Experimental Path to Echo-75 at NLCTA

Erik Hemsing on behalf of
the ECHO group
at SLAC NLCTA

ICFA Workshop on Future Light Sources
March 5-9, 2012
Thomas Jefferson National Accelerator Facility

SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

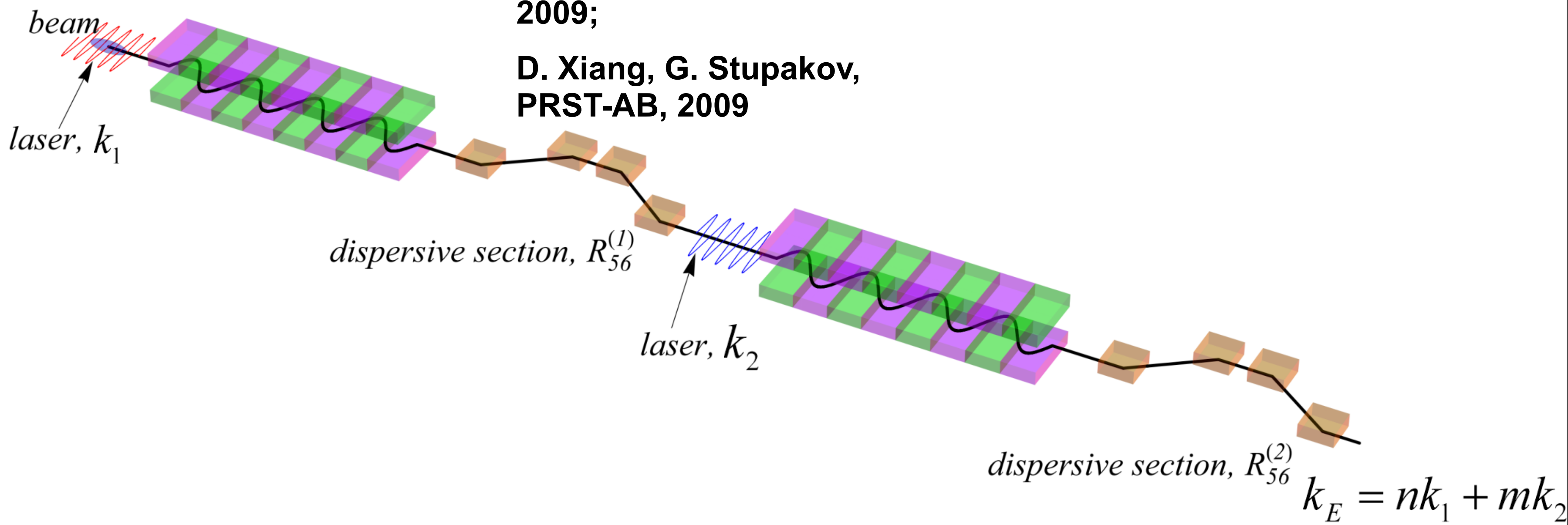
Motivation

- Ultimate goal: Seeding to generate transform limited x-ray pulses
- Several seeding approaches:
  - High Harmonic Generation (HHG)
  - High Gain Harmonic Generation (HGHG)
  - Various Self-seeding techniques (HXRSS and SXRSS)
  - Echo-Enabled Harmonic Generation (EEHG)
- Echo is a new approach where laser challenges are traded for beam manipulation challenges
  - Has advantage in that bunching is weak function of harmonic number and only small relative energy modulations required
- Echo (EEHG) demonstration to benchmark critical accelerator and laser physics issues
- Find optimal combination of high-harmonics and short wavelength seeds

Echo-Enabled Harmonic Generation (EEHG)

G. Stupakov, PRL, 2009;

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



(Courtesy of D. Xiang)

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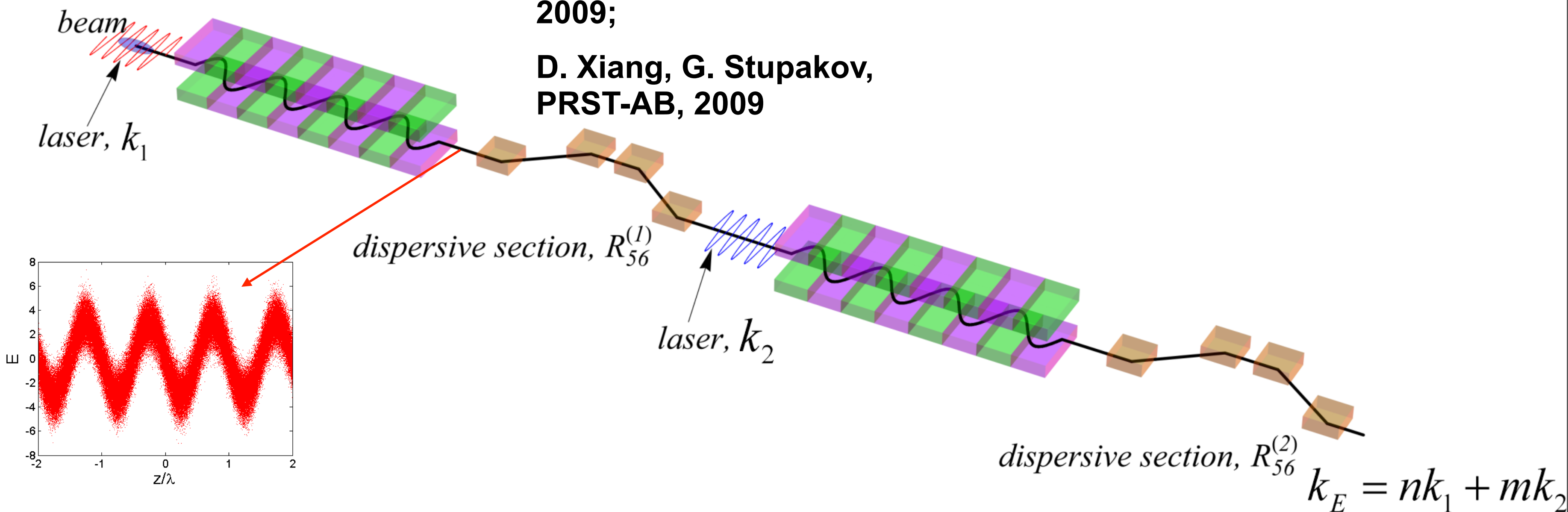

- First laser generates energy modulation in electron beam

(Courtesy of D. Xiang)

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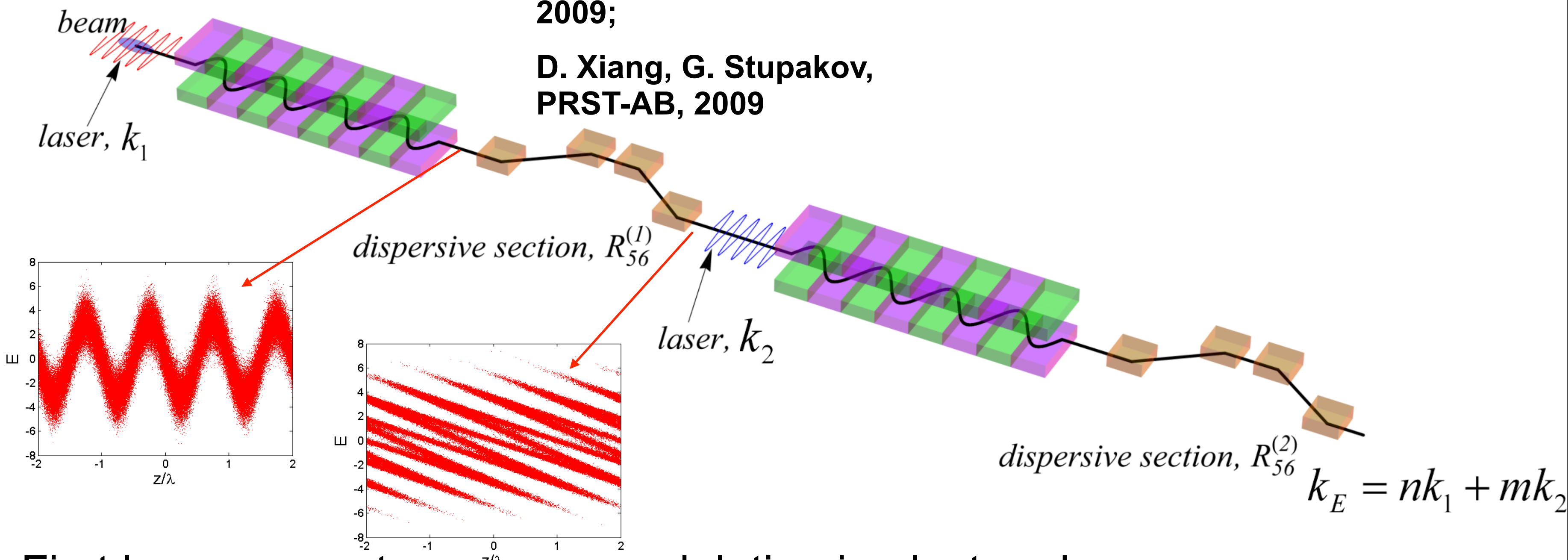

- First laser generates energy modulation in electron beam
- First strong chicane stratifies the longitudinal phase space

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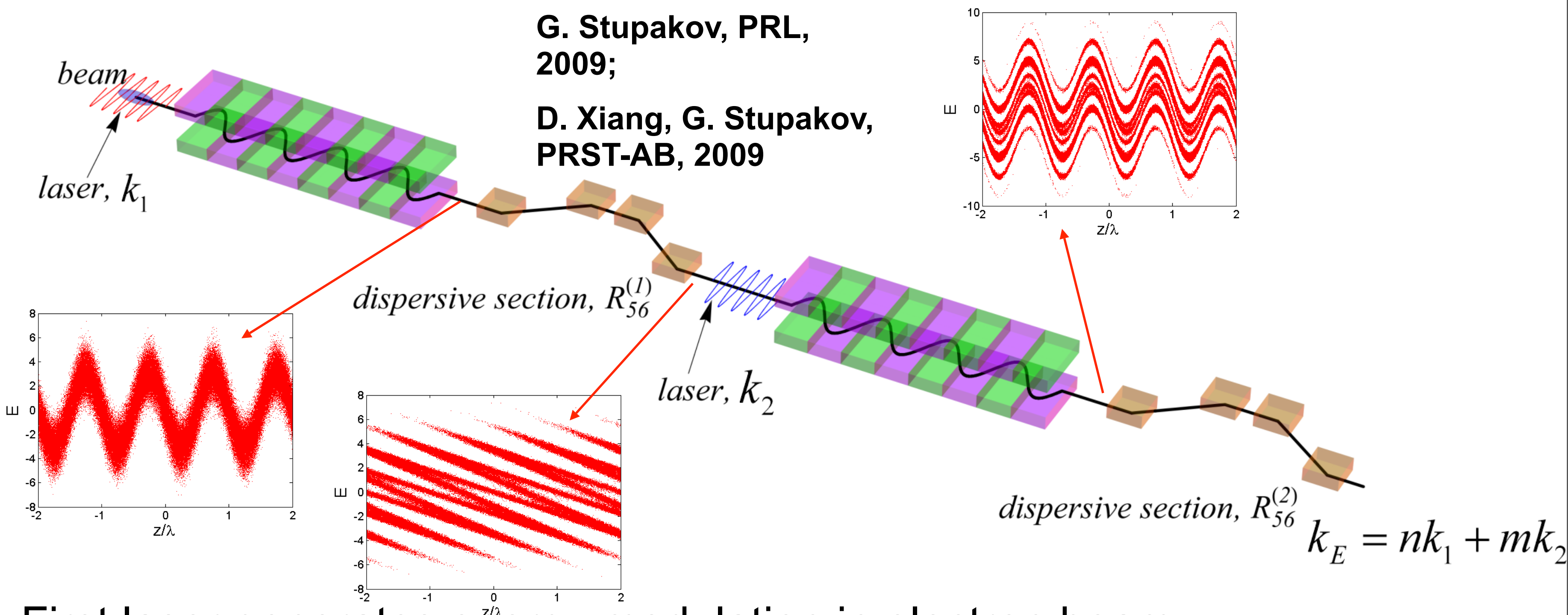

- First laser generates energy modulation in electron beam
- First strong chicane stratifies the longitudinal phase space
- Second laser imprints energy modulation

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(Courtesy of D. Xiang)

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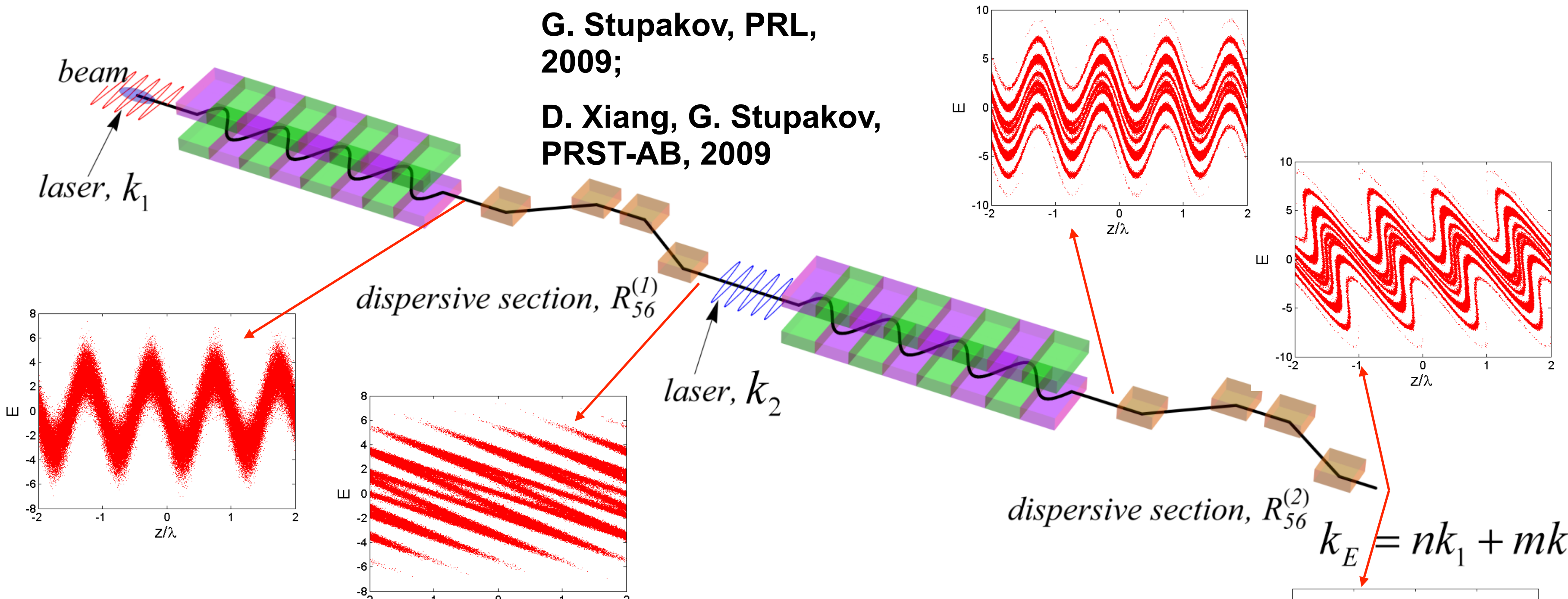

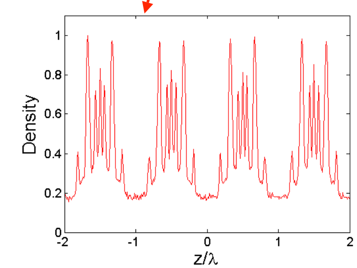

- First laser generates energy modulation in electron beam
- First strong chicane stratifies the longitudinal phase space
- Second laser imprints energy modulation
- Second chicane converts energy modulation into harmonic density modulation

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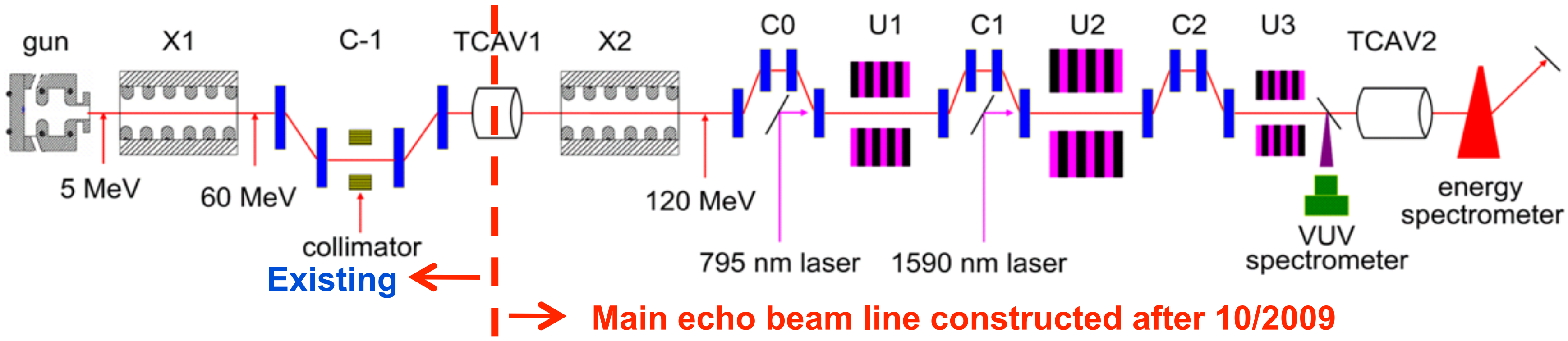
(Courtesy of D. Xiang)

EEHG FEL: Advantages and Challenges

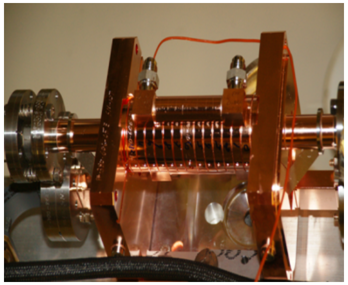
- **Advantages**
  - Excellent frequency up-conversion efficiency $$b_h \propto h^{-1/3}$$
  - High harmonics from small energy modulation
  - UV laser up-converted to soft x-rays in a single stage
  - Tunable through dispersion

- **Challenges**
  - Preservation of fine-grained phase-space correlations
  - Sensitive to SR and SC instabilities in transport,
  - higher-order transport coupling effects, and
  - laser quality and stability (x-verse mode purity, ~π/h phase control (A. Fry))

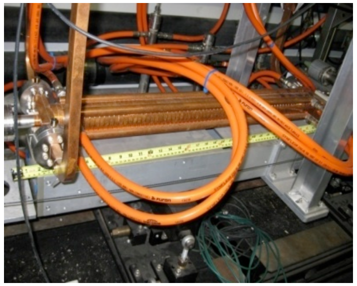
Echo experiment at NLCTA



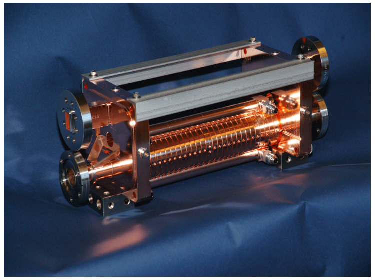
C-1



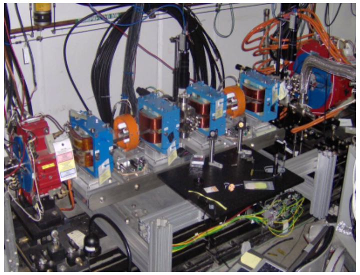
TCAV1



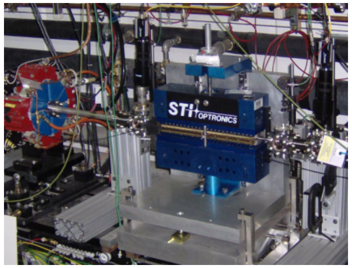
X2



TCAV2

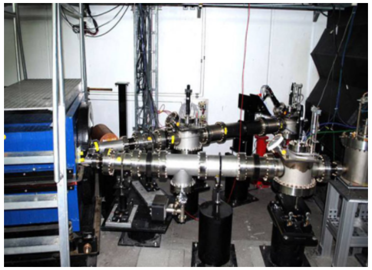


C1



U1

U2



spectrometer

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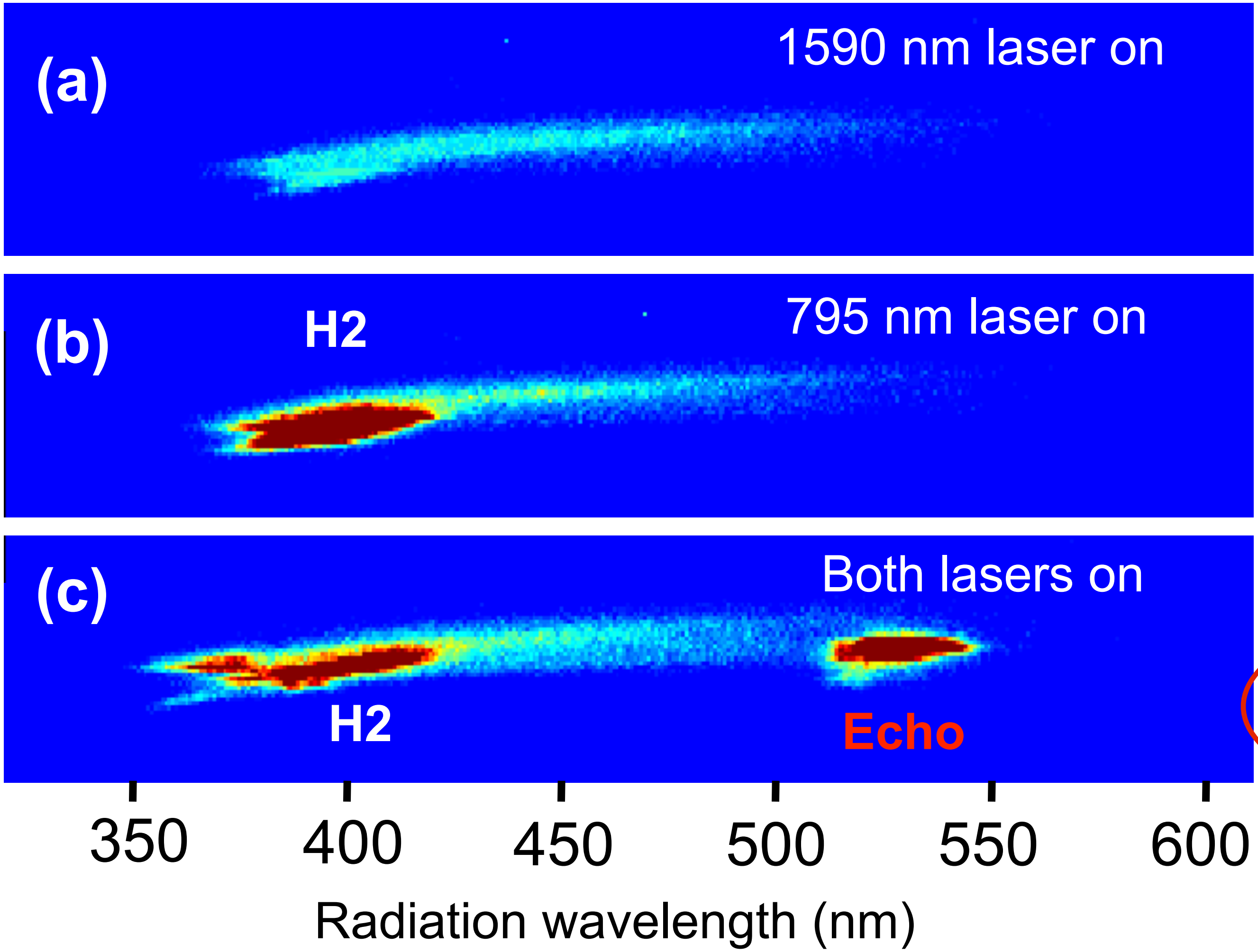
(Courtesy of D. Xiang)

First ECHO signal (2010)

D. Xiang *et al.*, PRL, 2010; Featured in Nature Photonics "News & Views"

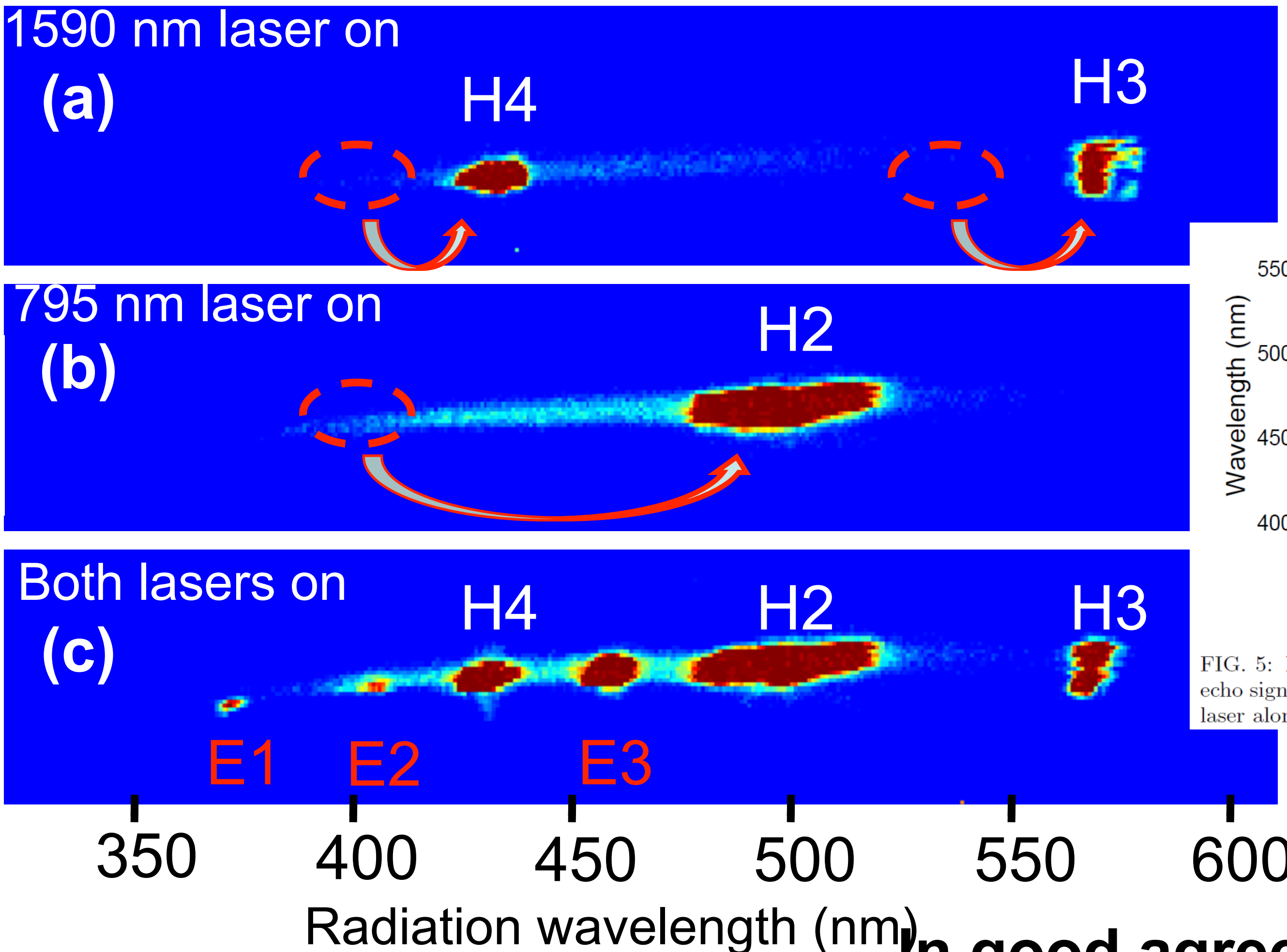


$$k_E = nk_1 + mk_2$$

$$n = -1$$
$$m = 5$$

$$k_E = 3k_2$$

First ECHO signals (2010)



Observation of multiple harmonics due to EEHG
Confirmed by varying beam chirp

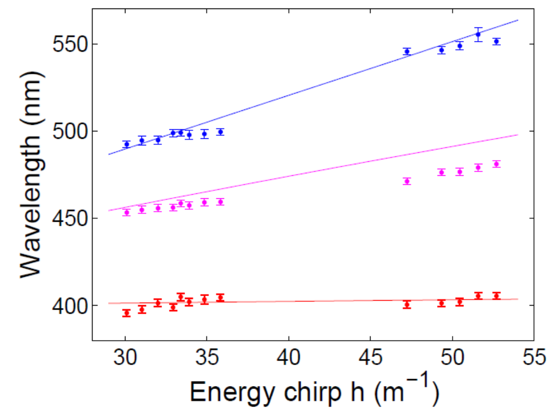
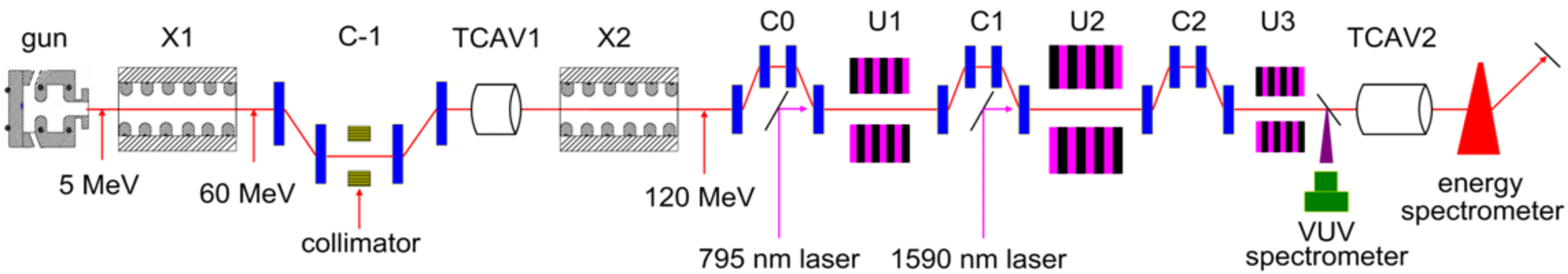


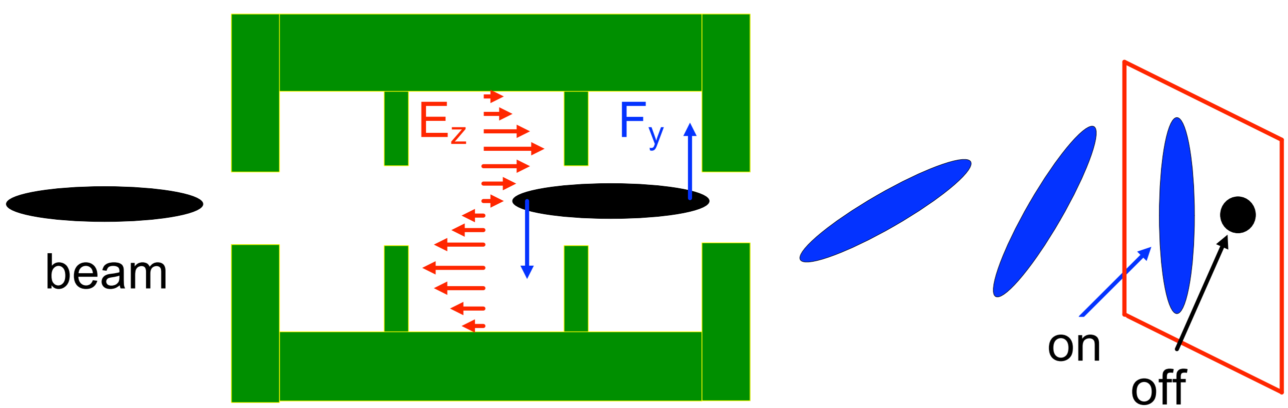
FIG. 5: Radiation wavelength vs beam energy chirp for the echo signal E2 (red), E3 (magenta) and that from the 795 nm laser alone H2 (blue).

In good agreement with theory

Pushing EEHG to realistic scenarios



- Advantage of EEHG lies in efficient upconversion even for $\Delta E \sim \sigma_E$
- Typically a 'laser heater' is used to increase beam slice energy spread
- RF transverse cavity used to increase slice energy spread



$$\delta = k\sigma_x$$

$$k = \frac{2\pi eV}{\lambda_{RF} E}$$

Reversible heater: C. Behrens, Z. Huang and D. Xiang, PRSTAB 15, 022802 (2012)

(Courtesy of D. Xiang)

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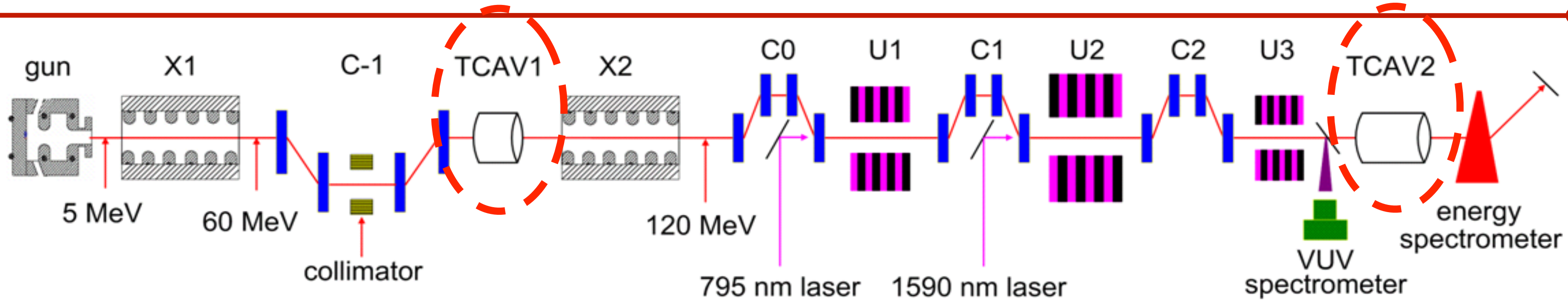
Pushing EEHG to realistic scenarios



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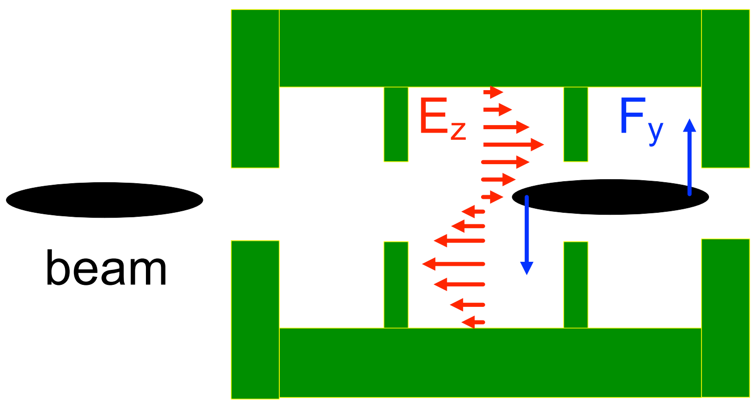

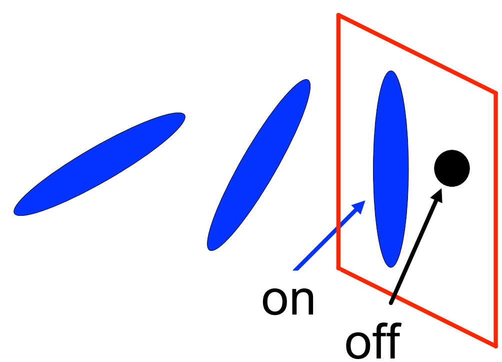

$$\delta = k\sigma_x$$

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Reversible heater: C. Behrens, Z. Huang and D. Xiang, PRSTAB 15, 022802 (2012)

(Courtesy of D. Xiang)

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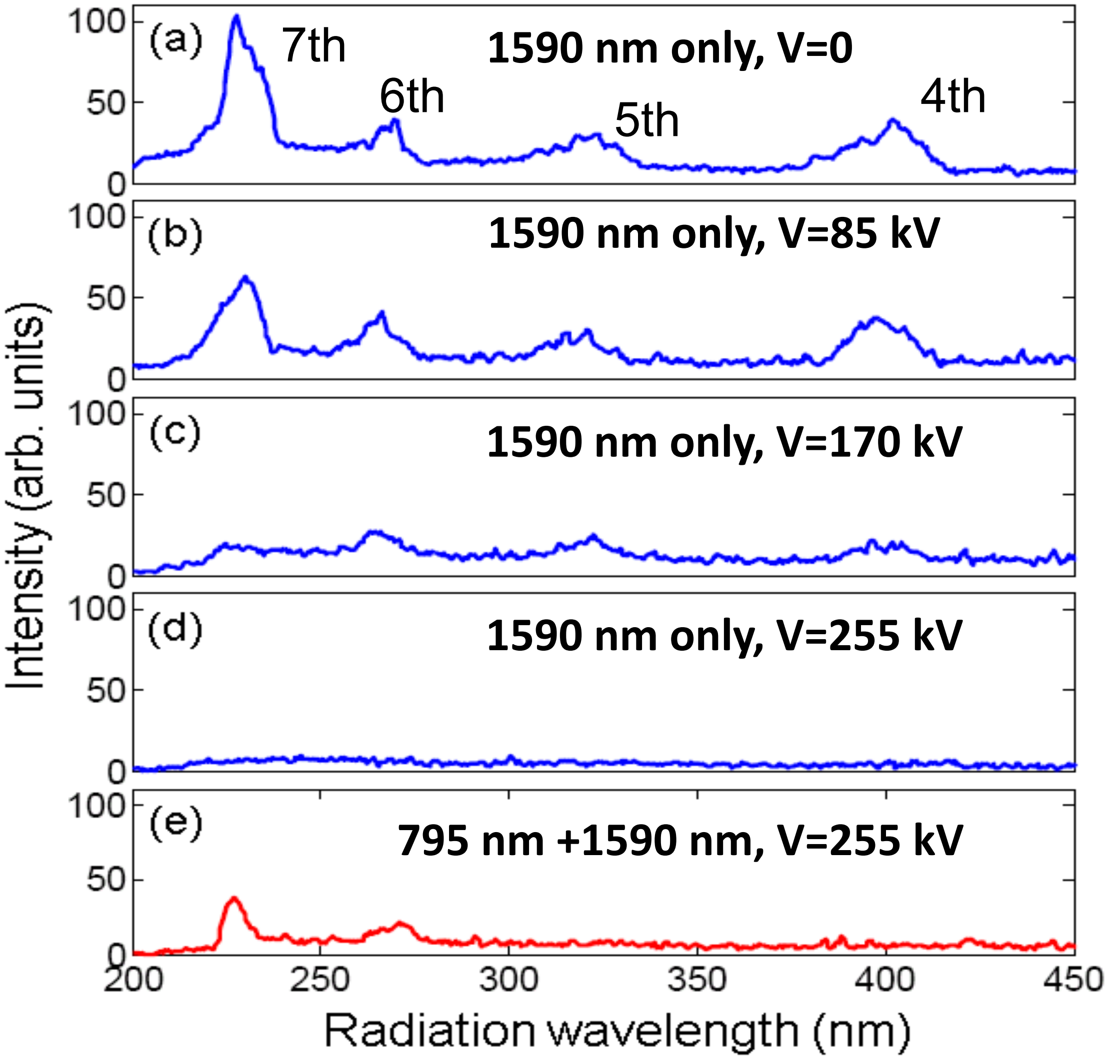
ECHO-7 (2011) $k_E = -2k_1 + 11k_2 = 7k_2$



- 4th to 7th harmonics from HGHG suppressed with increased beam slice energy spread from TCAV
- 7th harmonic reappears with the first laser on, like an echo
- 7th harmonic generated when energy modulation is about 2~3 times the beam slice energy spread

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

ECHO Publications thus far
(11 Journal articles; 9 conference Proceedings)

Journal Articles:

- Evidence of High Harmonics from Echo-Enabled Harmonic Generation for Seeding X-ray Free Electron Lasers, **PRL 108, 024802 (2012).**
- A novel diagnostic for measuring the laser modulation of the longitudinal phase space, Phys. Rev. ST Accel. Beams 14, 112801 (2011)**.**
- Triple modulator-chicane scheme for seeding sub-nanometer x-Ray free electron lasers.**Submitted to: New Journal of Physics (2011).**
- Laser assisted emittance transfer for storage ring lasing. **Submitted to:** P**hys. Rev. ST Accel.B eams (2011).**
- Longitudinal profile diagnostic scheme with subfemtosecond resolution for high-brightness electron beams. P**hys. Rev. ST Accel.B eams 14 (2011) 072802.**
- Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers. **Phys. Rev. Lett. 105 (2010) 114801.**
- Longitudinal-to-transverse mapping for femtosecond electron bunch length measurement. **Phys. Rev. ST Accel. Beams 13 (2010) 094001.**
- Laser Assisted Emittance Exchange: Downsizing the X-ray Free Electron Laser. **Phys.Rev.ST Accel. Beams 13 (2010) 010701.**
- Generation of intense attosecond x-ray pulses using ultraviolet laser induced microbunching in electron beams. **Phys .Rev. ST Accel. Beams 12 (2009) 060701.**
- Enhanced tunable narrow-band THz emission from laser-modulated electron beams. **Phys. Rev. ST Accel. Beams 12 (2009) 080701.**
- Echo-enabled Harmonic Generation Free Electron Laser. **Phys.Rev.ST Accel. Beams 12 (2009) 030702.**

Conference Proceedings:

- Observation and Characterization of Coherent Optical Radiation and Microbunching Instability in the SLAC Next Linear Collider Test Accelerator. PAC'11, SLAC-PUB-14451. (2011).
- Commissioning the Echo-Seeding Experiment Echo-7 at SLAC. FEL'10, SLAC-PUB-14450. (2011).
- Laser assisted emittance exchange. AIP Conf.Proc. 1299, 620-625 (2010).
- Echo-Enabled Harmonic Generation. IPAC'10, SLAC-PUB-14438 (2010).
- A Proof-of-principle Echo-enabled Harmonic Generation FEL Experiment at SLAC. IPAC'10, SLAC-PUB-14448, (2010).
- Preliminary results of the echo-seeding experiment ECHO-7 at SLAC. IPAC'10, SLAC-PUB-14450, (2010).
- Effects of energy chirp on echo-enabled harmonic generation free-electron lasers. SLAC-PUB-13547. (2009).
- Tolerance Study for the Echo-Enabled Harmonic Generation Free Electron Laser. SLAC-PUB-13644. (2009).
- Feasibility study for a seeded hard x-ray source based on a two-stage echo-enabled harmonic generation FEL. SLAC-PUB-13818. (2009).

(Courtesy of T. Raubenheimer)

Pushing towards higher harmonics

- Goal: Seeding to generate transform limited x-ray pulses

In going from UV to hard x-rays, beam manipulation and laser challenges suggest a dual path: EEHG+HHG

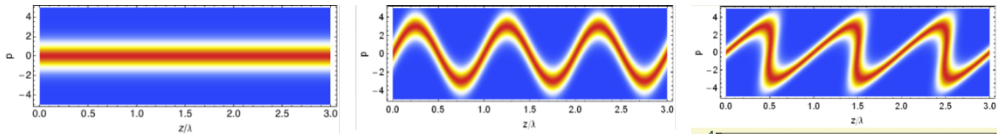
For EEHG:

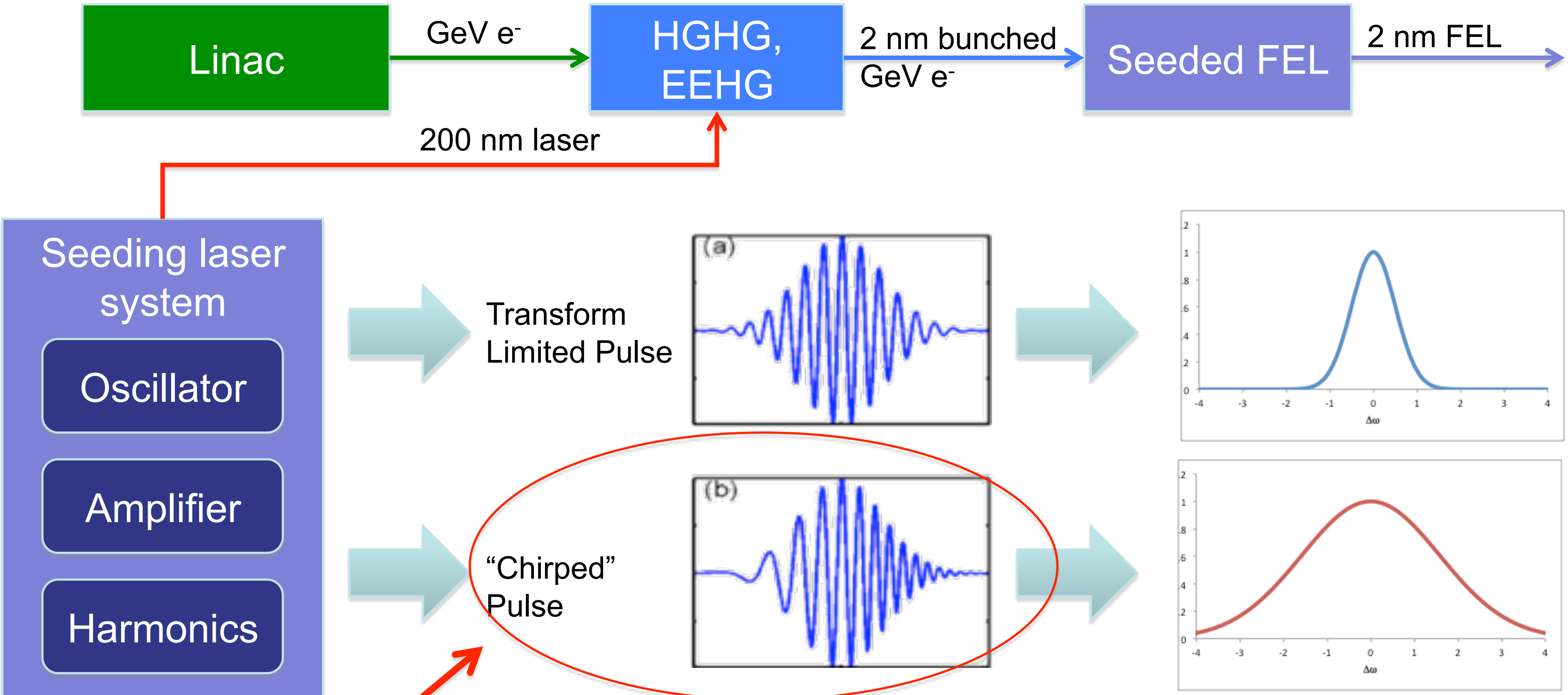
1) must be able to generate high-harmonics

2) and must be able to reliably reach x-ray wavelengths of interest

Parallel R&D on laser driven multiplicative seeding (example: N=100, 200nm laser 2nm x-rays)

e⁻ momentum





Need to **measure** and **control** laser spectral phase to better than ~π/N

(From of A. Fry, "**Laser phase control for FEL seeding**", **LBNL Workshop on seeding 2011**)

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Path to Echo-75

- **Phase-1: Echo-11 at 217 nm**
  - New OPA to provide seed laser at 2.385 um
  - Tune U2 (increase K from 2.09 to 2.76)
  - Parameterize EEHG versus slice emittance, slice energy spread
- **Phase-2: Echo-21 at 114 nm**
  - New X-band structure to increase beam energy to 165 MeV
  - New VUV spectrometer
- **Phase-3: Echo-32 at 75 nm**
  - New X-band structure to increase beam energy to 205 MeV
- **Phase-4: Echo-75 at 32 nm**
  - New chicane with R_{56} up to 15 mm
  - New undulator to generate fundamental radiation at 96 nm, with ample 3^{rd} harmonic at 32 nm

Phase-1: Echo-11 at 217nm

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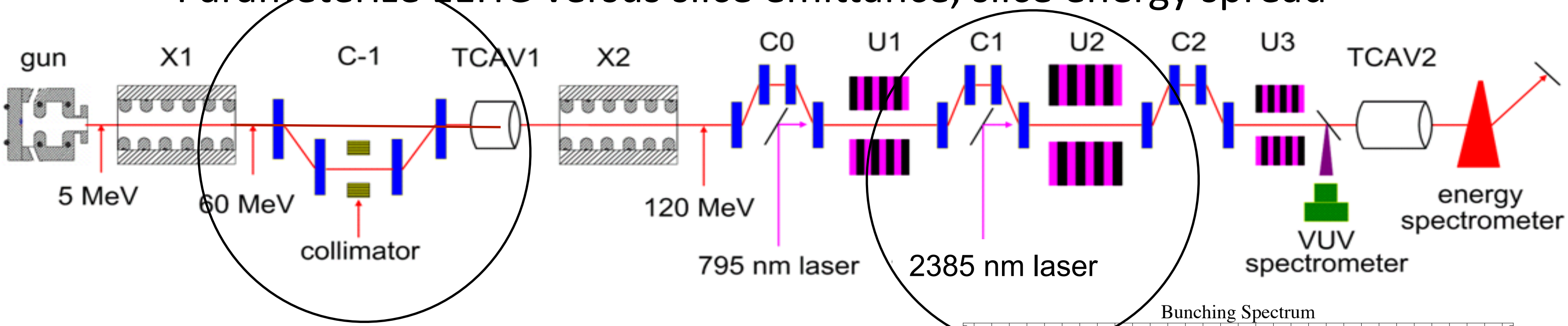

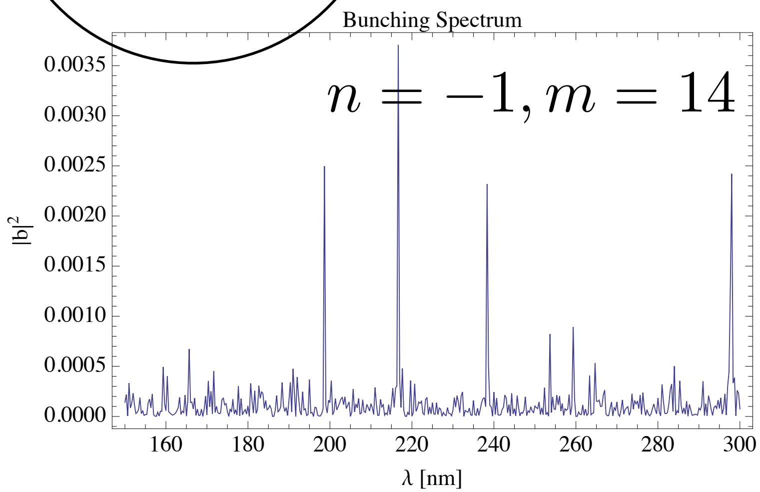

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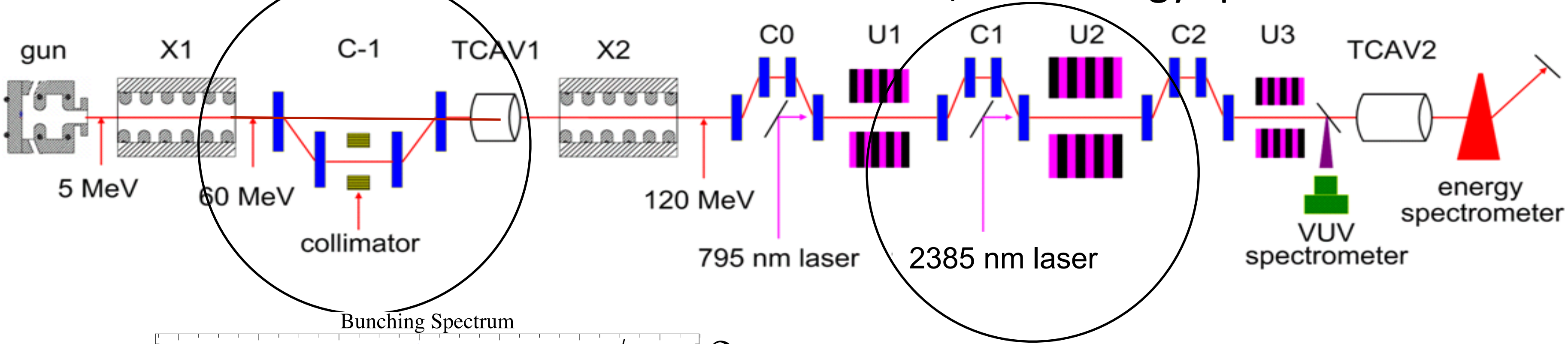

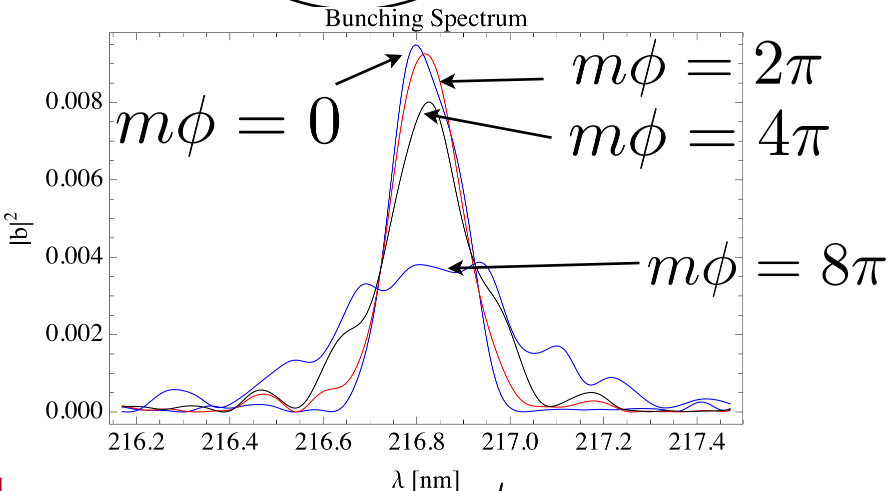

$n = -1, m = 14$

Laser phase error issues are relaxed for e-beam ≤ laser pulse length

ϕ = accumulated phase error over FWHM pulse of second laser

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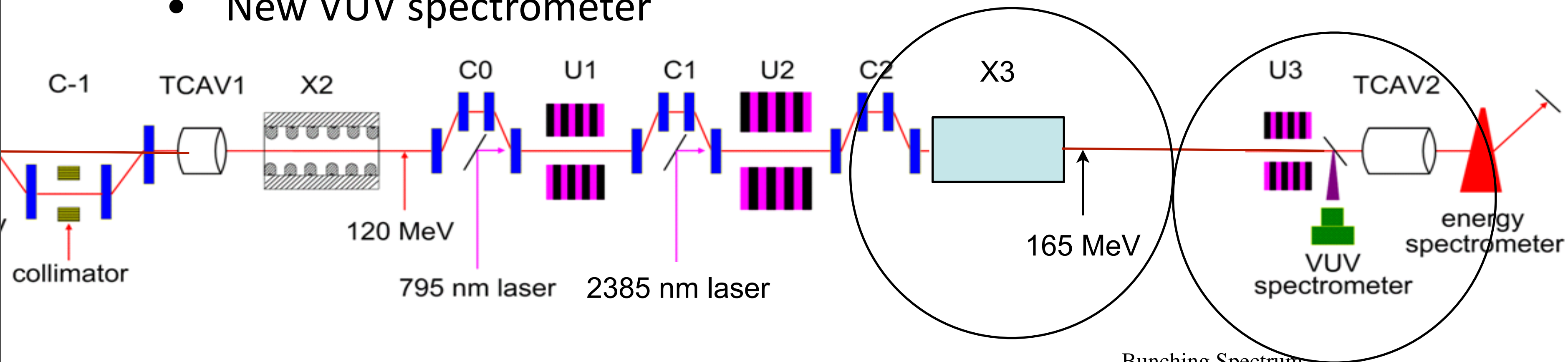
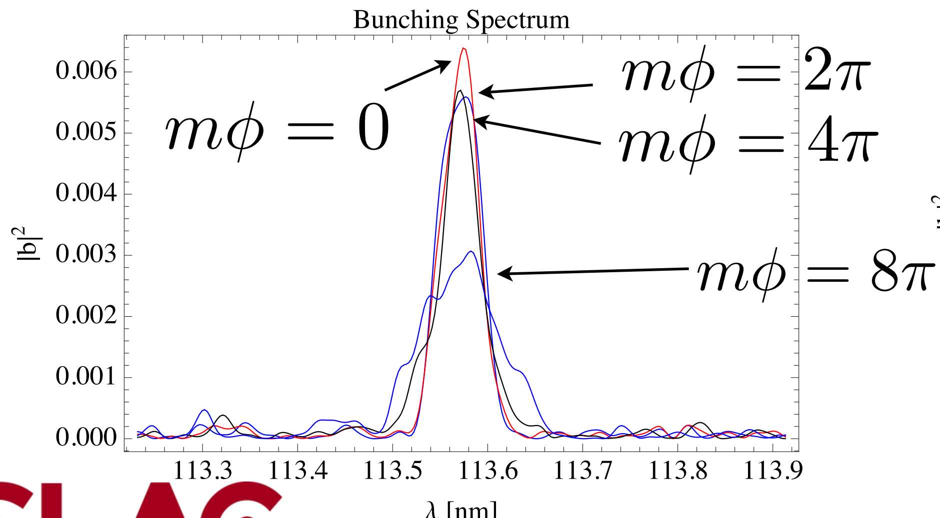
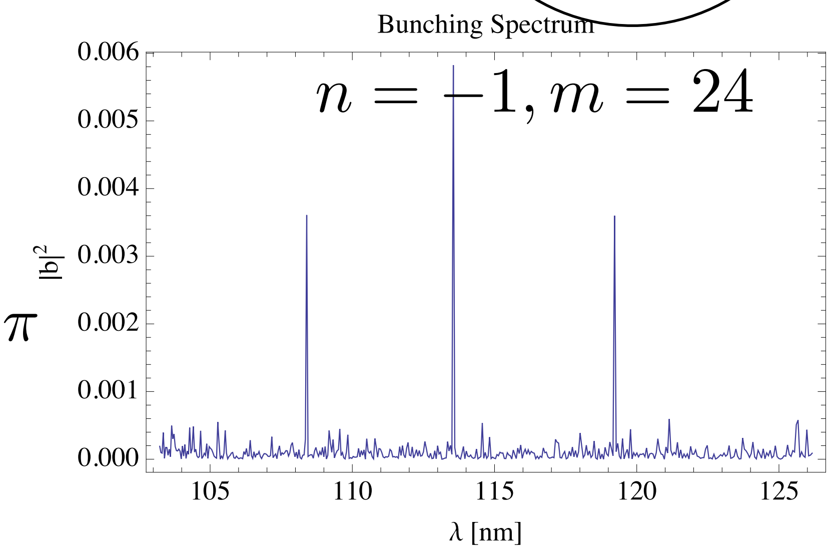
Phase-2: Echo-21 at 114 nm

- New X-band structure to increase beam energy to 165 MeV
- New VUV spectrometer

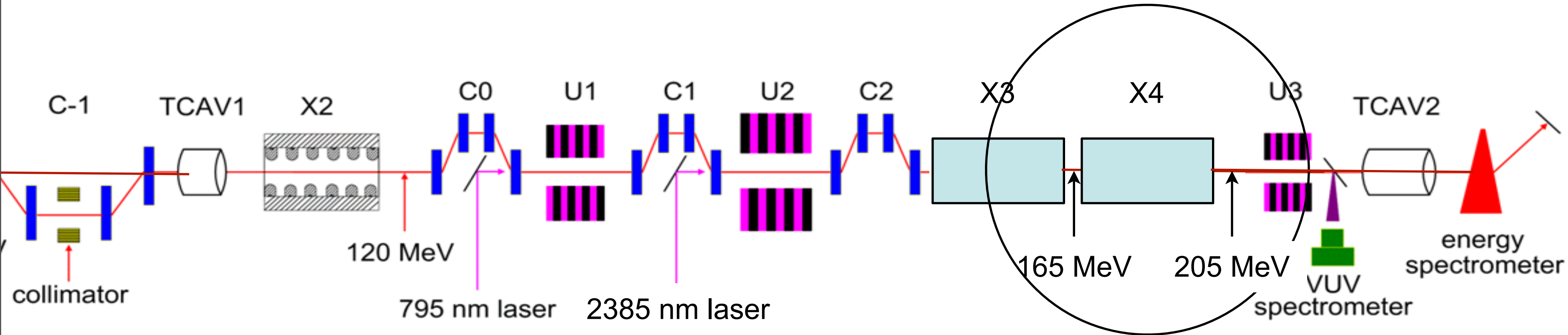


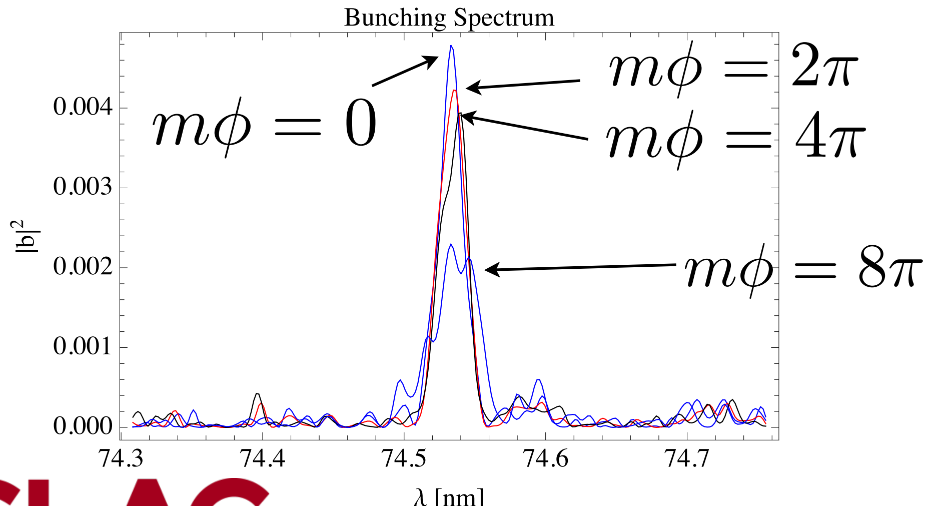


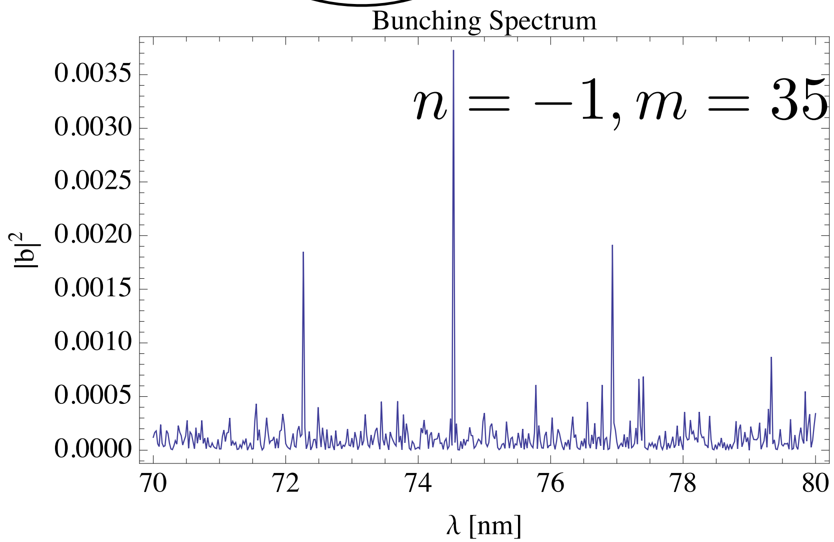


Phase-3: Echo-32 at 75 nm

- New X-band structure to increase beam energy to 205 MeV

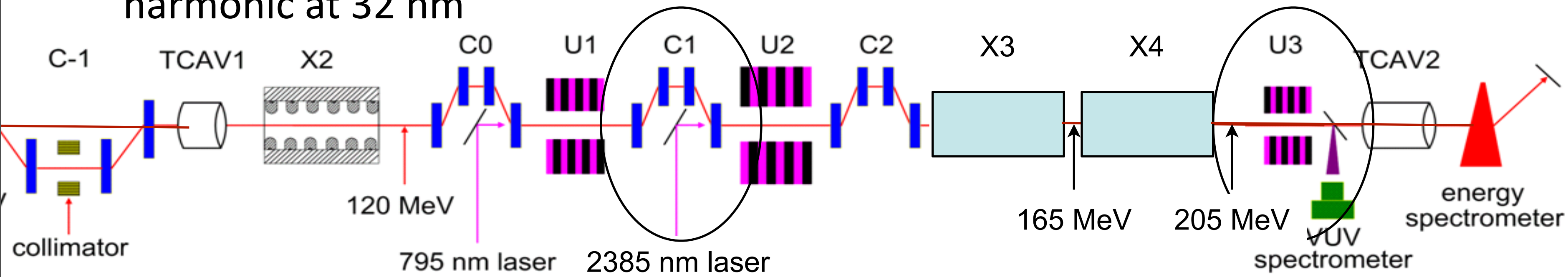


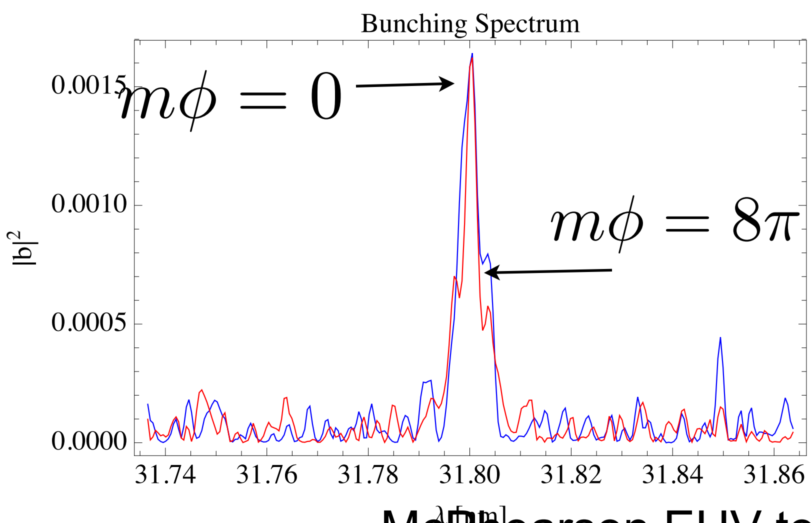




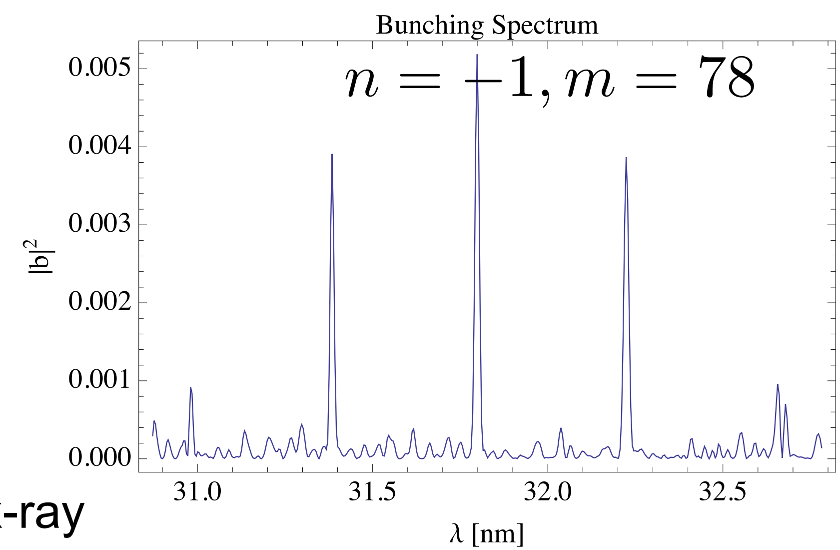
Phase-4: Echo-75 at 32 nm

- New chicane with R_{56} up to 15 mm
- New undulator to generate fundamental radiation at 96 nm, with ample 3rd harmonic at 32 nm





McPhearson EUV to soft x-ray spectrometer with <0.1 nm resolution, iCCD, MCP



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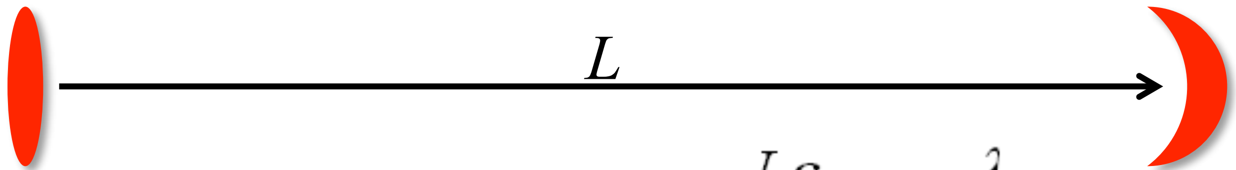
Summary

- EEHG is a promising scheme to generate fully coherent soft x-rays directly from UV lasers in a single stage
- EEHG's enhanced frequency up-conversion efficiency at the 7th harmonic has been demonstrated at SLAC's NLCTA
- Existing echo beamline, RF, and laser systems, provide firmly-established launching point to examine higher-harmonics in EEHG through a series of staged facility upgrades and dedicated experiments
- Parallel R&D in HHG and laser spectral phase effects and tolerances
- Use necessary upgrades to also benchmark collective effects, phase space manipulation and transport limitations

Thanks to Dao, Tor and to the Echo team!

Emittance effects

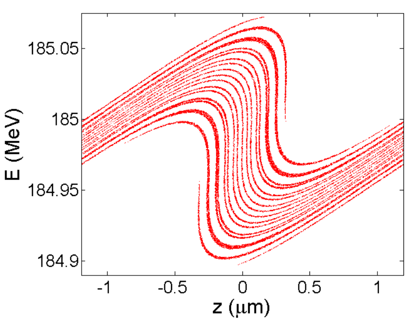
- Geometric aberration (path length   betatron amplitude)



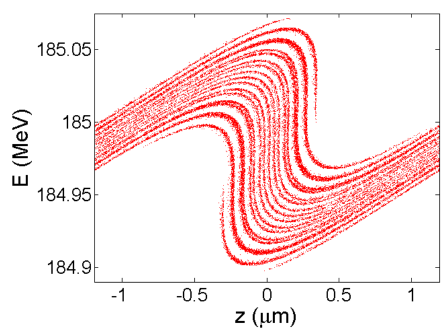
$$\Delta z \approx T_{522}\sigma_x'^2 + T_{544}\sigma_y'^2 \approx \frac{L\varepsilon_n}{\gamma < \beta >} < \frac{\lambda_{echo}}{2\pi}$$

- 1 µm emittance works for Echo-75

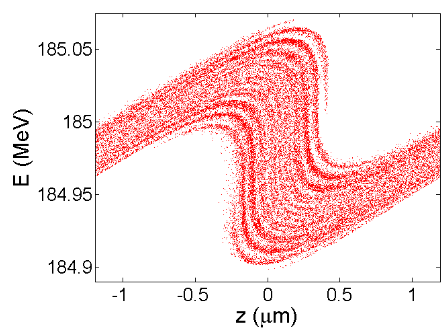
$$\Delta z \approx \frac{5[\mathrm{m}]\times 1000[\mathrm{nm}]}{360\times 5[\mathrm{m}]} \approx 2.8\mathrm{nm} < \frac{31.8}{2\pi}$$



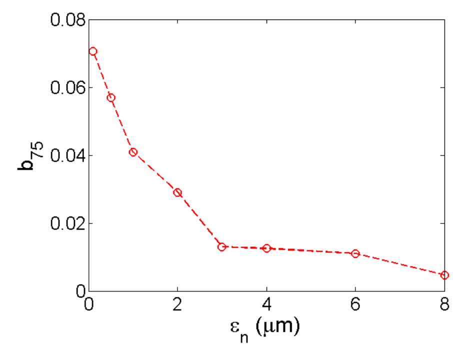
0.1 mm mrad



1.0 mm mrad



4.0 mm mrad



Bunching vs emittance

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(Courtesy of D. Xiang)