Echo-Enabled Harmonic Generation for seeded FELs - theory and experiment

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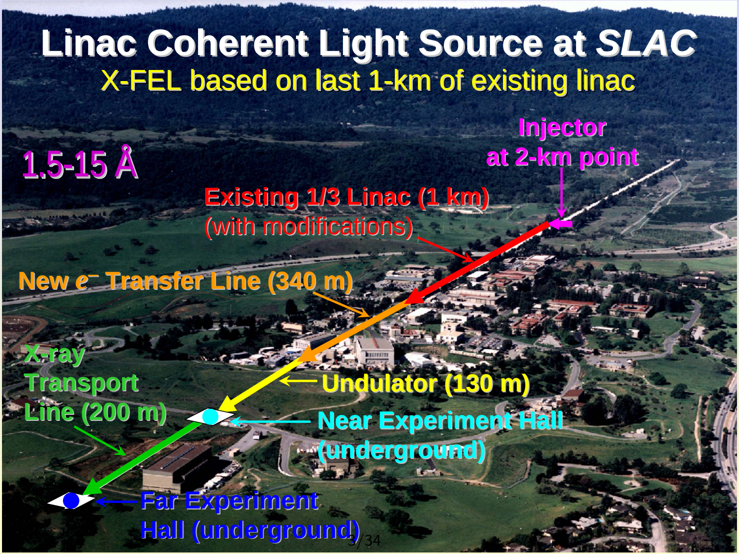
Outline of the talk

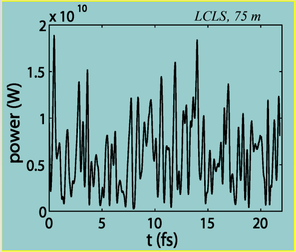
- Introduction and motivation, HGHG seeding
- Echo effect in physics
- Echo-Enabled Harmonic Generation (EEHG)
- Some practical issues: ISR, CSR, leaking R_{51}
- EEHG for FELs
  - VUV-Soft X-ray FEL at LBNL
  - Attosecond pulse generation using EEHG
  - EEHG in LCLS-II
- EEHG experiment at SLAC
- Conclusion

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.

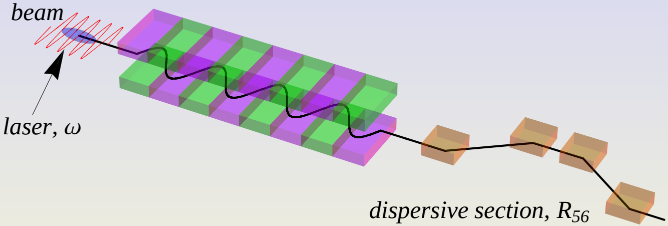


There are several approaches to generation of longitudinally coherent FEL radiation based on seeding techniques

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

HGHG seeding mechanism

HGHG modulates the FEL bunch current at a harmonic of the laser frequency.

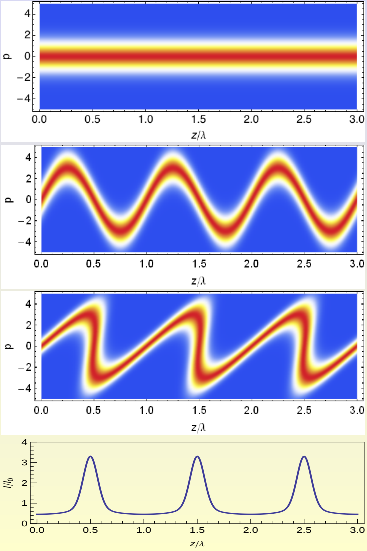


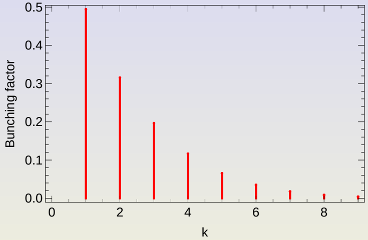
$$\omega_L = \frac{2k_u c\gamma^2}{1 + K^2/2}$$

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

HGHG and high harmonics

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





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.

Echo effect - shadow echo

Echo effect can be observed in various media: photon echo, plasma echo, spin echo, etc.
A simple illustration of the echo mechanism from the book by B. Kadomtsev, “Collective phenomena in plasma”.

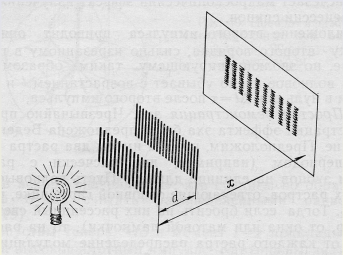
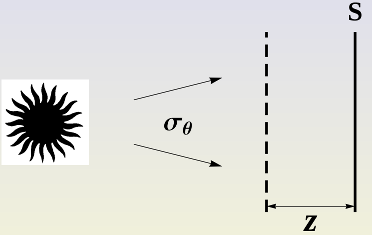


Рис. 50. Эхо на рассеянном свете

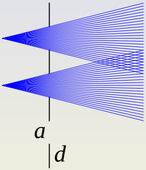
We expect that echo develops in time, but in this example the role of time is played by the distance x.

Mask is illuminated by light source

A thin mask with periodic slits of period $p = a + d$ is uniformly illuminated by light with angular spread σ_θ. Neglect diffraction and interference (small wavelength $\lambda \to 0$). The image is observed at the screen S.



Mask is illuminated by a light source

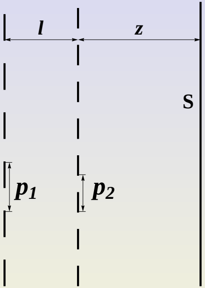


Rays begin to overlap at distance $z \sim d/\sigma_\theta$

If the distance $z \gg d/\sigma_\theta$, one sees a uniform illumination of the screen (Landau damping).

Shadow echo

Add another screen with period p_2 at distance l from the first one ($l, z \gg d/\sigma_\theta$). Notation: $k_1 = 1/p_1$, $k_2 = 1/p_2$.



If the screen is at the right position, one can observe a pattern on the screen—*shadow echo*:

$$z = \frac{nk_1}{mk_2 - nk_1} l$$

where m and n are integers. The patten has period p ($k = 1/p$)

$$k = |nk_1 - mk_2|$$

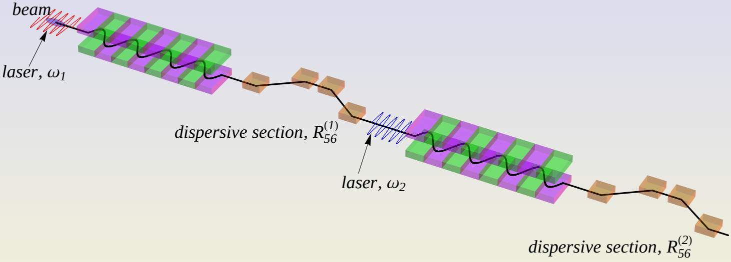
The animation shows the case $p_2 = \frac{1}{3} p_1$. For $m, n = 1$, echo should be observed at $z = \frac{1}{2} l$ with the period $p = \frac{1}{2} p_1$.

Shadow echo

(Loading shadow echo movie)

Using echo effect for high-frequency modulation

EEHG (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 $B_2 = R_{56}^{(1)} \kappa_L \sigma_E / E_0$.

Echo phase space evolution through the system

(Loading beam echo movie)

1D echo bunching theory

Echo generates the frequency $\omega = n\omega_1 + m\omega_2$ (recall shadow echo).

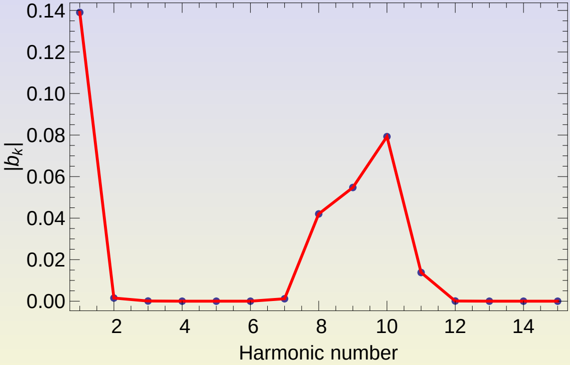
A general expression for the bunching factor b_k (Xiang, Stupakov. PRST-AB, 2009). Practically, the case $\omega_1 = \omega_2 = \omega$ can be realized with a single laser beam.

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

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

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

Modulation amplitude versus harmonic number

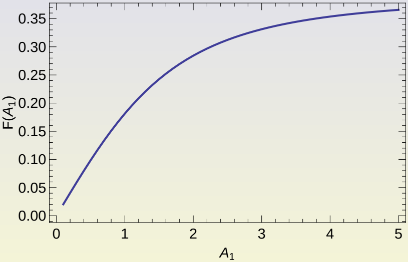


Echo excites a relatively narrow spectrum around the optimized harmonic.

Maximal echo modulation

What is the maximal echo modulation one can get 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 $B_1 \propto k$.

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	λ_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

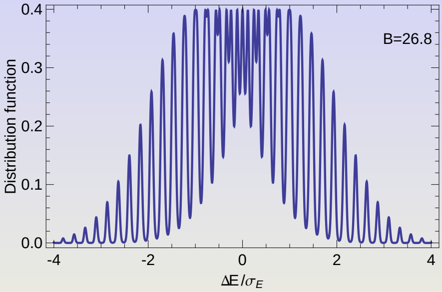
- Energy diffusion due to incoherent synchrotron radiation in chicanes
- CSR and associated microbunching instability

- 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, FEL09, IPAC10.

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

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

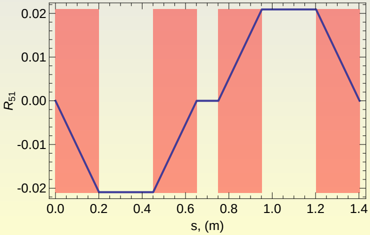
can be a fraction of keV. Choosing larger bending radius in the chicane would decrease $\Delta\sigma_E$.

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}.

The suppression factor due to R_{51}:

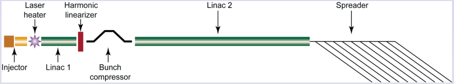
$$\sim \exp\left(-k_{\mathrm{mod}}^2 R_{51}^2 \sigma_x^2/2\right)$$



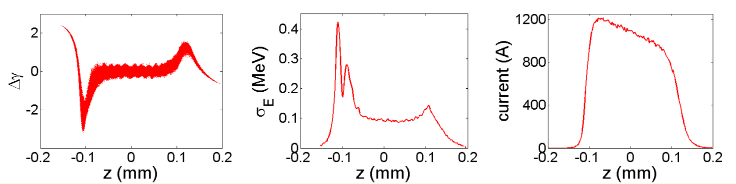
R_{51} in the second chicane. For $\sigma_x = 40$ μm and $R_{51} \sim 0.01$, microbunching with $\lambda_{\mathrm{mod}} < 1$ μm will be smeared out.

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

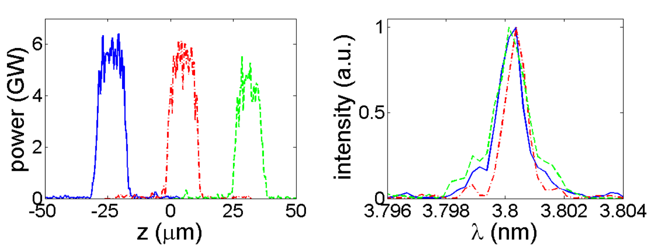


The beam distribution is obtained from IMPACT-Z simulation by J. Qiang.



Time dependent simulations for LBNL soft x-ray FEL

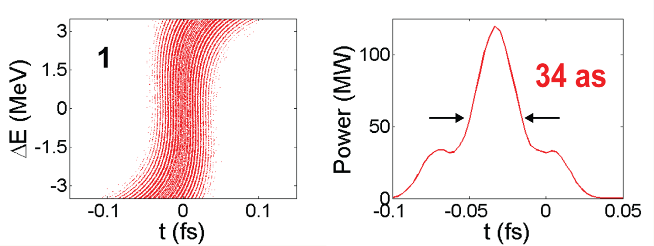
Radiation at 3.8 nm (50th harmonic of 190 nm laser). The spectrum is close to the Fourier limit.



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.

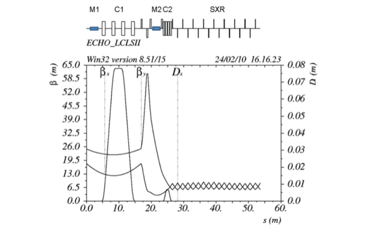


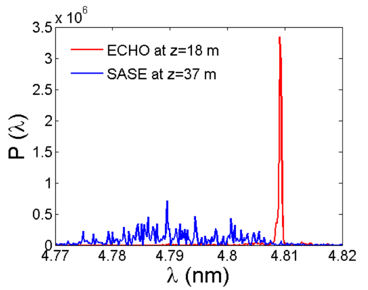
Zholents and Penn (NIM, 2009) proposed to use echo to generate two attosecond pulses, 2.27 nm and 3.03 nm, from the laser wavelength 200 nm and 800 nm.

EEGH for LCLS-II

Electron beam energy	4.3 GeV
Peak current	800 A
Normalized emittance	0.6 μm
Slice energy spread	700 keV
Seed laser wavelength	202 nm
Seed laser power	300 MW
$N_p \times \lambda_u$	8×35 cm
R_{56} for C1	4.4 mm
R_{56} for C2	109 μm

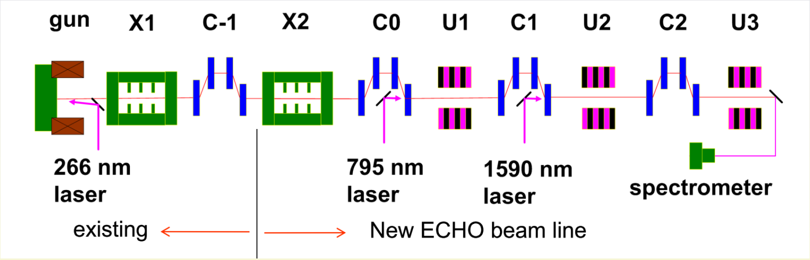
EEHG FEL power is about 8 GW after 18 m of the undulator.





EEHG proof-of-principle experiment at SLAC

A proof-of-principe experiment to demonstrate EEHG has been carried out at SLAC at the NLCTA facility (PRL, **105**, 114801 (2010)). 3/2009 - first planning, 7/2010 - first echo signal. NLCTA is equipped with an S-band injector (to ~ 100 pC), an X-band linac ($60 - 200$ MeV) and Ti:Sapphire laser systems.



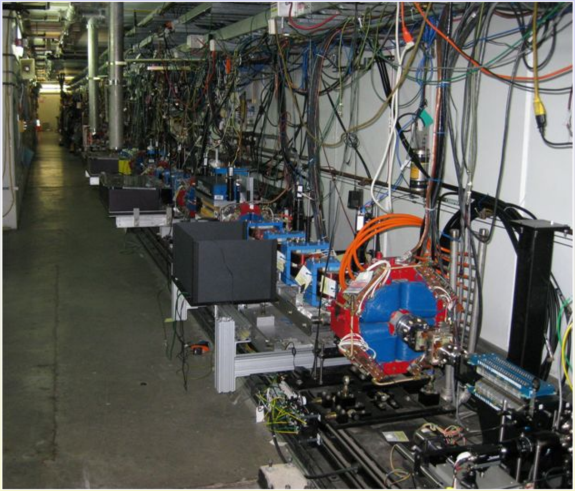
Layout of the ECHO-7 at the NLCTA.

Echo experiment at NLCTA at SLAC

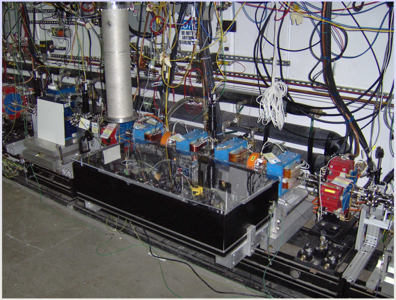
The parameters of the experiment:

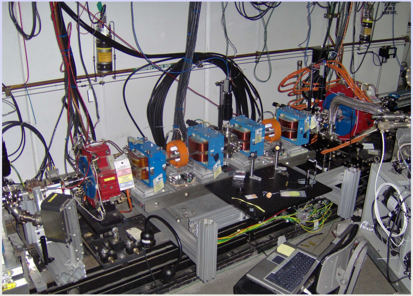
Electron beam energy	120 MeV
Bunch length	0.5-2.5 ps
Bunch charge	20-40 pC
Normalized emittance	$\sim 8\ \mu m$
Slice energy spread	~ 1 keV
First laser wavelength	795 nm
Second laser wavelength	1590 nm
$N_p \times \lambda_u$ for U1	10×3.3 cm
$N_p \times \lambda_u$ for U2	10×5.5 cm
$N_p \times \lambda_u$ for U3	10×2.0 cm
Peak energy modulation in U1 and U2	10-40 keV
R_{56} for C1 and C2	1-9 mm

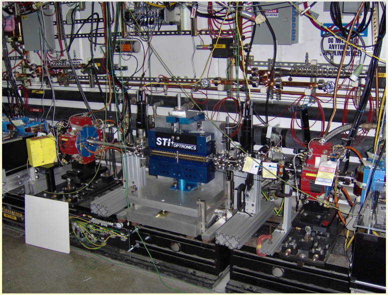
Upstream view

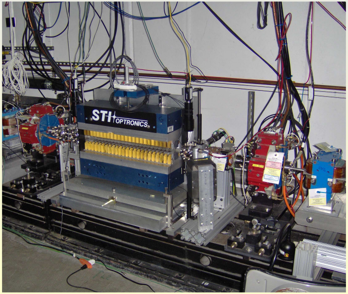


Chicanes and undulators in the NLCTA







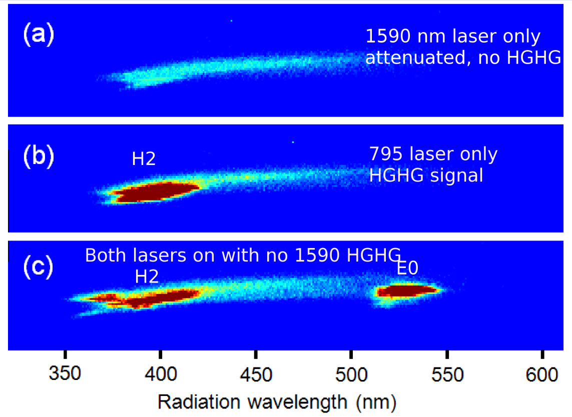


Experimental challenges

The main challenge in this experiment was that the beam energy spread was small (in contrast to a real FEL), and the amplitude of the energy modulation due to interaction with the laser was large (this was required in order to keep the chicane strength reasonable). In this situation, both HGHG and EEHG generate high harmonics. Different laser wavelengths help to partially separate HGHG from EEHG.

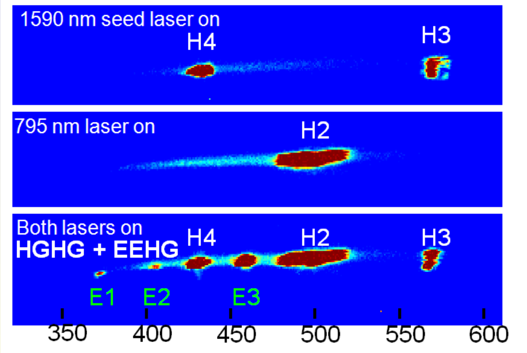
First echo signal

ECHO signals, no energy chirp: a) only 1590 nm laser is on, b) only 795 nm laser is on, c) both lasers are on.



Echo signal with energy chirp

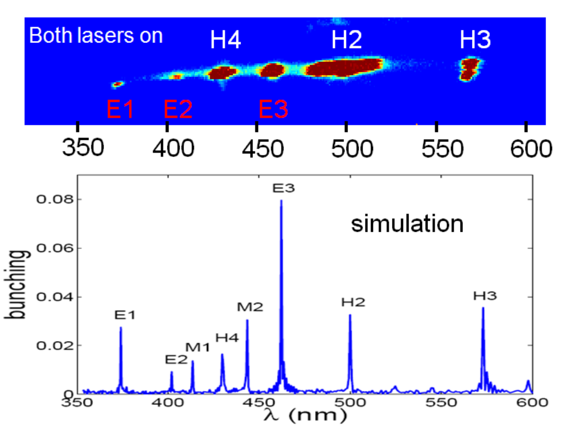
ECHO signals when beam has energy chirp $\sim 33.4\ \text{m}^{-1}$.



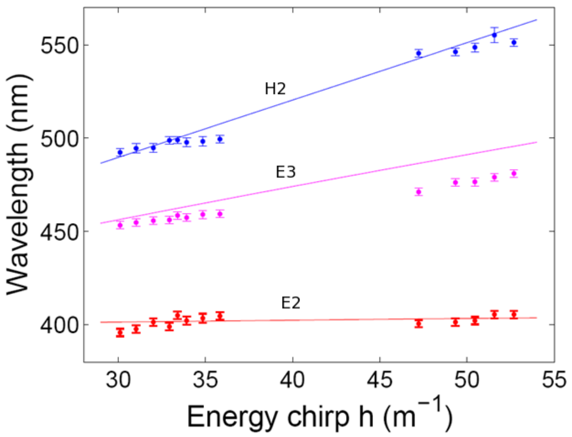
To fully separate HGHG and EEHG, we introduced energy chirp h in the beam.

$$\omega = \frac{n\omega_1 + (1 + hR_{56}^{(1)})m\omega_2}{1 + h(R_{56}^{(1)} + R_{56}^{(2)})}$$

Comparison with simulations



Wavelength versus energy chirp



EEHG promise - I

Echo Enabled Harmonic Generation (EEHG) seems promising for generation of harmonics up to 40-100. The harmonic amplitude scales as $\sim n^{-1/3}$. With the seed laser wavelength of about 200 nm, one can achieve seeding of soft x-ray FELs. Typical parameters

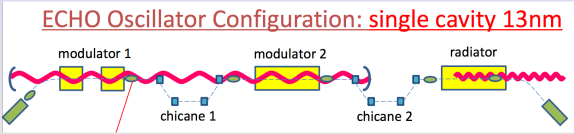
Electron beam energy	1-2 GeV
Energy spread	100-200 keV
Laser wavelength	200 nm
Harmonic number	20-100
FEL wavelength	a few nm

Several soft xray FEL projects in the world can benefit from the EEHG: FERMI@ELETTRA (Trieste, Italy), SwissFEL (PSI, Switzerland), SDUV-FEL (Shanghai, China), LBNL FEL (USA), LCLS-II . . . .

EEHG promise - II

Further development of the echo idea:

- J. Wurtele: using echo oscillator (FEL 2010).



- D. Ratner and A. Chao: steady state microbunching in storage ring (PRL, **105**, 154801, (2010)).