# Echo-Enabled Harmonic Generation

G. Stupakov
SLAC NAL, Stanford, CA 94309

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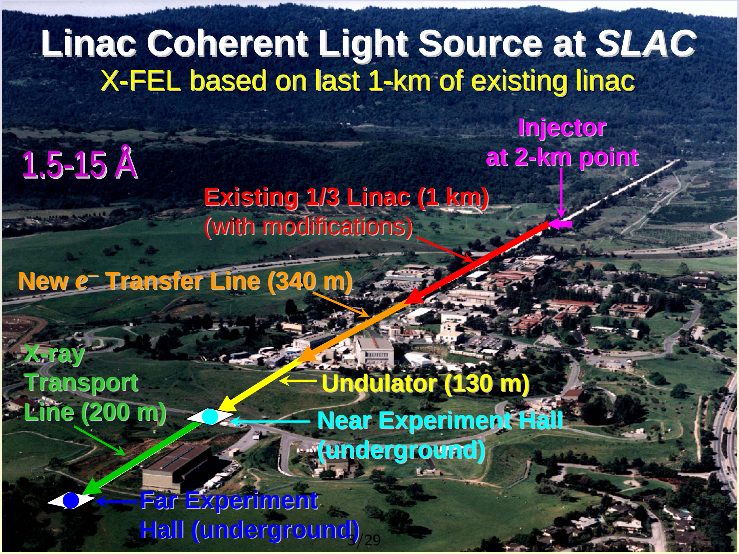
# Outline of the talk

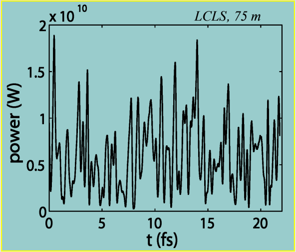
- Generation of microbunching in the beam using the echo effect mechanism
  - HG seeding
  - Seeding using the echo mechanism
  - Why call it "echo"?
  - Some practical issues: ISR, CSR, leaking $R_{51}$
- Echo-Enabled Harmonic Generation (EEHG) for FELs
  - VUV-Soft X-ray FEL at LBNL
  - Attosecond pulse generation using EEGH
- EEHG experiment at SLAC
- Conclusions

# Linac Coherent Light Source at SLAC



# 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.

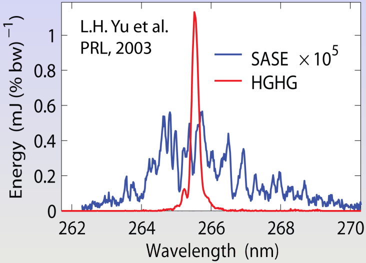



There are several approaches to generation of longitudinally coherent FEL radiation based on seeding techniques

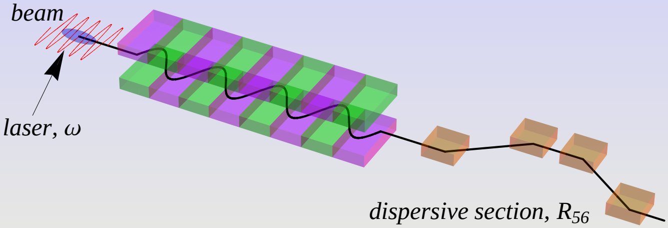
- High Harmonic Generation (HHG)
- High-Gain Harmonic Generation (HGHG)
- Echo-Enabled Harmonic Generation (EEHG)
- Self seeding

# HGHG experiment

HGHG has been demonstrated at 3d harmonic of 800 nm at the NSLS [L. H. Yu et al., PRL, **91**, 074801, 2003]



# HGHG seeding mechanism

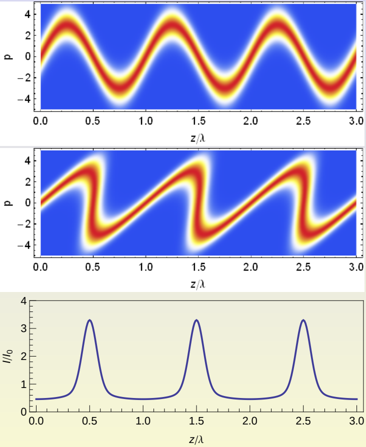


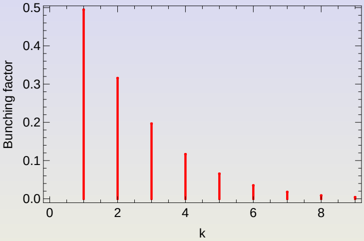

$$\omega_L = \frac{2k_u c\gamma^2}{1 + K^2/2}$$

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

# HGHG and high harmonics

## HGHG phase space and current modulation for $A = \Delta E_{mod}/\sigma_E = 3$



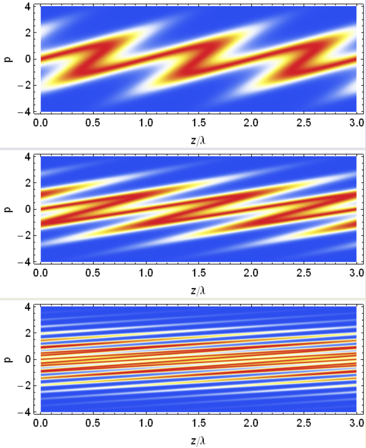

### HGHG harmonics

In the limit of large $k$, the optimized bunching factor,

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

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.

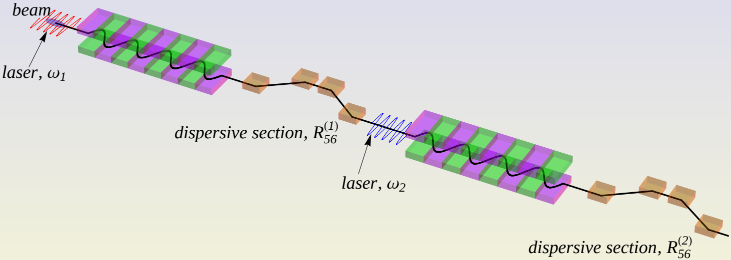
# Very strong chicane?




Increased chicane strength generates fine structures in the phase space, but smears out the current modulation.

# Using echo effect for high-frequency modulation

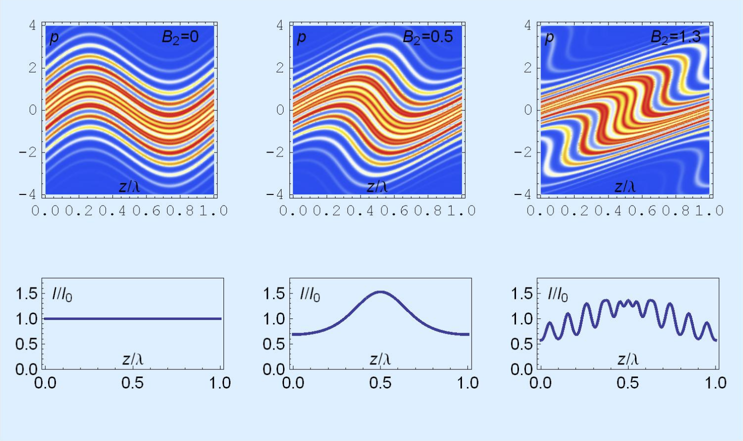
Novel approach (Stupakov, PRL, 2009): use a strong dispersion element in the first modulator and add one more modulator-chicane:



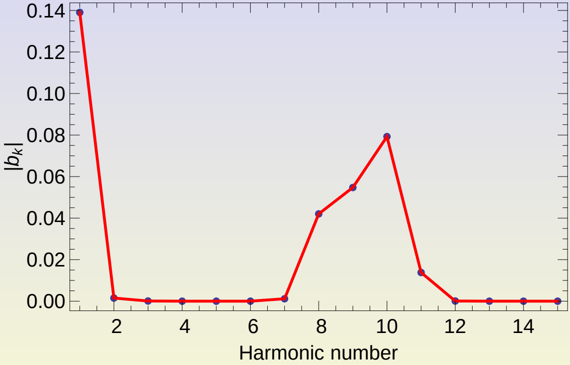

4 parameters: dimensionless energy modulations $A_1 = \Delta E_1/\sigma_E$, $A_2 = \Delta E_2/\sigma_E$, and dimensionless strengths of chicanes $B_1 = R_{56}^{(1)}\kappa_L\sigma_E/E_0$, and $B_2 = R_{56}^{(1)}\kappa_L\sigma_E/E_0$.

# 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.

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

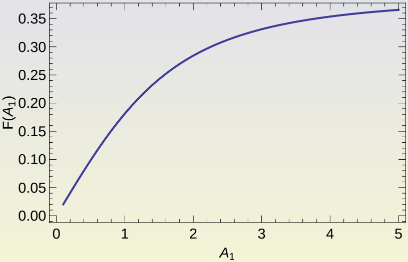
$$b_k = \Bigg| \sum_{m=-\infty}^{\infty} e^{im\phi} J_{-m-k}\left(A_1((m+k)B_1 + kB_2)\right) \times J_m\left(kA_2B_2\right) e^{-\frac{1}{2}((m+k)B_1+kB_2)^2} \Bigg|$$

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

# Maximal echo modulation

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

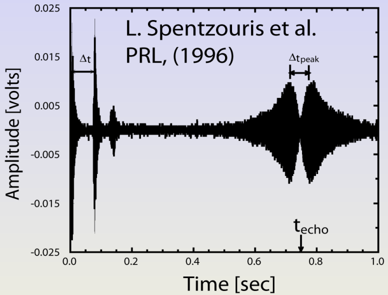
$$|b_k| = \frac{F(A_1)}{k^{1/3}}$$




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

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

# Physics issues with EEHG

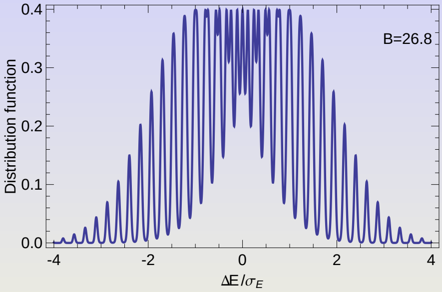
- Energy diffusion due to incoherent synchrotron radiation in chicanes
- CSR and associated microbunching instability

- 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 issued 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 and FEL09 papers.

# 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 $\Delta E \sim \sigma_E / k$.



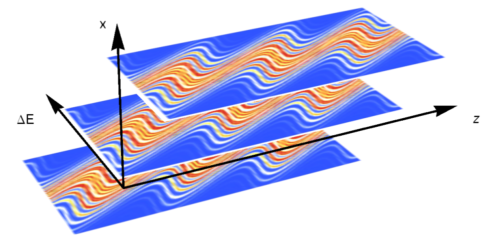

The incoherent energy spread after passing a dipole

$$\Delta\sigma_E = 6.4\ \mathrm{KeV} \times \sqrt{\frac{L\,(\mathrm{m})}{[\rho\,(\mathrm{m})]^3}}\,[E\,(\mathrm{GeV})]^{7/2}$$

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

# 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 $R_{52}$.

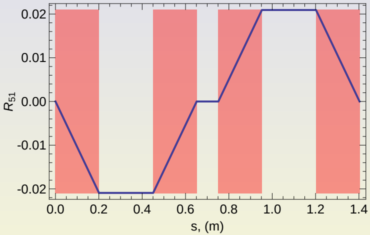



Phase-planes $(\Delta E, z)$ are shifted in $z$-direction, $\Delta z = R_{51} x$; this results in washing out of the density modulation when projected onto the $z$ axis.

# Parasitic beam modulation and the CSR effect

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

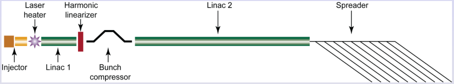
$$\sim \exp\left(-k_{\mathrm{mod}}^2 R_{51}^2 \sigma_x^2/2\right)$$



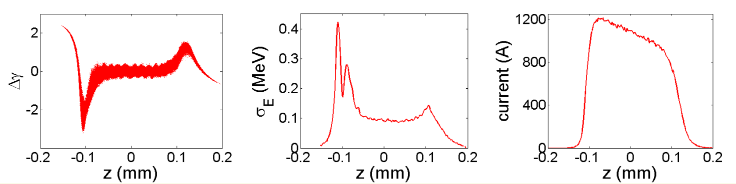

$R_{51}$ in the second chicane. For $\sigma_x = 40$ μm and $R_{51} \sim 0.01$, microbunching with $\lambda_{\mathrm{mod}} < 1$ μm will be smeared out.

# 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

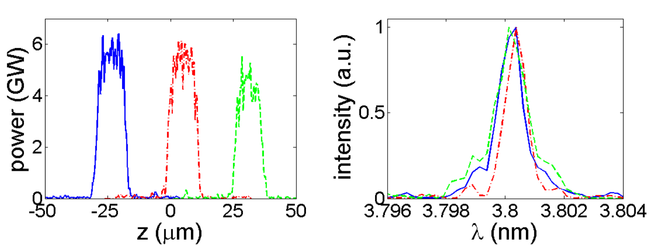



The beam distribution is obtained from IMPACT-Z simulation by J. Qiang.



# Time dependent simulations for LBNL soft x-ray FEL

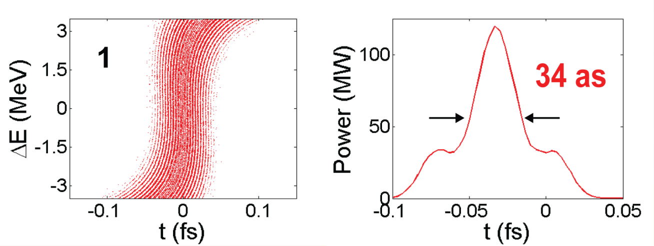
Radiation at 3.8 nm (50th harmonic of 190 nm laser). The spectrum is close to the Fourier limit.




Simulations were carried out with GENESIS.

# Attosecond x-ray pulses with EEGH FEL

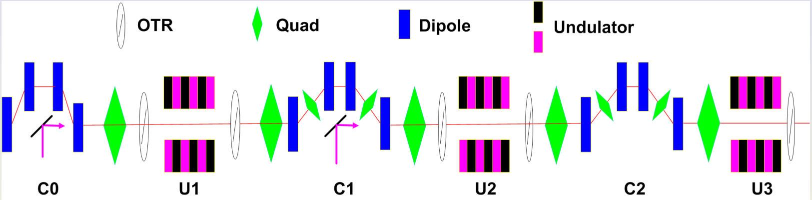
Adding a chirp element to the system results in additional compression of the microbunching (Xiang, Huang, Stupakov. PRST-AB, 2009). The chirp is provided by a short long-wavelength (800 nm) laser pulse. The echo generates 20th harmonic which is further compressed by a factor of 10.




Zholents and Penn (NIM, 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.

# Echo experiment at NLCTA at SLAC

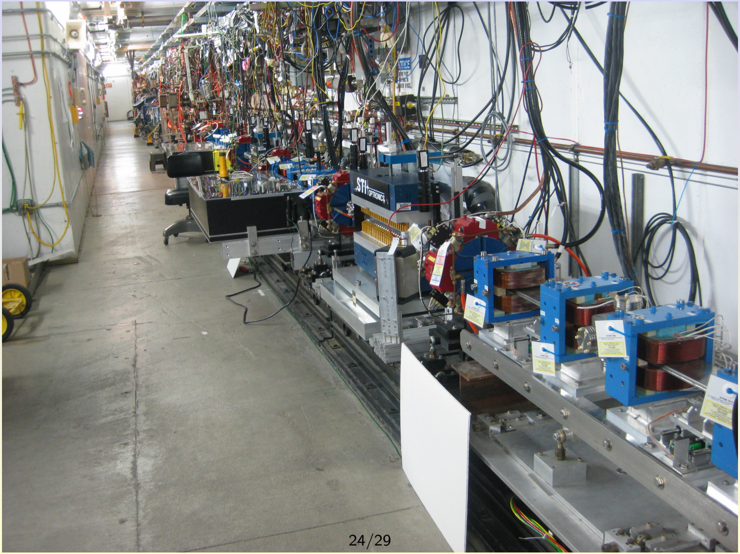
A proof-of-principe experiment to demonstrate EEHG is currently in the commissioning phase at SLAC. NLCTA at SLAC is a facility with an rf gun, x-band linac and a laser.




The experiment was designed and built over the last year. It is aimed at generation of 5th and 7th harmonic of the second laser.

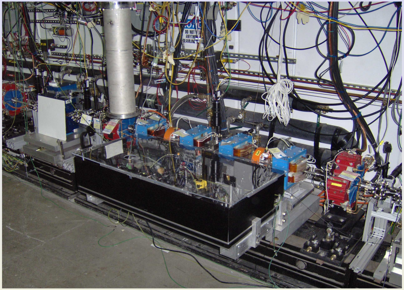
Papers TUPE069 and TUPE072 have details of the design and preliminary results of the experiment.

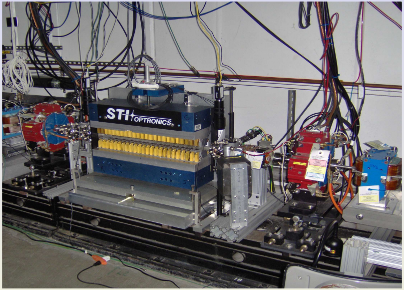
# NLCTA at SLAC



# Echo experiment

## Chicane C1 and undulator U2





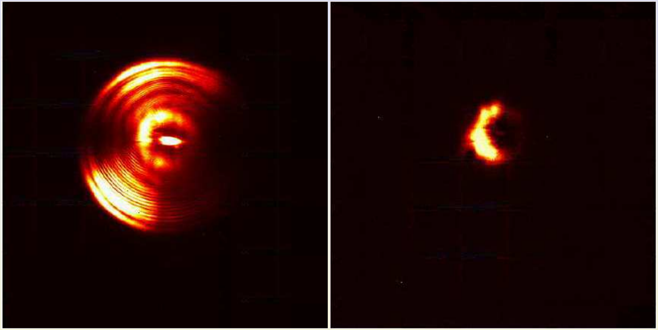
# Echo experiment at NLCTA at SLAC

Main parameters of the EEHG experiment

| | |
|---|---|
| Beam energy | 120 MeV |
| Normalized emittance | 8 mm mrad |
| Bunch charge | 20~30 pC |
| Laser wavelength in U1 | 795 nm |
| Laser wavelength in U2 | 1590 nm |
| Slice energy spread | 2~10 keV |
| $N_p \times \lambda_u$ for U1 | 10 ×3.3 cm |
| $N_p \times \lambda_u$ for U2 | 10 ×5.5 cm |
| $N_p \times \lambda_u$ for U3 | 10 ×2 cm |
| Peak energy modulation in U1 and U2 | 10~40 keV |
| $R_{56}$ for C1 and C2 | 1.0 ~ 9.0 mm |
| Radiation wavelength in radiator | 318 and 227 nm |

# 4-th harmonic of the second laser

We achieved overlapping of both laser pulses with the beam both transversely and temporarily.



Radiation intensity recorded with a UV-sensitive CCD on an OTR screen downstream of U3 with (right) and without (left) a 10 nm bandpass filter centered at 395 nm.

# Conclusions

- A new method of FEL seeding is proposed. The main advantage of the method is that it allows for generation of high harmonics of the seeding laser without excessive increase of the slice energy spread of the beam.
- Various physical effects that tend to smear out the microbunching were studied and simulated in 3D which show practicality of EEHG for soft x-ray FELs.
- Simulations show a feasibility of achieving 20-50th harmonic in EEGH FEL.
- An experiment is currently being conducted at SLAC aimed at demonstration 5th and 7th harmonic generation with EEHG.

# 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.