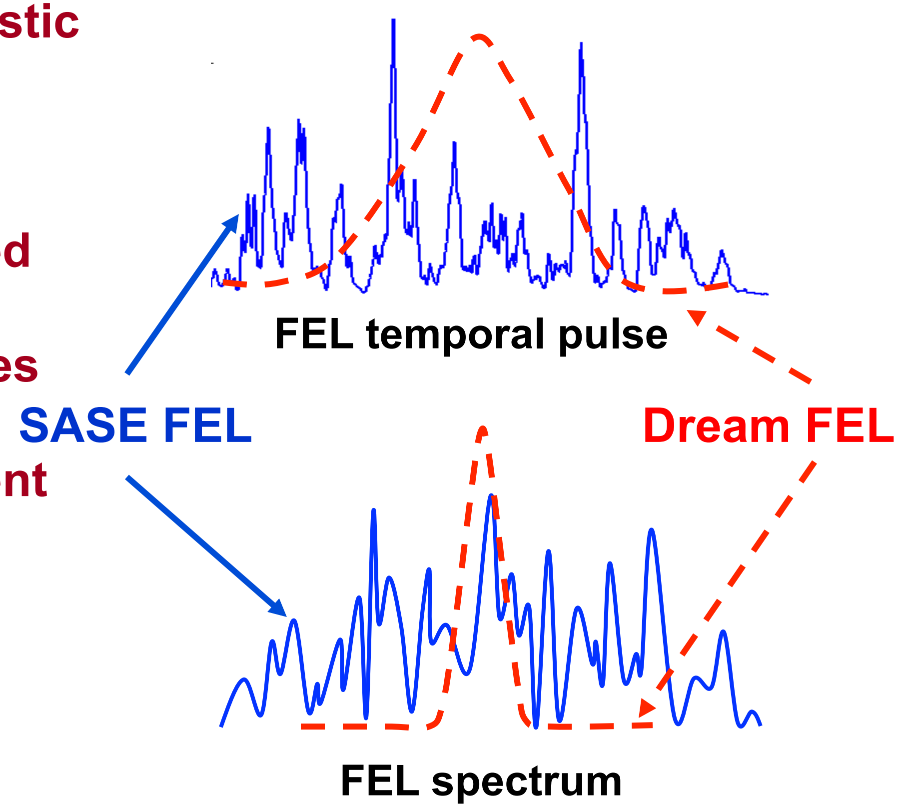
- Free-electron lasers (FELs) use relativistic electrons to produce intense pulses of tunable radiation
- Shot noise produces pulses with limited temporal coherence and a spectrum comprised of random, fluctuating spikes
- Seeding is the introduction of a coherent signal that is amplified to significantly increase the FEL spectral brightness



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



Seeding would make an FEL an extraordinarily good laser

Seeding Motivation and Techniques

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Ultimate goal: Generate transform limited, stable, and controllable x-ray pulses

Capability requests for LCLS-II beyond the baseline include:

- Pump-probe synchronization to <20 fs (X-ray/optical, X-ray/X-ray)
- High res spectroscopy & dynamics:
    - Tunable time/BW tradeoff @0.25-1.25 keV (10-200 fs)

Seeding approaches

- **Direct Seeding - High Harmonic Generation (HHG) – [State Of The Art: 38 nm]**
    - FEL amplification 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.
- **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 soon in use @4nm**
- **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.
    - 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).

Harmonics through density bunching with lasers

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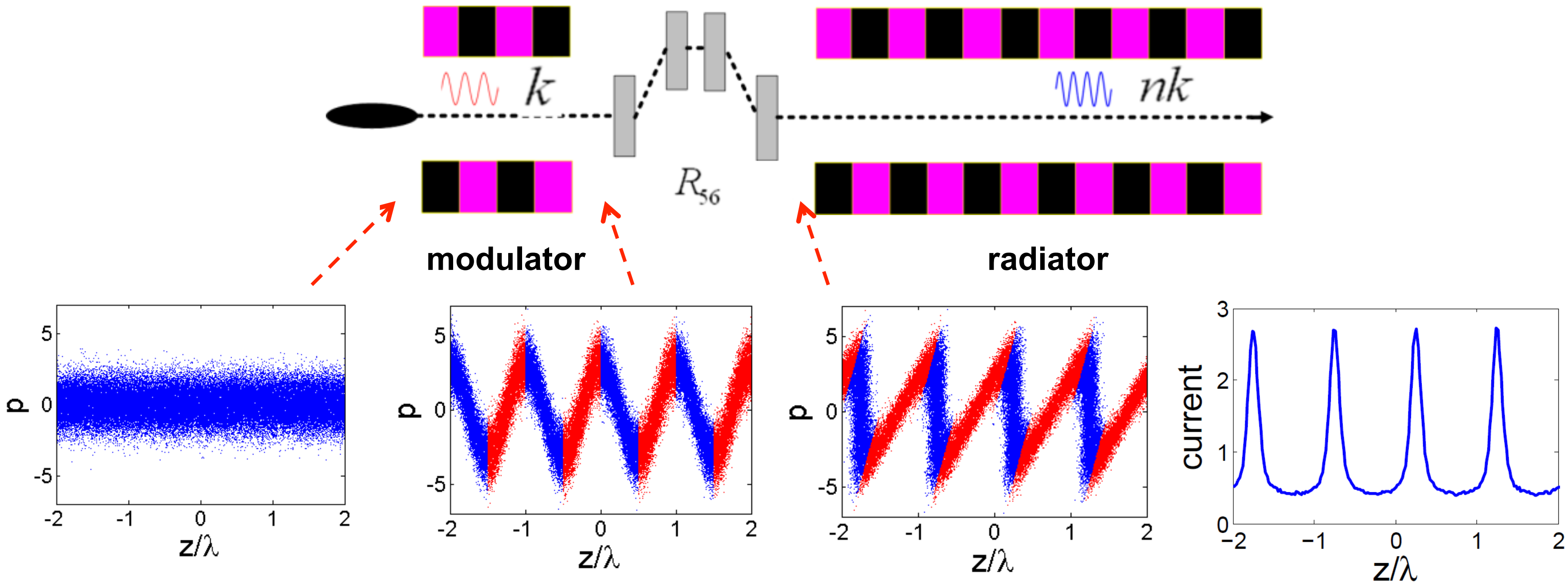
High-Gain Harmonic Generation (HGHG)

Single modulator-chicane system



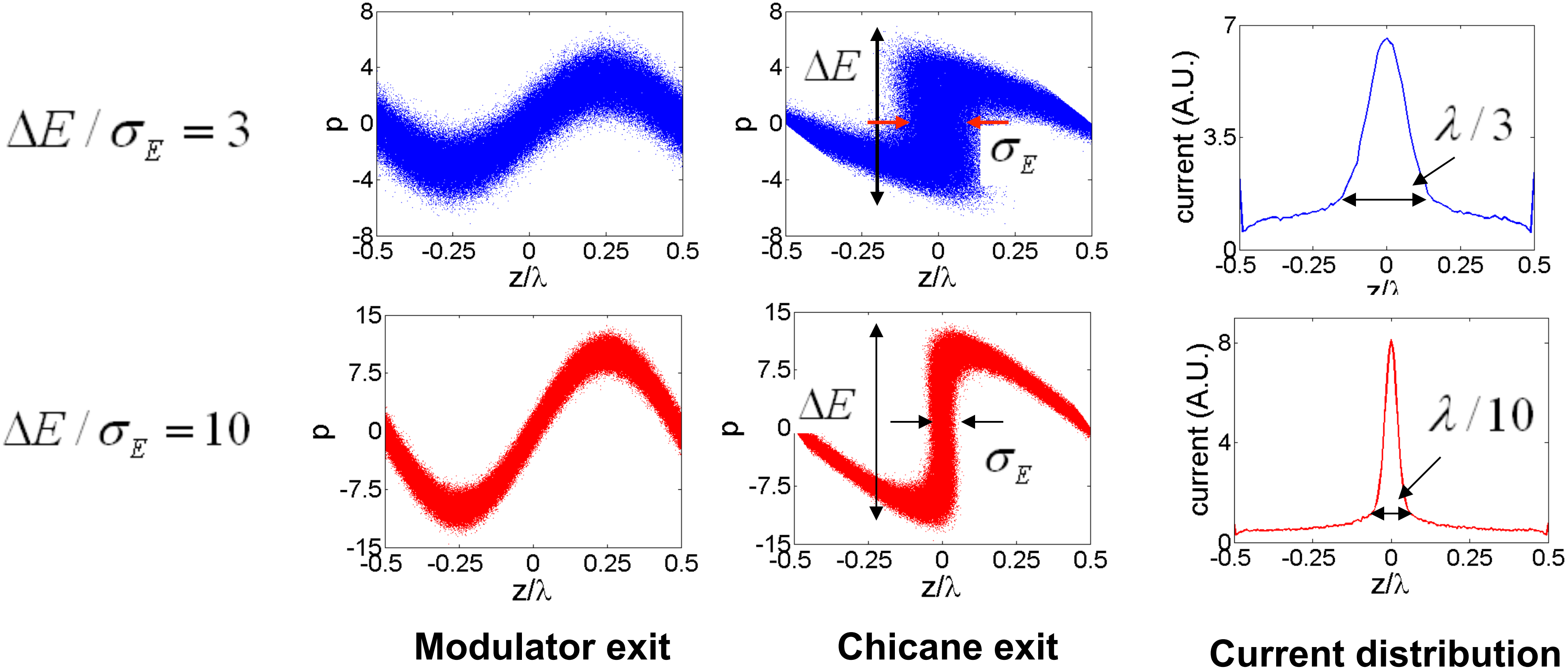
Energy modulation in a modulator
Energy modulation converted to density modulation
Coherent radiation at *nk* amplified to saturation in a radiator
Harmonic number $n \approx \Delta E / \sigma_E$

Yu et al., Science, 2000
Yu et al., PRL, 2003

Slide courtesy D. Xiang

Limitations on single stage HGHG

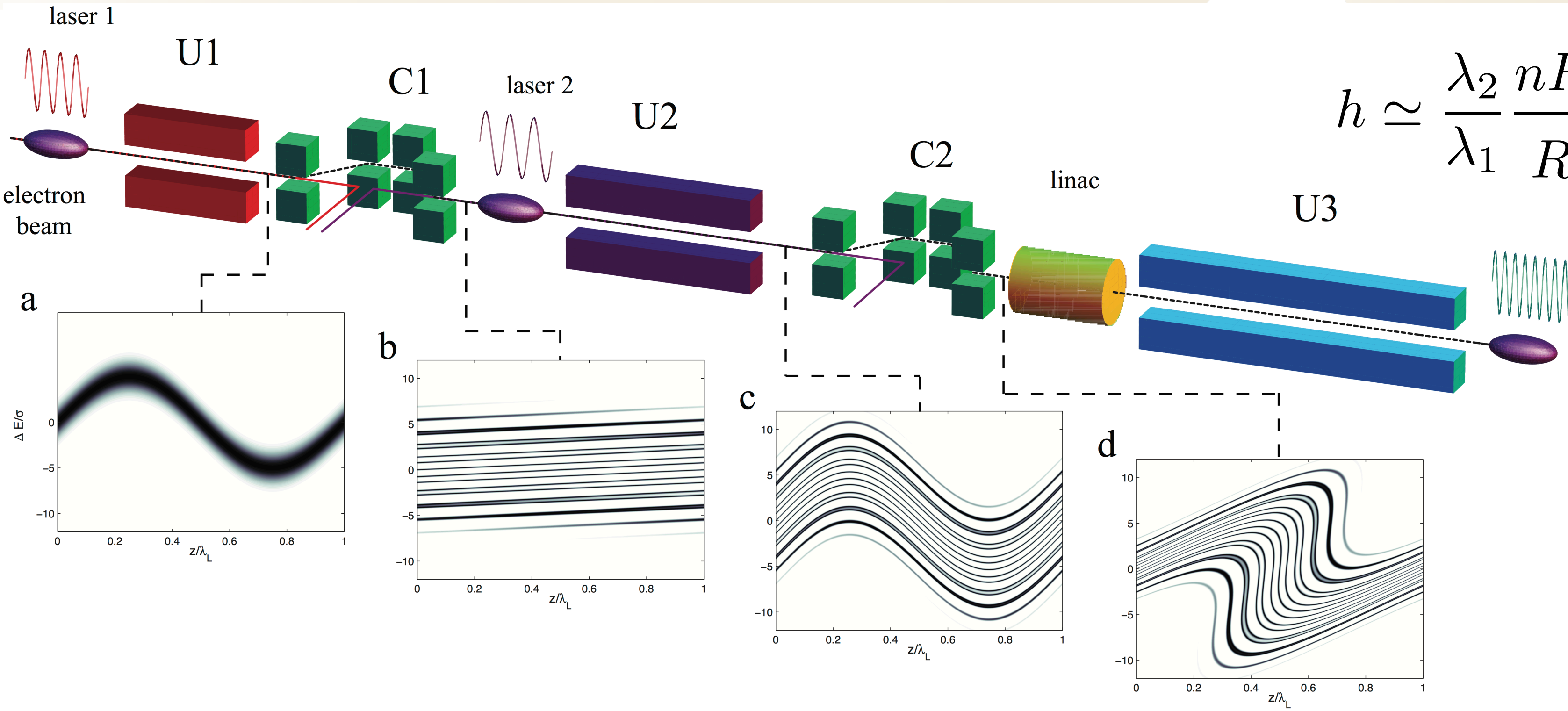
- **Low up-frequency conversion efficiency:** $\Delta E / \sigma_E \approx n$



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

Slide courtesy D. Xiang

Echo-Enabled Harmonic Generation (EEHG)



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

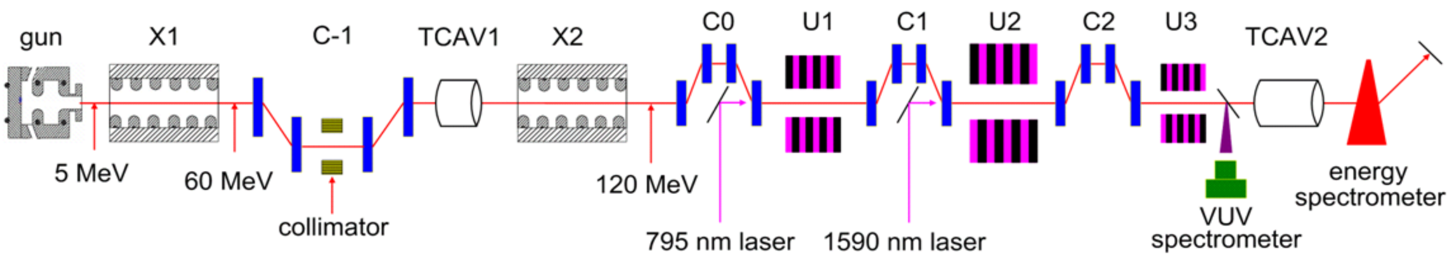
$$hk_2 = nk_1 + mk_2$$

<u>Advantages</u>
- 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

<u>Challenges</u>
- Preservation of fine phase space correlations
- Sensitive to intrabeam scattering, diffusion, and laser quality

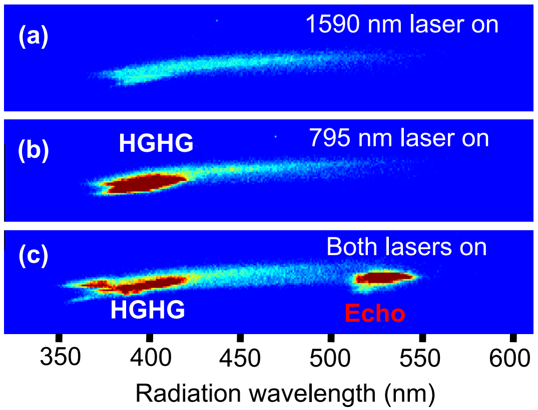
G. Stupakov, PRL 102, 074801 (2009)
D. Xiang and G. Stupakov, 12, 030702 (2009)

First EEHG experiments at SLAC's NLCTA



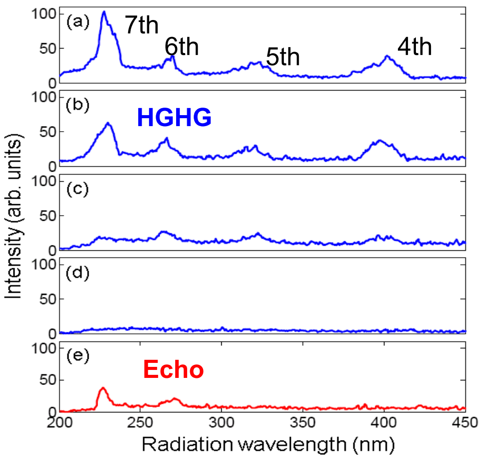
- •3yr Echo-7 experimental effort proposed and funded in 2009 by LDRD and BES
- •Progressive facility upgrades enabled staged demonstration of higher harmonics
- • Basic physics of EEHG verified
- • phase space correlations can be preserved
- •experimental observations well explained by EEHG theory

ECHO-3 (2010)



D. Xiang *et al., PRL 105, 114801* (2010)

ECHO-7 (2012)



D. Xiang, et al, PRL 108, 024802 (2012).

"The theory and experimental realization of EEHG are both groundbreaking, with profound implications for FEL science."
--*Nature Photonics*, 4, 739 (2010)

EEHG in High Harmonic Regime

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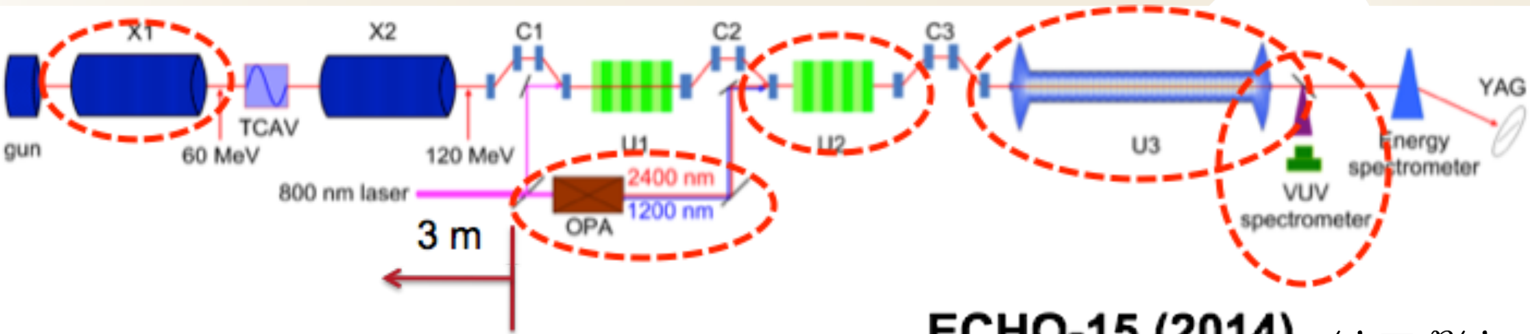


- New 3yr Echo-75 experimental effort proposed and BES funded in 2012
- Extensive facility upgrades
- Moved entire Echo line (modulators, chicanes) upstream by 3m to accommodate new structures
  - Replaced X1 linacs with single RDDS (better alignment, no SLED) Installed chicane bypass (cleaner phase space)
  - Upgraded laser systems and PLCs U2 retuned to be resonant with 2400 nm laser
  - New OPA purchased and commissioned
  - RF undulator installed (PhD Thesis, M. Shumail, Stanford, 2014; S. Tantawi, et al PRL 112, 164802 (2014))

ECHO-15 (2014) $\omega = n\omega_1 + m\omega_2$

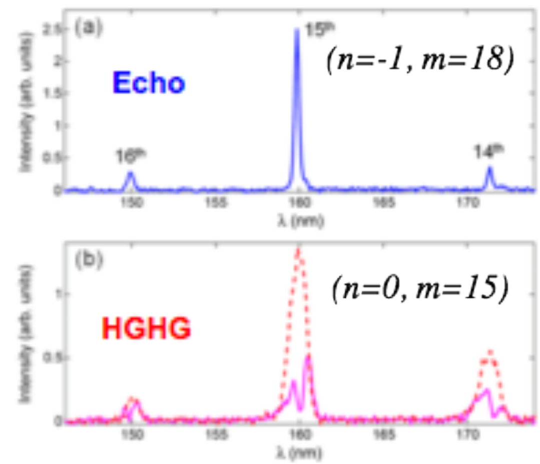
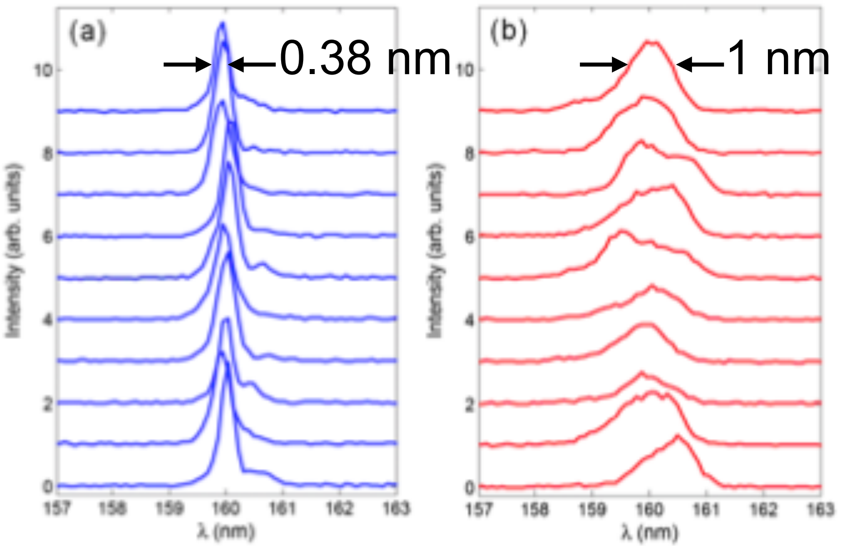


FIG. 4. Representative single-shot radiation spectrum for EEHG (a) and HGHG (b).

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

EEHG has 60% higher spectral brightness and narrower bandwidth comparing optimized cases

EEHG vs HGHG Bandwidth comparison

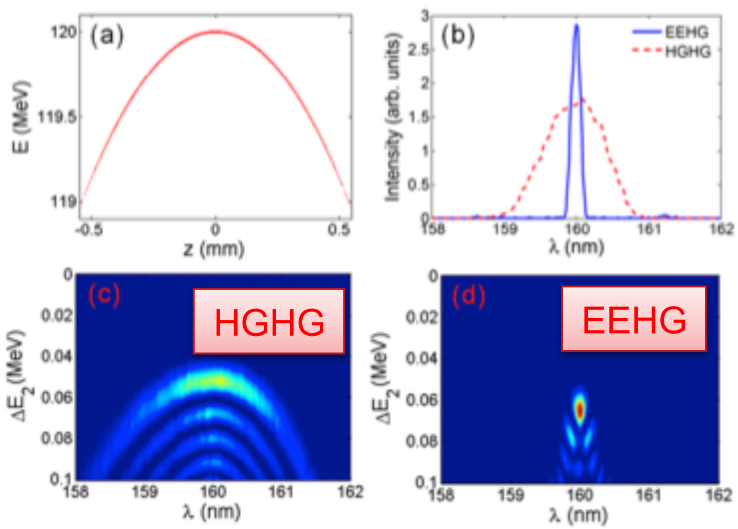


EEHG signal has narrower bandwidth
($\Delta\lambda/\lambda$=0.23% vs 0.62 %)

Two effects:

- different dependence of EEHG and HGHG on local phase space distribution and
- finite length laser pulse

- Non-linear curvature adds more bandwidth to HGHG by shifting wavelengths across the beam
- front is compressed, back is decompressed
- EEHG less sensitive because strong initial R_{56} removes this smooth variation



Central wavelength stability

- Reduced sensitivity of EEHG to phase space distortions stabilizes central wavelength
- RF timing drift or jitter in e-beam can change chirp –> shift in central wavelength
- OR, timing jitter between laser and e-beam (ie, energy jitter) changes laser overlap and selects differently chirped region

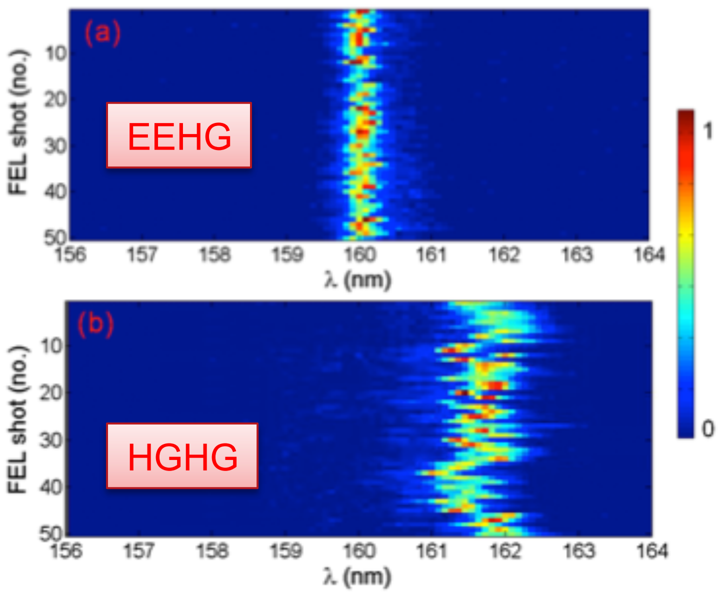
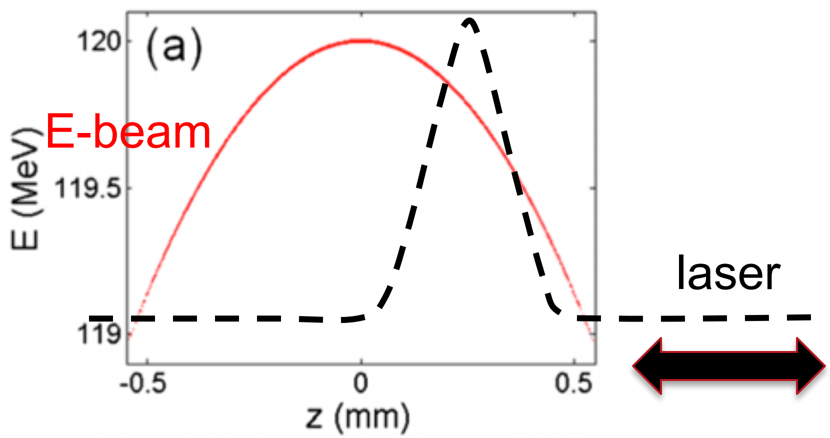
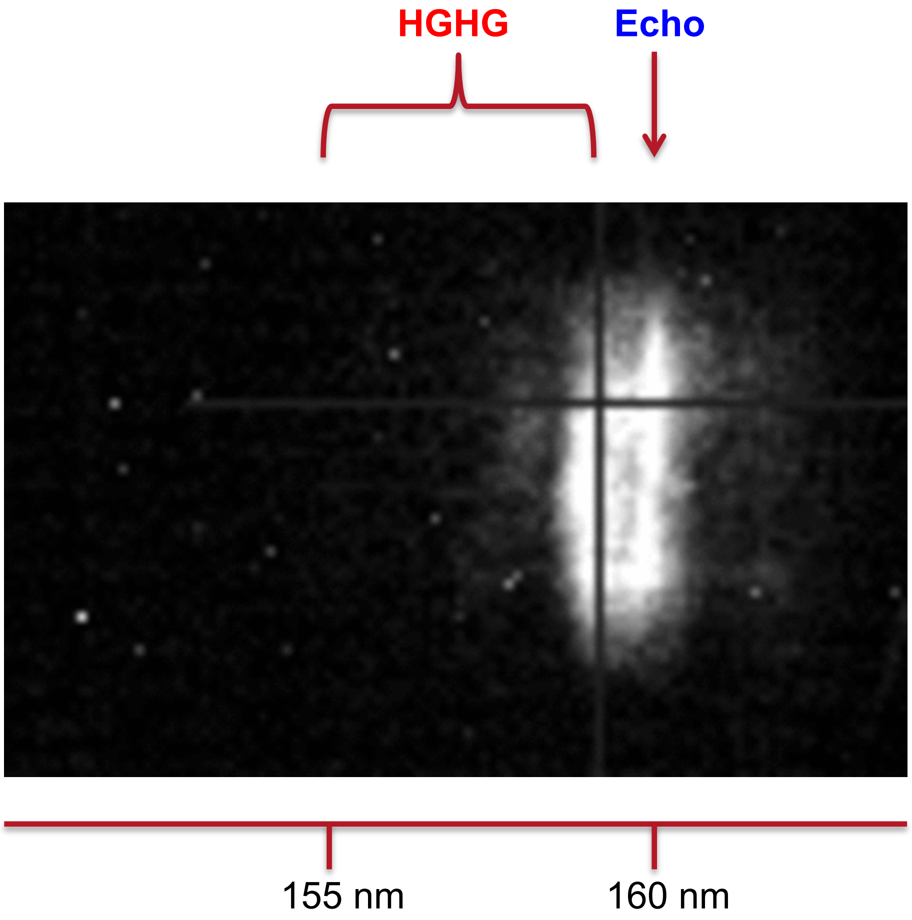


FIG. 7. Fifty consecutive radiation spectra for EEHG (a) and HGHG (b) with a chirped beam. Note, the central wavelength of HGHG signal is shifted by the linear chirp and the bandwidth of the HGHG signal is increased by the nonlinear chirp, while those for EEHG are essentially unaffected.



Simultaneous ECHO and HGHG in same beam

- Echo appears insensitivity to e-beam phase space distortions leads to more stable central wavelength and narrower bandwidth



Pushing EEHG to the ultra-high harmonic regime

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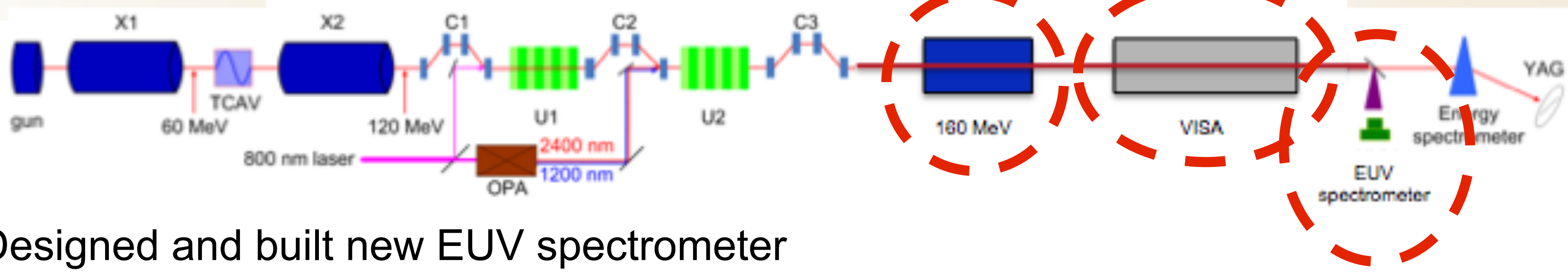
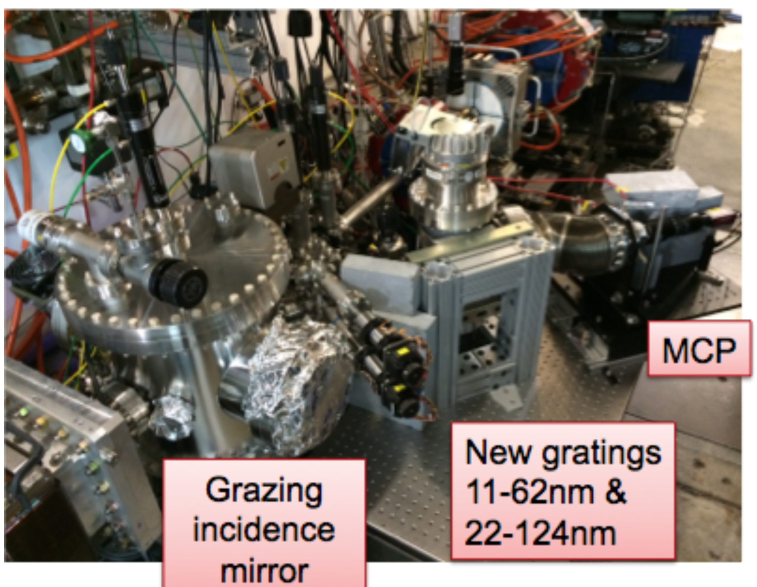
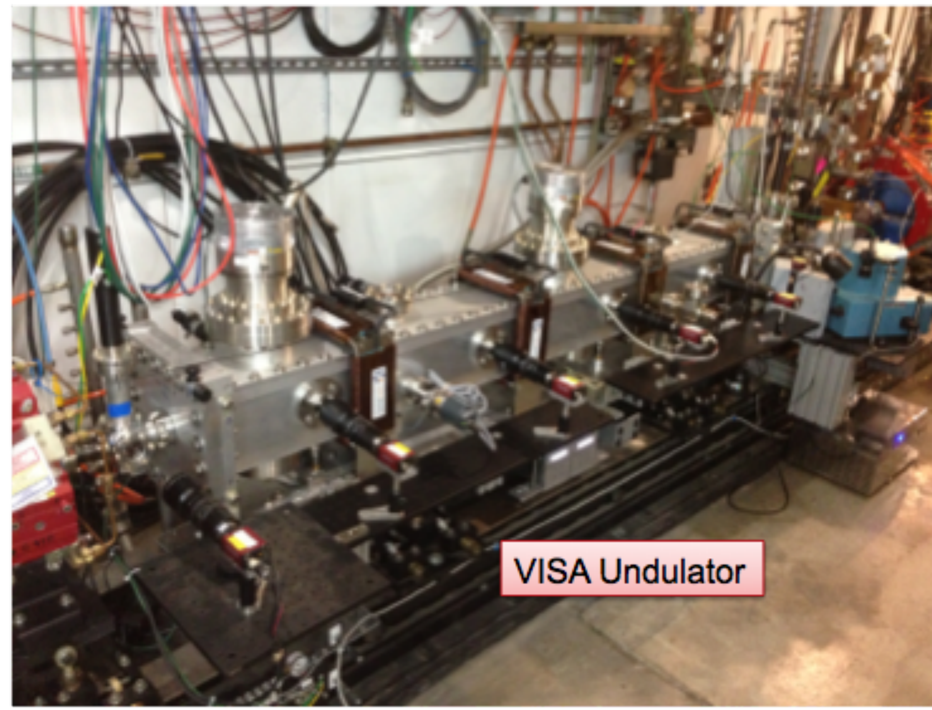


- Designed and built new EUV spectrometer
- Installed linac to boost beam energy to 160-190 MeV (access shorter wavelengths, more tunability)
- Installed 2m VISA undulator from SDL @ BNL (courtesy E. Johnson)





- λ_u=1.8 cm, 110 periods, K=1.26

NLCTA Studies of Echo at h=60th harmonic

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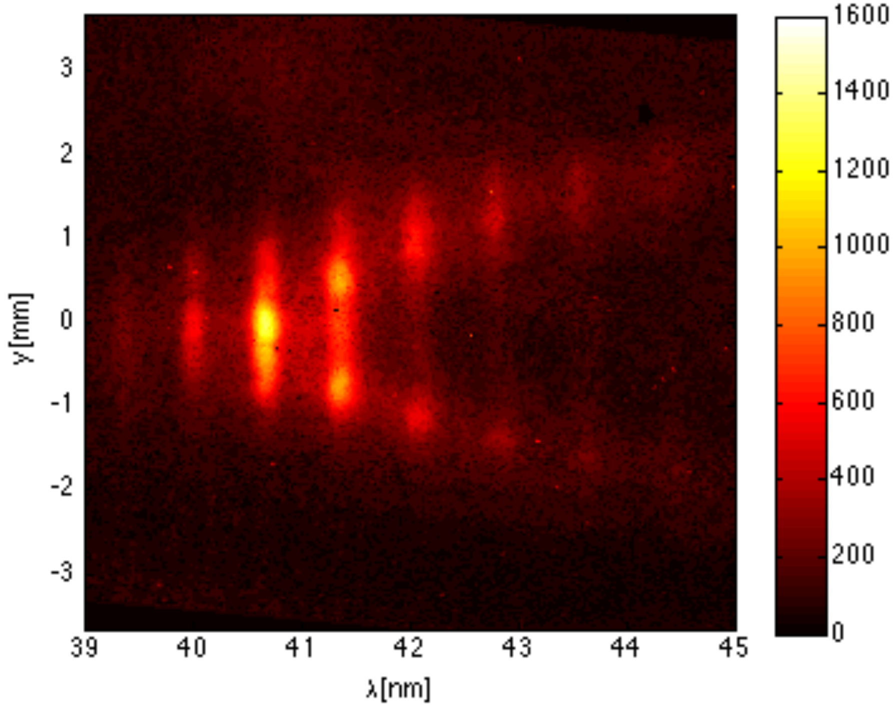
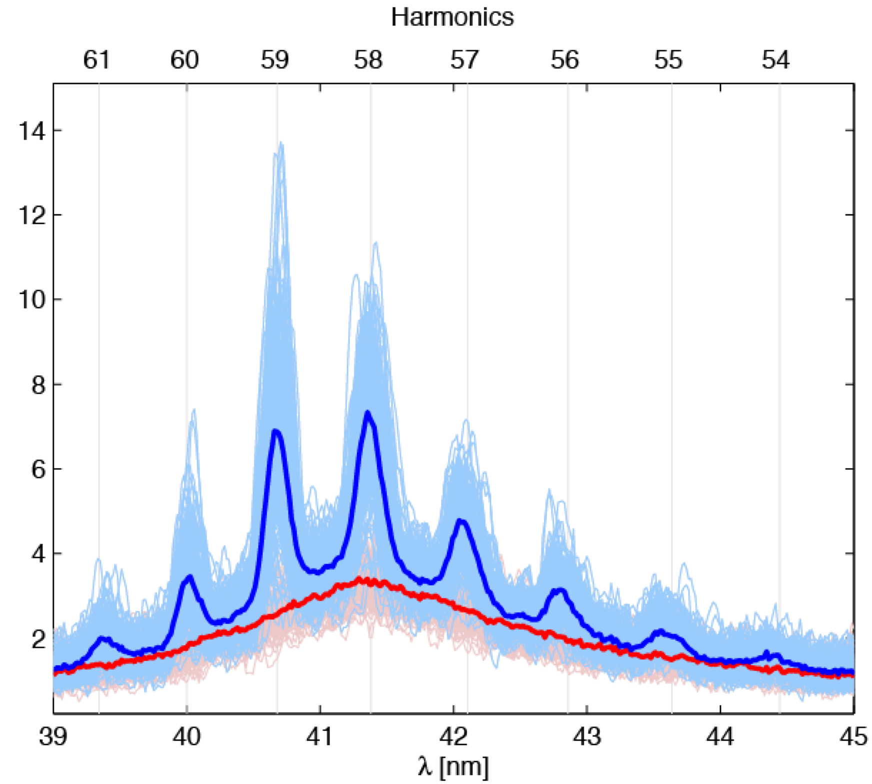
- 2400 nm to 40nm
- 190 MeV
- Signal at 3rd harmonic of VISA undulator

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

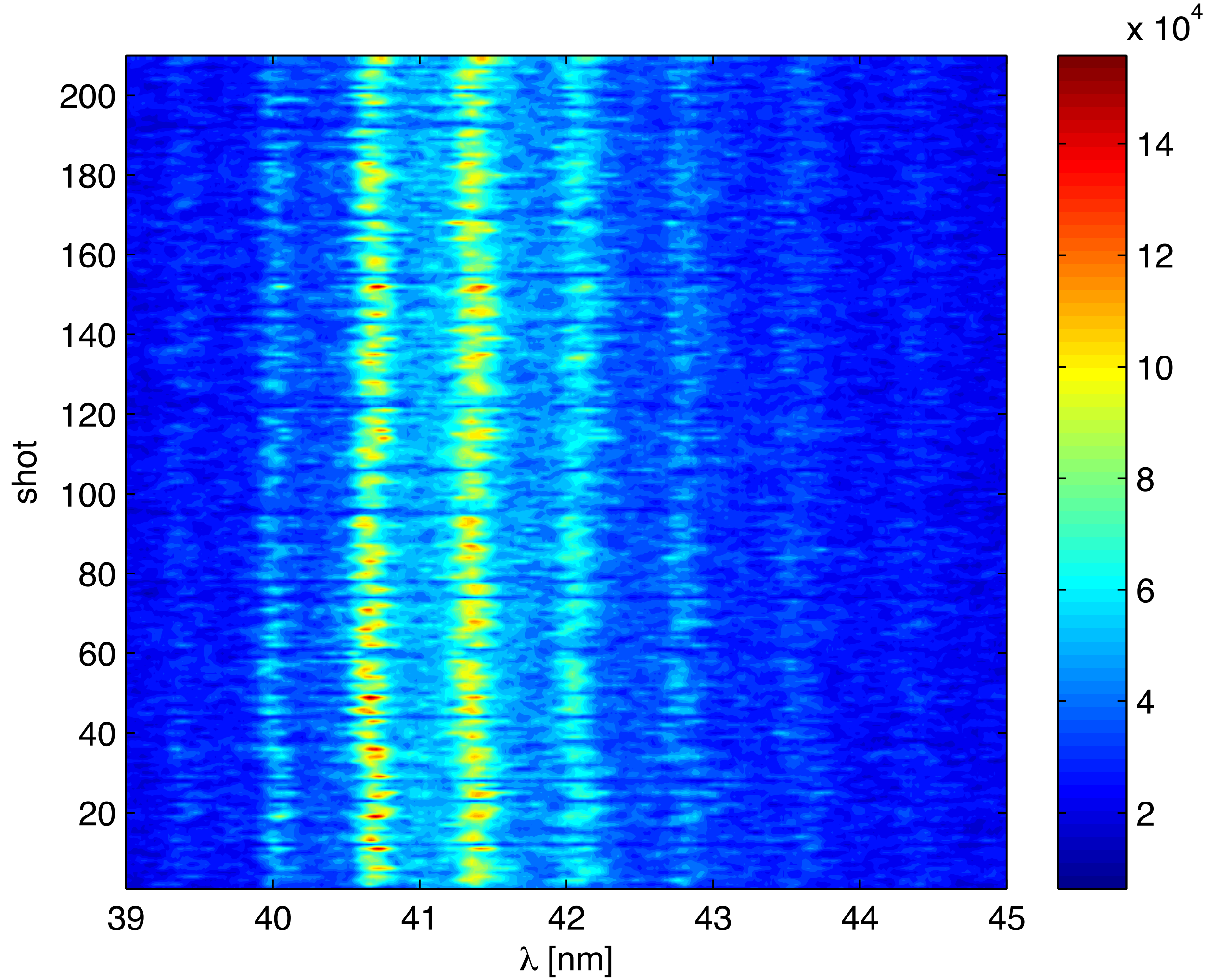
$R_{56}^{(1)}$	$R_{56}^{(2)}$
12.5 mm	600um

Spectrum at MCP





Echo 60 Spectral stability

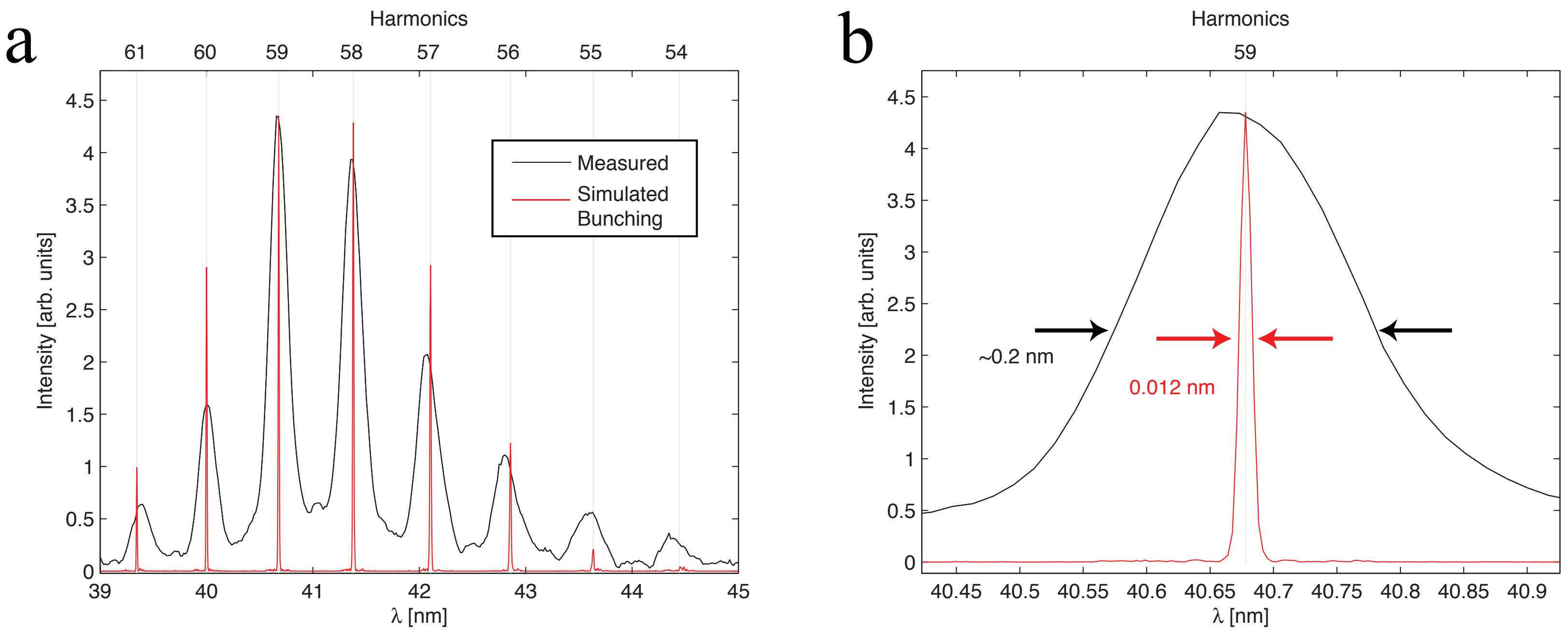


Echo 60 simulation comparison

Spontaneous subtracted

Simulation parameters

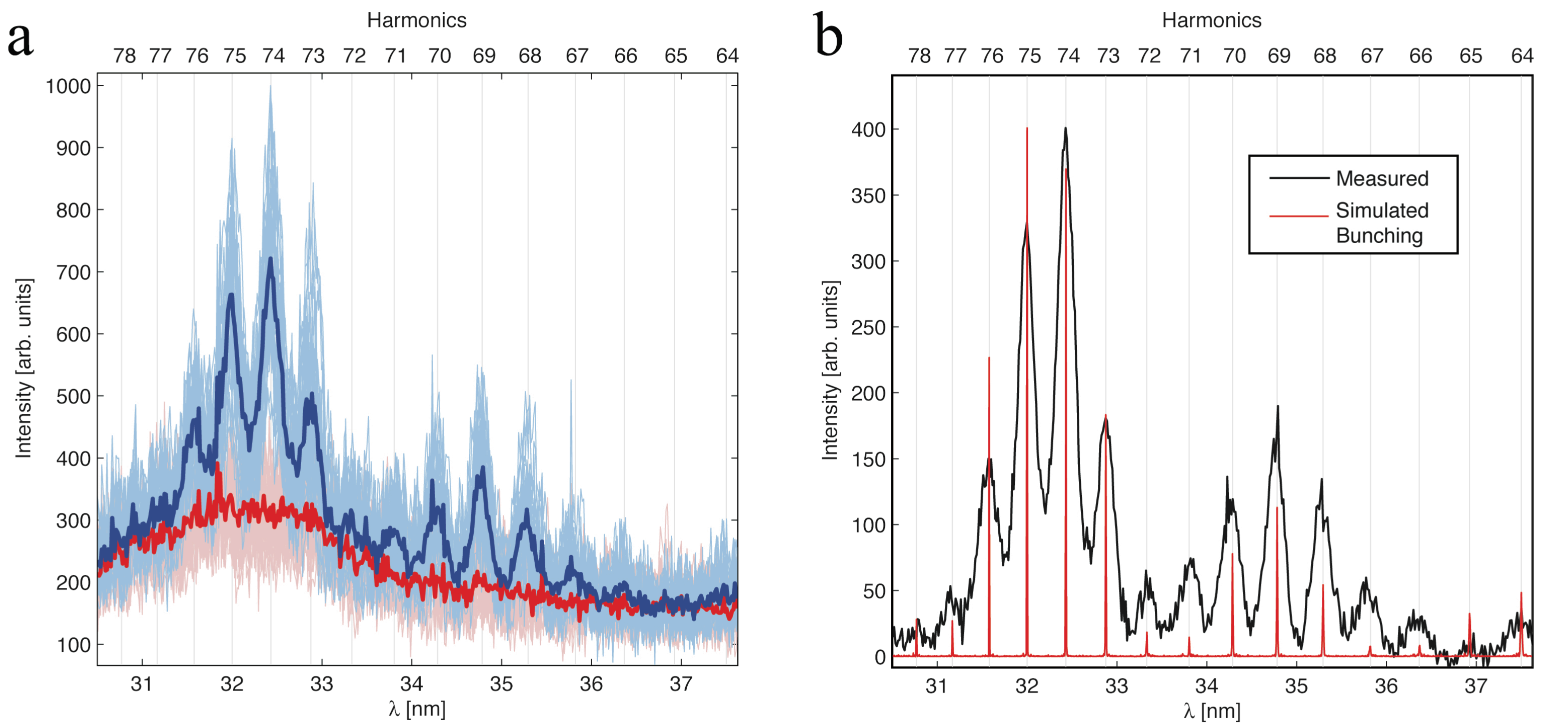
ΔE_1	ΔE_2	$R_{56}^{(1)}$	$R_{56}^{(2)}$
38 keV	84 keV	12.5 mm	600um



Echo at 75th harmonic

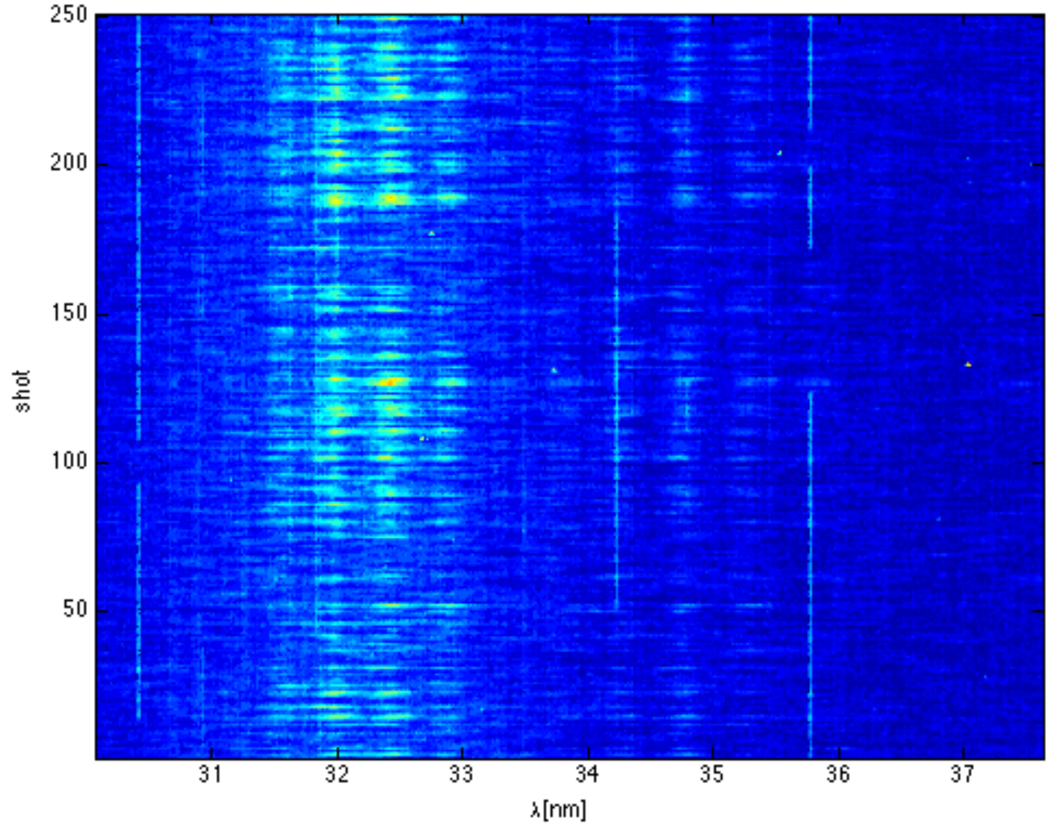
- **2400 nm to 32nm**
- **Signal at 4th harmonic of VISA undulator**
- **Results in agreement with theoretical expectations**

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



Echo 75 Spectral stability

- **Higher sensitivity to stability than Echo 60**



Beam transport in VISA-II Undulator

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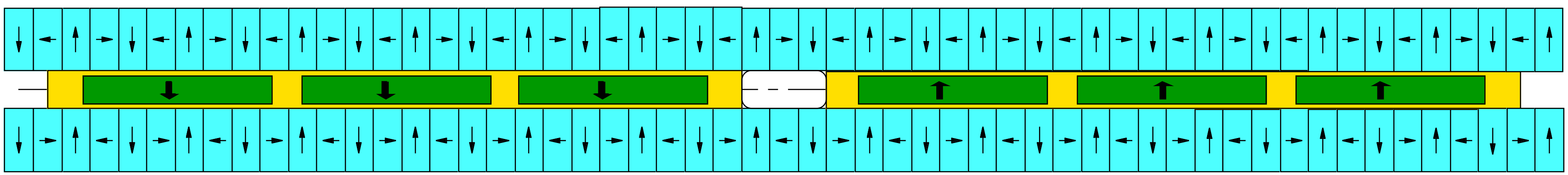
Halbach-type Pure-Permanent Magnet Undulator with Distributed Strong Focusing



Undulator Period = 18 mm (blue blocks)

FODO Cell (green blocks)= 24.75 cm

= 13.75 undulator periods*

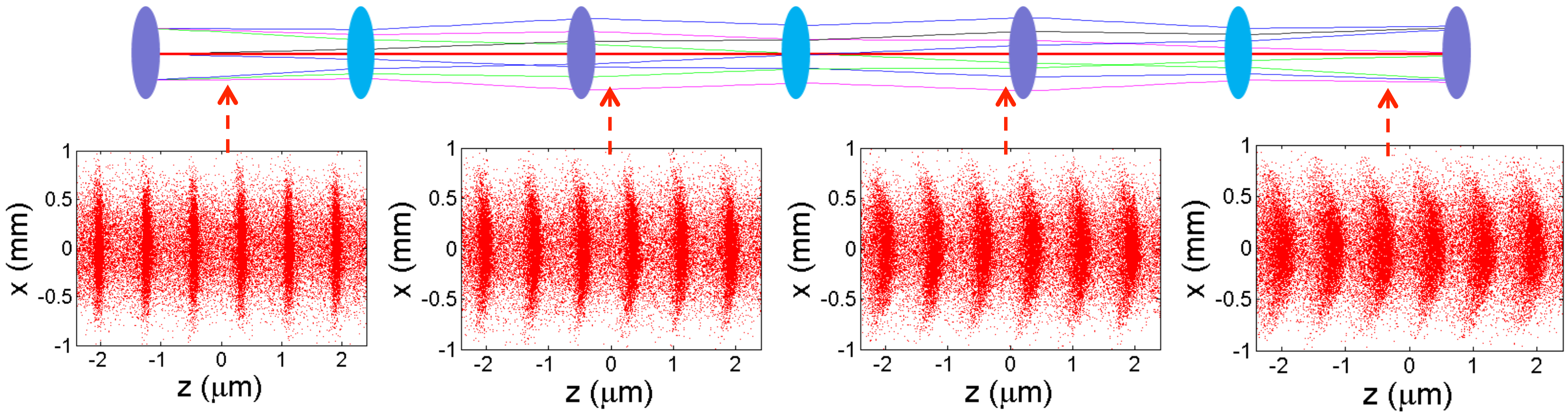
(* 4 FODO Cells = 55 Undulator periods)

Total Length = 110 Periods = 8 FODO cells, built in two 99 cm long sections + terminations

Slide courtesy G. Rakowsky

Reduction of bunching due to transport

Smearing of micro-bunches when they propagate in a FODO lattice



Particles with larger betatron amplitudes have longer path lengths

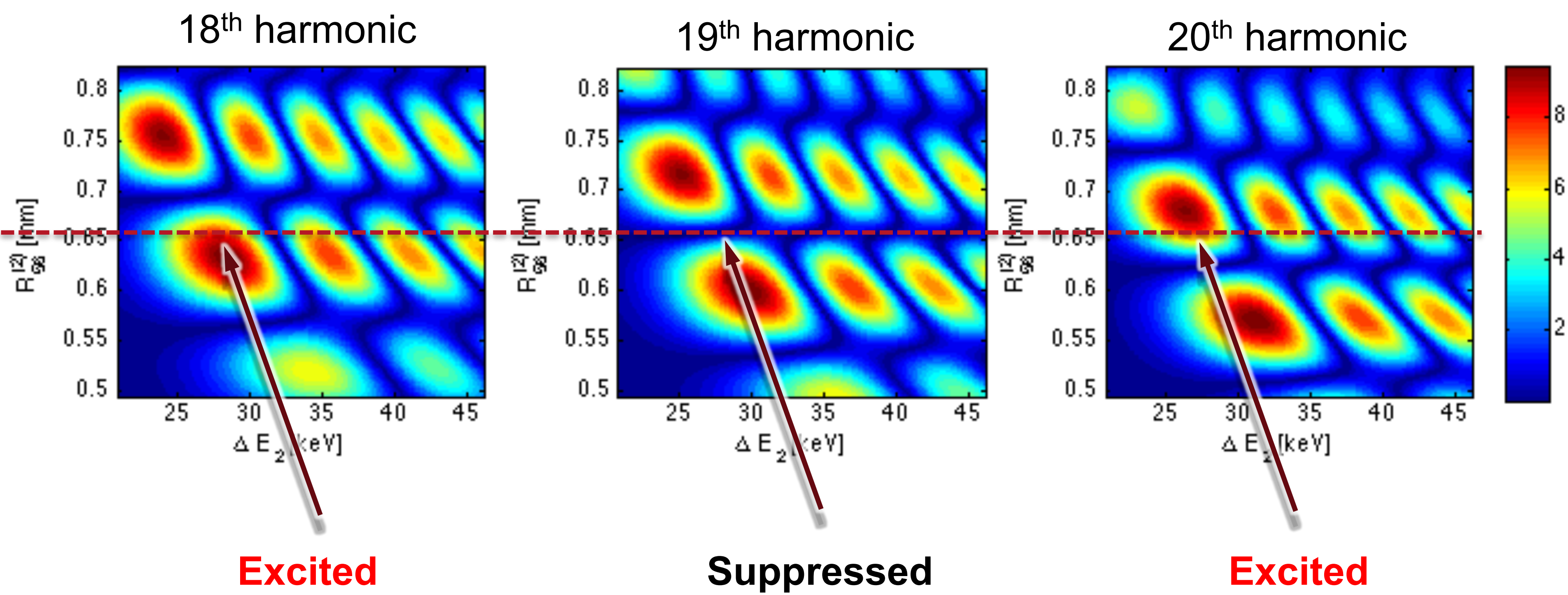
Ideally: $$\sigma_{\Delta s} \approx \frac{L\sqrt{\varepsilon_{nx}^2 + \varepsilon_{ny}^2}}{\gamma\langle\beta\rangle\cos^2(\mu/2)} \approx \frac{\sqrt{2}L\varepsilon_n}{\gamma\langle\beta\rangle} << \frac{\lambda}{2\pi}$$

Not true in our case. Longitudinal smearing is comparable to short wavelengths -> **bunching is suppressed**

Tuning harmonics with dispersion

- Each harmonic has a slightly different dependence on dispersion
- Individual harmonics can be enhanced or suppressed within the harmonic envelope

Example: harmonic bunching of two 800 nm seed lasers

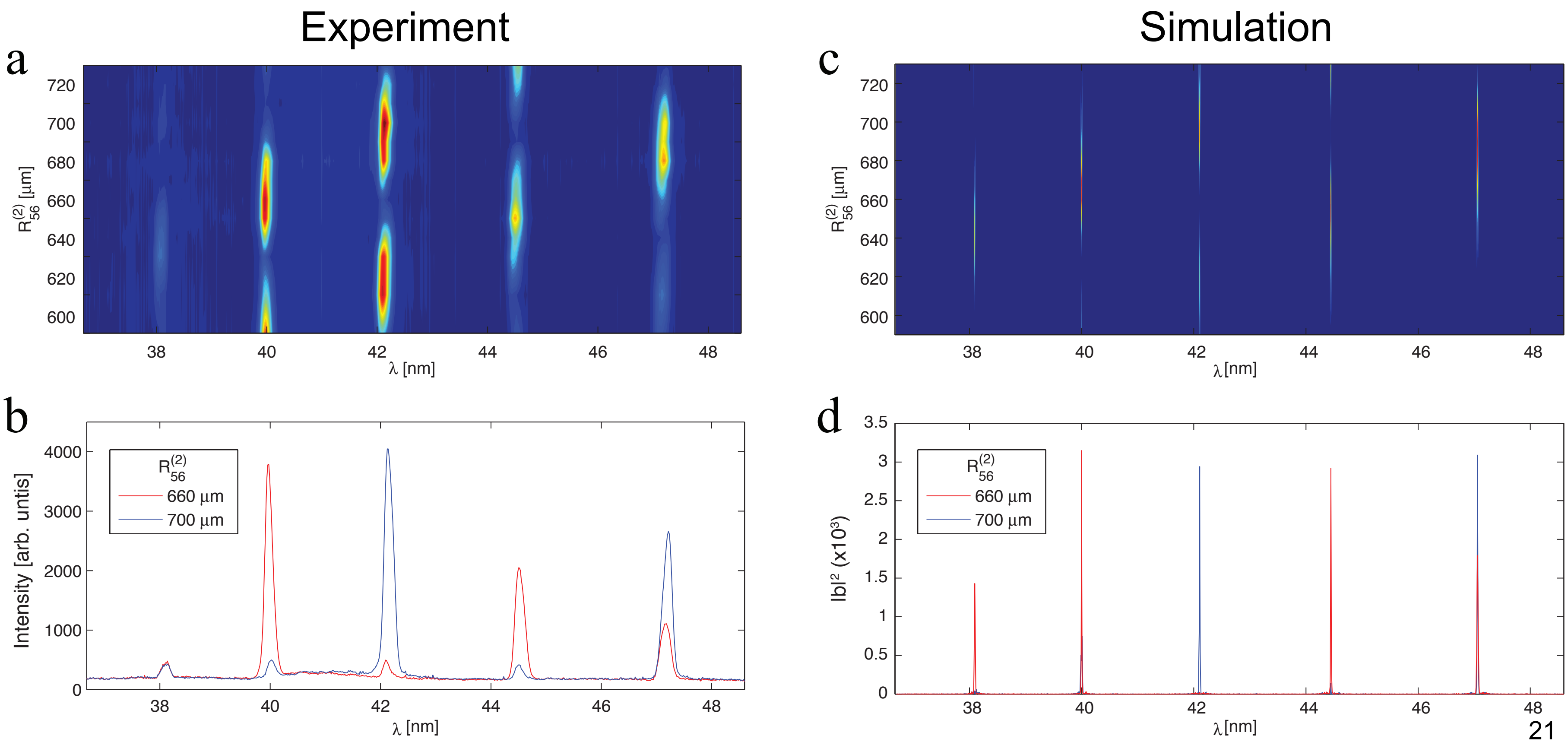


Precision control of single harmonics with dispersion

- Bypassed OPA for better stability
- Echo harmonics with two 800 nm lasers near 40 nm
- Scan second R56 to tune harmonics
- nm-scale control of spectrum observed

Simulation parameters

ΔE_1	ΔE_2	$R_{56}^{(1)}$
29 keV	27 keV	12.5 mm



Moving to x-rays: EEHG vs Self Seeding @ LCLS

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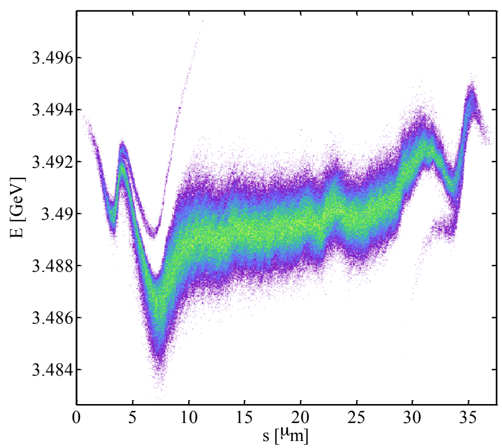
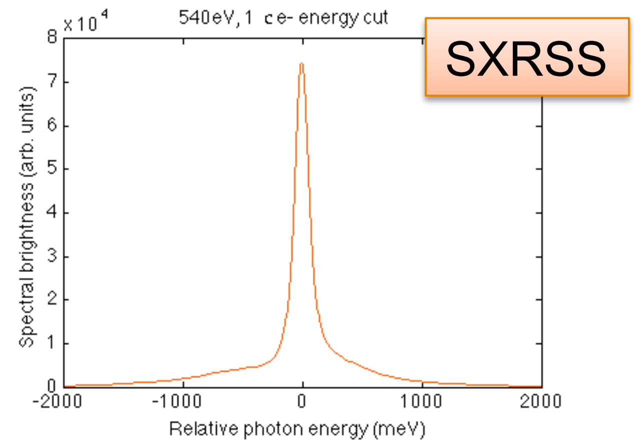
Simulation comparison with SRXSS results

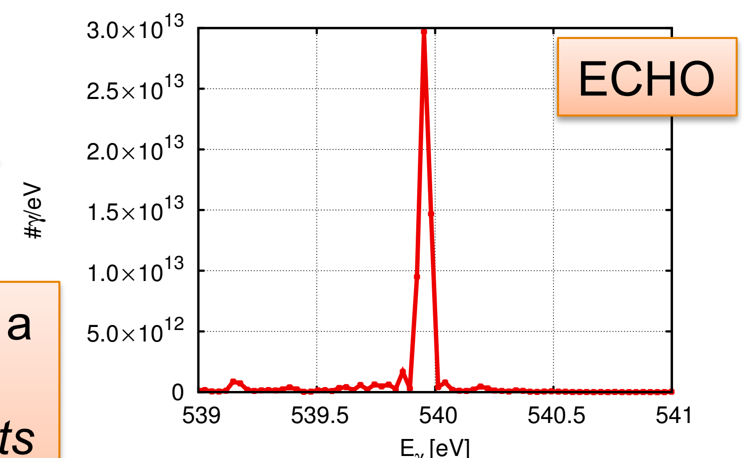
Echo seems more robust to MBI

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

Images courtesy of G. Penn, G. Marcus, and D. Ratner.







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

Summary

- Echo 60 and 75 observed. Results in good agreement with theory
- EEHG now in same harmonic regime as cascaded HGHG -> soft x-rays from UV lasers
- Individual harmonics tuned with dispersion. Sub-wavelength control over harmonic envelope
- EEHG seeding offers distinct opportunities to address science cases for tunability/stability in SXRs, particularly for high rep rate where self-seeding may be damage-limited
- SLAC exploring EEHG options for LCLS-II
- Collaborations with FERMI ramping up for various possible EEHG experiments at soft x-rays

- Thanks to NLCTA team
- And Thank you for your attention!