

# Beam Echo Effect for Generation of Short Wavelength Radiation

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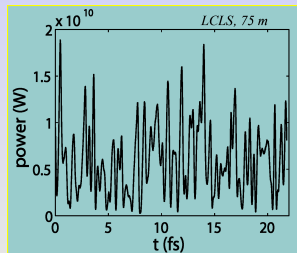
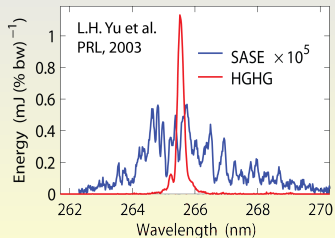


# Outline of the talk

- Generation of microbunching in the beam using the echo effect mechanism
  - HG seeding
  - Seeding using the echo mechanism
  - Why call it “echo”?
  - Some practical issues: ISR, CSR, leaking  $R_{51}$
- Echo-enhanced Harmonic Generation (EEHG) for FELs
  - FERMI@ELETTRA
  - LBNL proposal
  - Attosecond pulse generation using EEGH
  - Generation of THz radiation
- Planning EEHG experiment at SLAC
- Conclusions

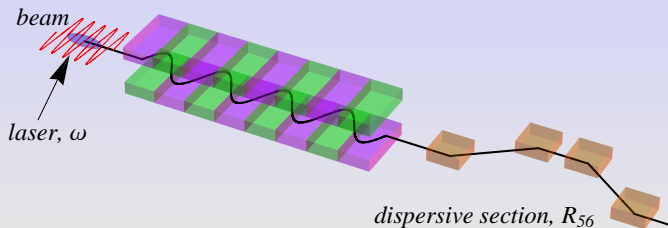
# Motivation

The SASE radiation starts from initial shot noise in the beam, with the resulting radiation having an excellent spatial coherence, but a rather poor temporal one.



One of the main advantages of the harmonic generation (HG) approach over the SASE FEL is that, by using up-frequency conversion of the initial seed signal, it allows to produce not only transversely, but also temporally coherent pulses. One has to use frequency multiplication of an existing laser.

# Standard approach to harmonic generation (HG)



$$\omega_L = \frac{2k_u c \gamma^2}{1 + K^2/2}$$

The laser-beam interaction in the undulator, through the IFEL mechanism, generates energy modulation in the beam at the laser wavelength with some amplitude  $\Delta E_{\text{mod}}$ . The laser power is proportional to  $\Delta E_{\text{mod}}^2$ .

# Computing beam density modulation

Dimensionless variables:  $A = \Delta E_{\text{mod}}/\sigma_E$  and  $B = R_{56}\kappa_L\sigma_E/E_0$   
where  $\kappa_L = \omega_L/c$ , and  $\sigma_E$  is the rms energy spread. One unit of B corresponds to the shift  $\approx \frac{1}{6}\lambda_L$  for a particle with  $\Delta E = 1\sigma_E$ .  
Beam current after the modulator

$$I(z)/I_0 = 1 + \sum_{k=1}^{\infty} 2b_k \cos(k\kappa_L z)$$

$b_k$  – the bunching factor for harmonic  $k$  ( $J_k$  is the Bessel function),

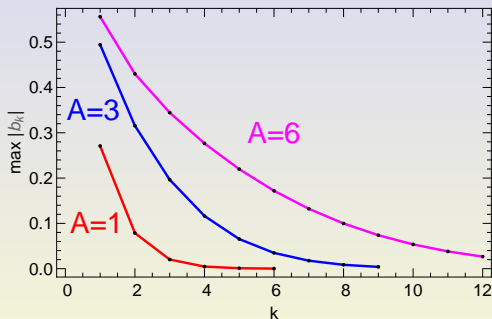
$$|b_k| = e^{-\frac{1}{2}B^2k^2} |J_k(ABk)|$$

In the limit of large  $k$ , optimized over B value,

$$|b_k| \approx \frac{0.68}{k^{1/3}} e^{-\frac{k^2}{2A^2}}$$

# High harmonics require large $A$

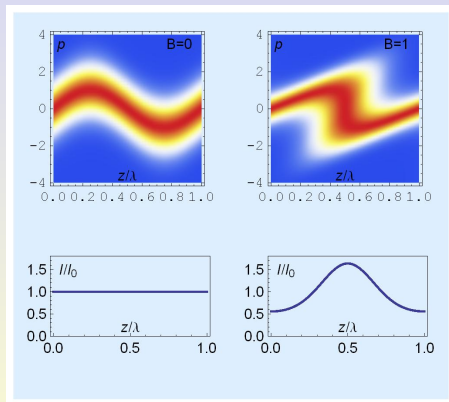
In the traditional approach, a very large energy modulation is required to get to higher harmonics,  $A \propto k$ . The  $R_{56}$  in these cases is small,  $B \sim 1/k$ .



Large  $A$  deteriorates beam properties as a lasing medium, and requires a large laser energy. Several stages are necessary to get to x-ray wavelengths.

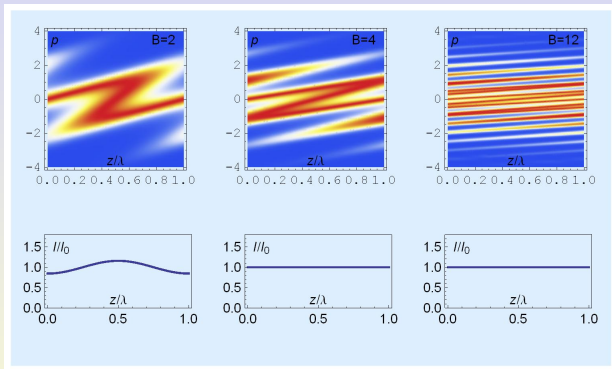
# Phase plots of density modulation

Case  $A = 1$ , various dispersion strengths.  $B = 1$  corresponds to the horizontal shift  $\lambda/2\pi$  for  $p = 1$ . Shown is one laser period.



# Increased chicane strength

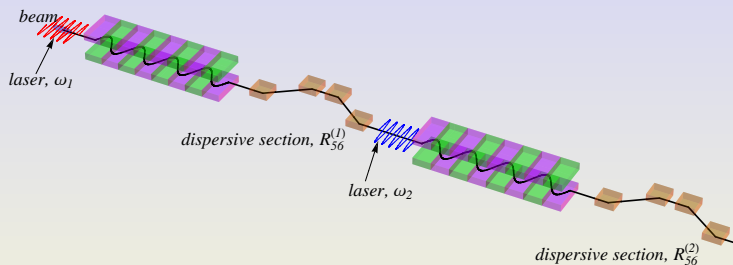
Increased chicane strength smears out the current modulation but introduces energy modulation in the phase space.



This energy modulation lowers the gain length for the FEL instability: see poster MOPC46.

# Using echo effect for high-frequency modulation

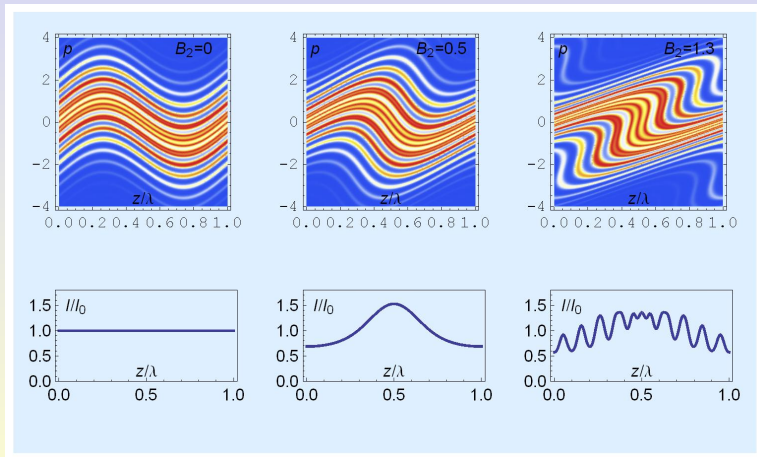
Novel approach (Stupakov, PRL, 2009): use a strong dispersion element in the first modulator and add one more:



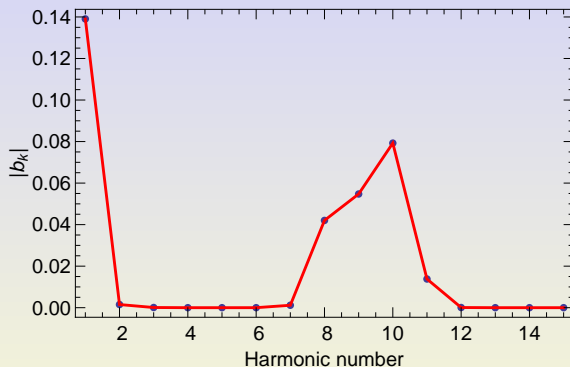
4 parameters: dimensionless energy modulations  $A_1$ ,  $A_2$ , and dimensionless strengths of chicanes  $B_1$ , and  $B_2$ .

# Phase plots of echo induced modulation

Phase space after the second modulator for  $A_1 = 1$ ,  $A_2 = 1$ ,  $B_1 = 12.1$  and various dispersion strengths  $B_2$ ,  $\omega_1 = \omega_2$ .



# Modulation amplitude versus harmonic number



Echo excites a relatively narrow spectrum around the optimized harmonic.

# 1D echo bunching theory

A general expression for the bunching factor  $b_k$  can be derived for arbitrary  $\omega_1$  and  $\omega_2$  (Xiang, Stupakov. PRST-AB, 2009). Practically, the case  $\omega_1 = \omega_2 = \omega$  can be realized with a single laser beam.

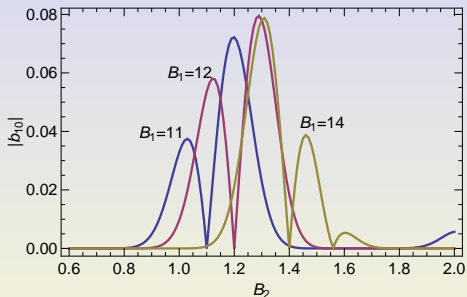
$$I(z)/I_0 = 1 + \sum_{k=1}^{\infty} 2b_k \cos(k\kappa_L z + \psi_k).$$

$$b_k = \left| \sum_{m=-\infty}^{\infty} e^{im\phi} J_{-m-k}(A_1((m+k)B_1 + kB_2)) \right. \\ \left. \times J_m(kA_2B_2) e^{-\frac{1}{2}((m+k)B_1 + kB_2)^2} \right|$$

where  $\phi$  is the phase between the laser beams 1 and 2. The maximized value of  $|b_k|$  does not depend on  $\phi$  (for  $\omega_1 = \omega_2$ )!

## An example, 10th harmonic

Assume  $A_1, A_2 = 1$  and optimize the amplitude of the 10th harmonic.



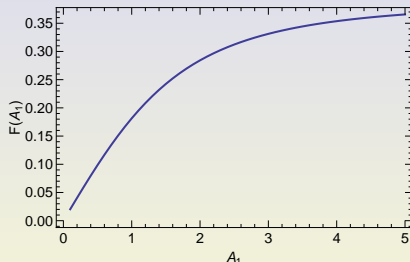
The bunching factor for  $k = 10$  as a function of parameter  $B_2$  for different values of  $B_1$ .

The maximal value of  $b_{10}$  is attained at  $B_1 = 12.1$ ,  $B_2 = 1.3$ , and is equal to 0.08. RMS energy spread of the beam is increased by 40%.

# Maximal echo modulation

What is the maximal echo modulation one can get with for given amplitudes  $A_1$ ,  $A_2$  and optimized dispersions?

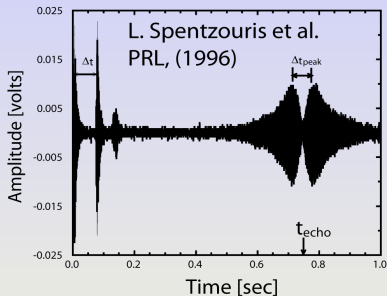
$$|b_k| = \frac{F(A_1)}{k^{1/3}}$$



In contrast to HG, there is no exponential suppression factor for large  $k$ ! The amplitude  $A_1$  may not be large, but the optimized strength  $B_1 \propto k$ .

# Why echo? Longitudinal orbital echo in accelerators

Echo effect can be observed in various media. They exhibit excitations which decay in time due to phase mixing of different components of the excitation without involving energy dissipation or diffusion. Echo in accelerators - Stupakov (1992).



Experiment at FNAL at the Antiproton Accumulator with a coasting beam,  $h_1 = 9$ ,  $h_2 = 10$ . The echo signal was observed at  $h = 1$ . Later similar experiments were performed on the CERN SPS. Theoretical development of longitudinal echo was carried out by E. Shaposhnikova and O. Brüning at CERN. In the FNAL experiment slippage is proportional to time; in echo microbunching the slippage is  $\propto R_{56}$  and is controlled by chicanes.

# Numerical examples for parameters of FERMI@ELETTRA

Beam parameters for the FERMI@ELETTRA project: the beam energy  $E_0 = 1.2$  GeV, the beam energy spread  $\sigma_E = 150$  keV and the laser wavelength is 0.24 micron.

Numerical examples

k	$ b_k $	$\lambda_r$ , nm	$A_1$	$A_2$	$R_{56}^{(1)}$ , mm	$R_{56}^{(2)}$ , mm
24	0.11	10	3	1	8.2	0.35
48	0.09	5	3	2	8.1	0.16
24	0.11	10	3	3	2.5	0.12

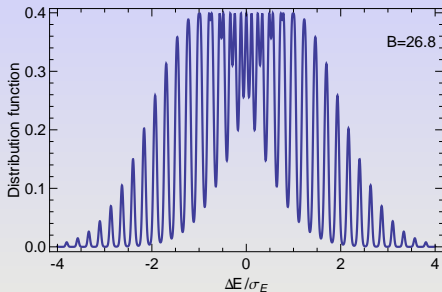
# Physics issues with EEHG

- Energy diffusion due to incoherent synchrotron radiation in chicanes
- CSR and associated microbunching instability
- Lattice nonlinearities and emittance effects—simulations with elegant
- Tolerances on magnetic field (leaking  $R_{51}$ ) -  $\Delta B/B \approx 10^{-3}$
- Finite laser beam size:  $\sigma_{L\perp} > 4\sigma_{B\perp}$
- Energy chirp in the beam

These issues are addressed in: D. Xiang and G. Stupakov, PRST-AB, 030702 (2009); Z. Huang, D. Ratner, G. Stupakov, D. Xiang, SLAC-PUB-13547 (2009); D. Xiang and G. Stupakov, SLAC-PUB-13644, (2009); PAC09 paper.

# Incoherent synchrotron radiation in the first chicane

Large value of  $R_{56}^{(1)}$  generates a fine structure over the energy. For  $\lambda_r = 10$  nm case the width of the modulation is  $\sim 0.2\sigma_E \sim 30$  KeV. The scaling is  $\Delta E \sim \sigma_E/k$ .



The incoherent energy spread after passing a dipole

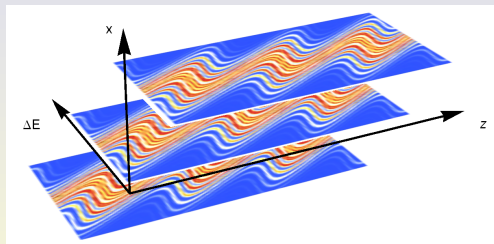
$$\Delta\sigma_E = 4.5 \text{ KeV} \times \sqrt{\frac{L \text{ (m)}}{[\rho \text{ (m)}]^3} [E \text{ (GeV)}]^{7/2}}$$

can be a fraction of keV. Choosing larger bending radius in the chicane would decrease  $\Delta\sigma_E$ .

ISR will limit the harmonic number  $k$  at large energies of the beam.

# Parasitic beam modulation and the CSR effect

As the beam travels through the chicanes, it senses variable  $R_{56}$ . In combination with the energy modulation, in 1D, this will generate undesirable microbunching inside the dipoles of the dispersion sections. The microbunching would result in CSR and uncontrolled energy modulation of the beam. Fortunately, this modulation is suppressed due to  $R_{51}$  and  $R_{52}$ .

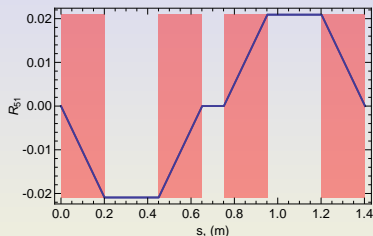


Phase-planes  $(\Delta E, z)$  are shifted in  $z$ -direction,  $\Delta z = R_{51} x$ ; this results in washing out of the density modulation when projected onto the  $z$  axis.

# Parasitic beam modulation and the CSR effect

The suppression factor due to  $R_{51}$ :

$$\sim \exp\left(-k_{\text{mod}}^2 R_{51}^2 \sigma_x^2 / 2\right)$$



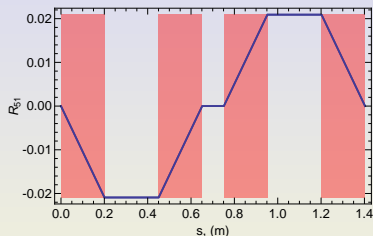
$R_{51}$  in the second chicane. For  $\sigma_x = 40 \mu\text{m}$  and  $R_{51} \sim 0.01$ , microbunching with  $\lambda_{\text{mod}} < 1 \mu\text{m}$  will be smeared out.

Caveat! This is the mechanism which the LCLS laser heater relies on to smear out modulation introduced into the beam by the energy modulation in the heater. There are some unexplained effects in the laser heater ("trickle heating") which might indicate a more complicated dynamics of the modulation. See Z. Huang's talk on Wednesday.

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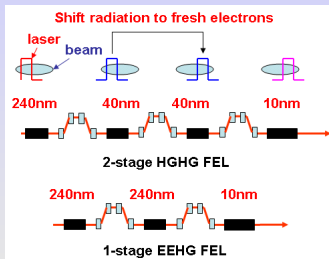
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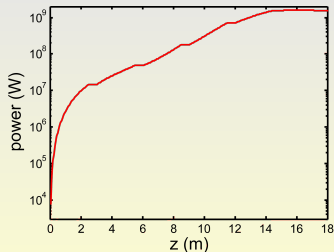
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# EEHG for FERMI@ELETTRA—10 nm case



Main parameters:  
Beam energy: 1.2 GeV  
Energy spread: 150 keV  
Emittance: 1.5 mm mrad  
Peak current: 800 A



EEHG at 24th harmonic of 240 nm.  
The peak power at 10 nm is 1.6 GW.  
Advantages of EEHG: enhances FEL performance, simplifies design.

# LBNL soft x-ray FEL with EEHG

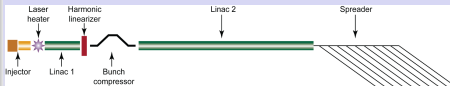
Main parameters:

Beam energy 2.4 GeV

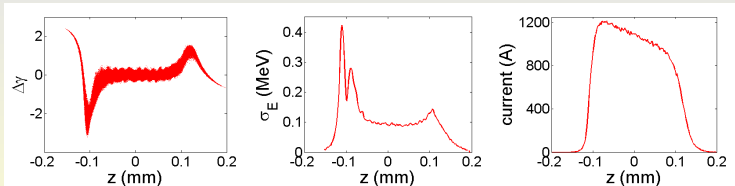
Energy spread: 100 keV

Emittance: 0.7 mm mrad

Peak current: 1 kA

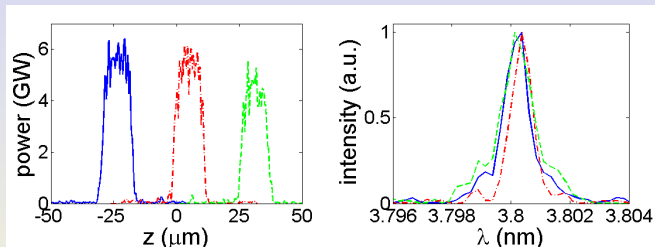


The beam distribution is obtained from IMPACT-Z simulation by J. Qiang.



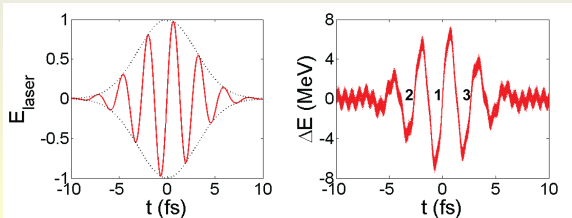
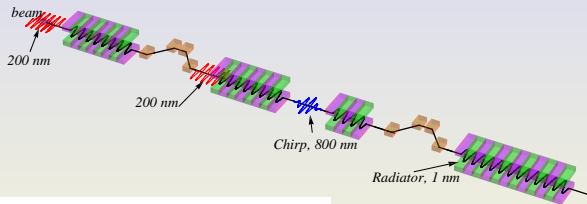
# Time dependent simulations for LBNL soft x-ray FEL

Radiation at 3.8 nm (50th harmonic of 190 nm laser). The spectrum is close to the Fourier limit.



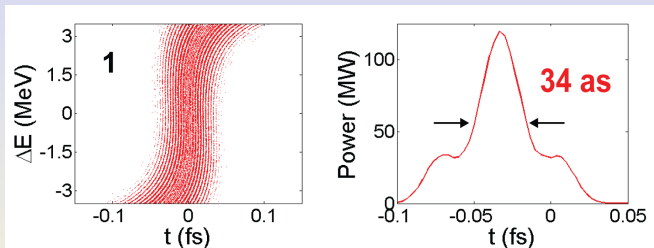
# Generation of attosecond x-ray pulses using EEGH FEL

Adding a chirp element to the system results in additional compression of the microbunching (Xiang, Huang, Stupakov. PRST-AB, 2009). The chirp is provided by a short long-wavelength (800 nm) laser pulse. The echo generates 20th harmonic which is further compressed by a factor of 10.



# Generation of attosecond x-ray pulses using EEGH FEL

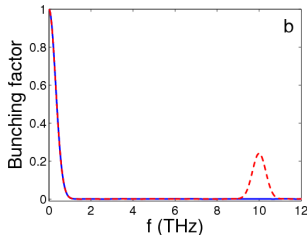
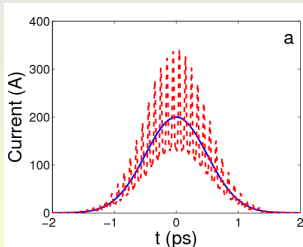
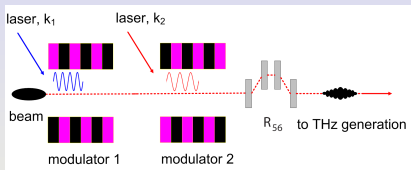
The 'right' chop at position 1 generates a single x-ray spike of attosecond duration.



Zholents and Penn (CBP Tech Note 402, 2009) proposed to use echo to generate two attosecond pulses, 2.27 nm and 3.03 nm, from the laser wavelength 200 nm and 800 nm.

# Using two-wave mixing for THz radiation

Beam energy  $E = 60$  MeV. Mixing two laser frequencies,  $\lambda_1 = 800$  and  $\lambda_2 = 1560$ , generates  $f = 10$  THz modulation in the beam (Xiang, Stupakov. PRST-AB, 2009).

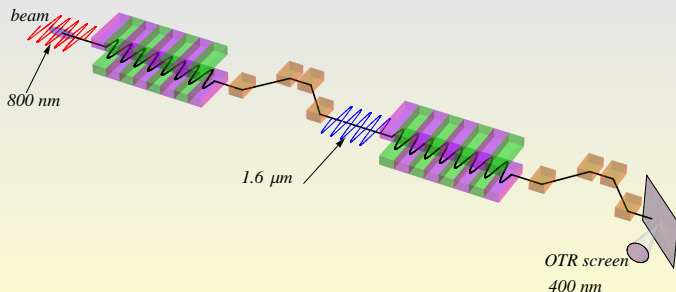


## EEHG related papers at FEL09

- MOPC02. E. Allaria *et al.* Feasibility Studies for Single Stage Echo-Enabled Harmonic in FERMI FEL-2.
- MOPC45. Z. Huang *et al.* Effects of energy chirp on echo-enabled harmonic generation free-electron lasers.
- MOPC46. G. Stupakov *et al.* FEL and optical klystron gain for an electron beam with modulated energy distribution.
- MOPC73. G. Penn, A. Zholents. Synchronized attosecond pulses for X-ray spectroscopy.
- MOPC79. D. Xiang *et al.* Feasibility study for a seeded hard x-ray source based on a two-stage echo-enabled harmonic generation FEL.
- MOPC80. D. Xiang *et al.* Generation of attosecond x-ray pulses beyond the atomic unit of time using laser induced microbunching in electron beams.

# Planning an echo experiment at NLCTA at SLAC

A proof-of-principle experiment to demonstrate EEHG is currently being planned at SLAC National Accelerator Laboratory. NLCTA at SLAC is a facility with an rf gun, beam linac and a laser. The beam energy is 60 – 200 MeV. There is about 8-10 m of free space for a new experiment.



# Echo experiment at NLCTA at SLAC

The parameters of the experiment:

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Electron beam energy	120 MeV
Normalized emittance	$< 8 \mu\text{m}$
Slice energy spread	$< 10 \text{ keV}$
First laser wavelength	785 nm
Second laser wavelength	1570 nm

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The echo induced modulation at 7th harmonic of the second laser (224 nm) will be generated in the beam. The spectrum of the coherent OTR signal at this harmonic will be measured with a high-resolution optical-UV spectrometer.

# Conclusions

- We proposed a new method of seeding high-frequency microbunching in an electron beam. The main advantage of the method is its high efficiency of upshifting the laser frequency. Analytical theory in 1D is confirmed by 3D simulations.
- Various physical effects that tend to smear out the microbunching were studied and simulated in 3D and the tolerances were formulated.
- We simulated the FEL performance for parameters of several projects based on HGHG. The results of the simulations show a feasibility of achieving 20-50th harmonic in EEGH FEL.
- An experiment at SLAC is being planned to demonstrate the echo microbunching.

# Thanks

Thanks to my collaborator Dao Xiang, who made crucial contributions to many aspects of the EEHG studies. Thanks to Z. Huang, D. Ratner and Y. Ding.