Introduction to Echo-Enabled Harmonic Generation Experiments

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Acknowledgements:

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IMSS seminar, KEK

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Outline

1. EEHG principle

2. EEHG experiments@SLAC

3. Concerns of experimental design for ERL@KEK

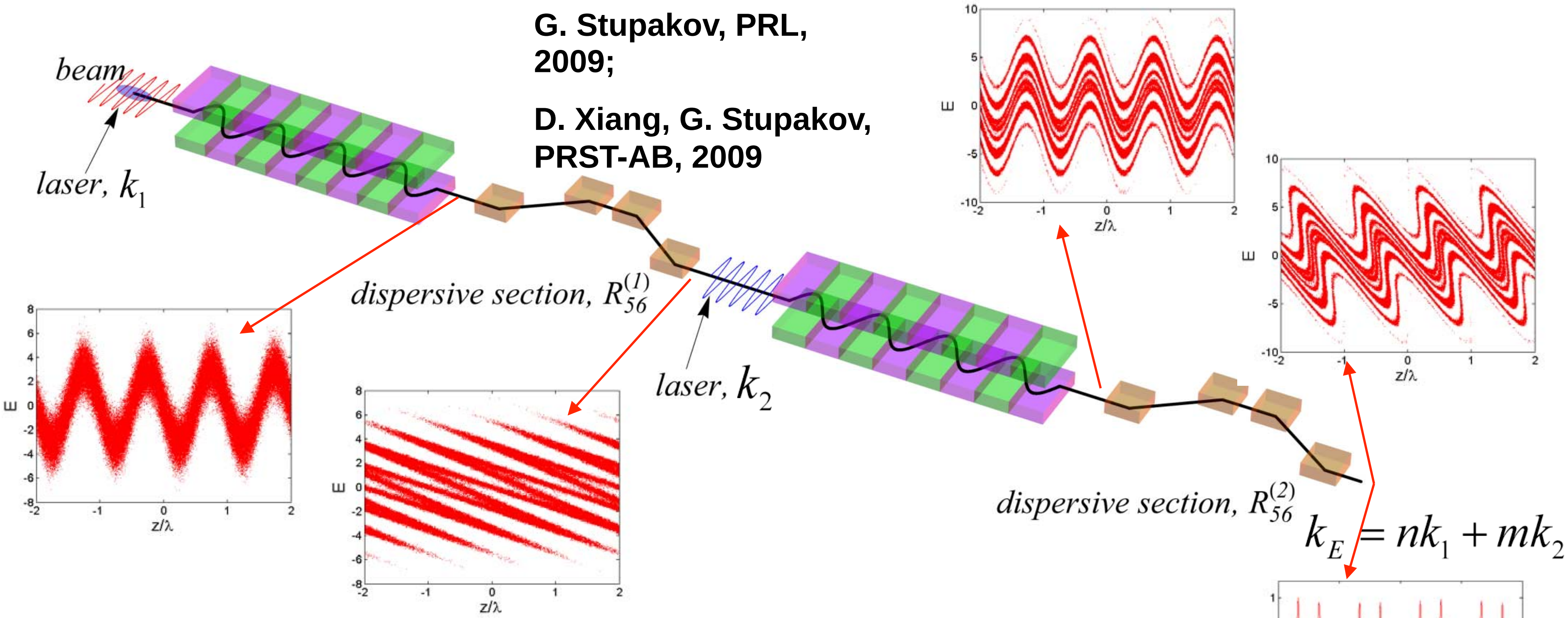
4. Possible end-to-end simulations

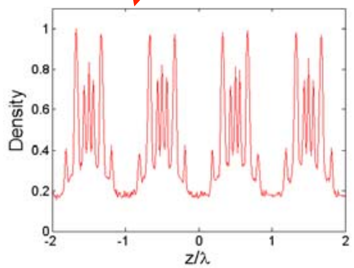
5. Summary

1. EEHG principle - Standard layout

G. Stupakov, PRL, 2009;

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





- First laser to generate energy modulation in electron beam
- First strong chicane to split the phase space
- Second laser to imprint energy modulation
- Second chicane to convert energy modulation into density modulation

Courtesy of D. Xiang, FEL11

1. EEHG principle - Advantages and challenges

Advantages and Challenges of EEHG FEL:

Advantages (against HGHG):

- ➤ **High up-frequency conversion efficiency: $b_n \sim n^{-1/3}$**
- ➤ **High harmonics from small energy modulation ($\Delta E/\sigma_E \sim 3$)**
- ➤ **UV lasers ⇝ Soft x-ray in a single stage**

Challenges:

- ➤ **Long-term preservation of phase space correlations**
- ➤ **CSR/ISR in chicanes, Intra-beam scattering (IBS)**
- ➤ **Laser stability**

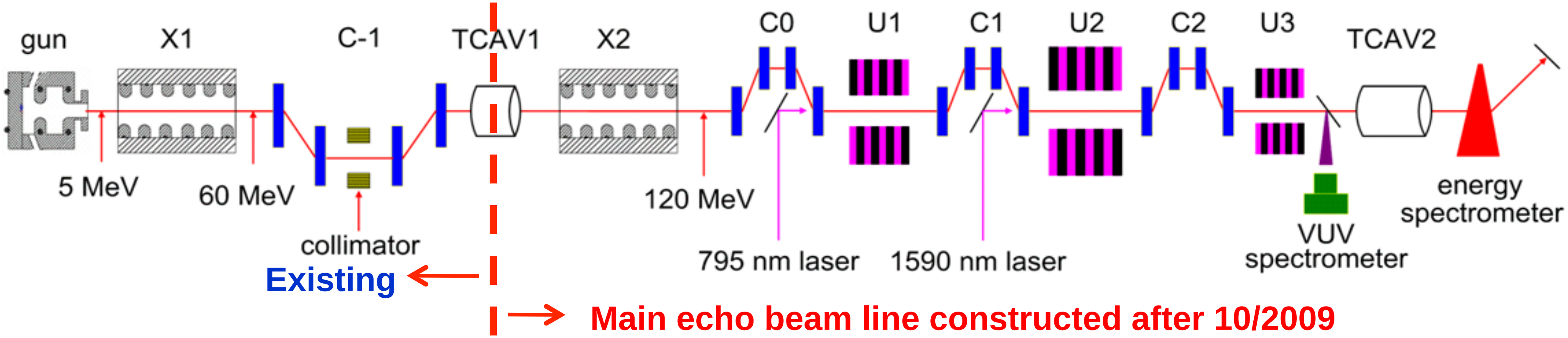
Other issues:

Lattice optimization (minimize high-order effects and avoid x-z coupling), tolerance on field errors and alignment errors ...

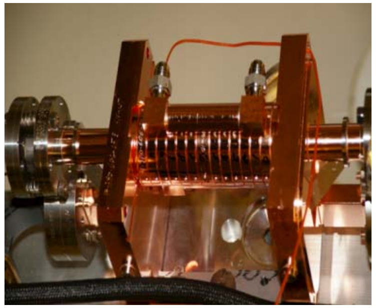
Courtesy of D. Xiang, FEL11

2. EEHG experiments@SLAC

Experimental setup at NLCTA:

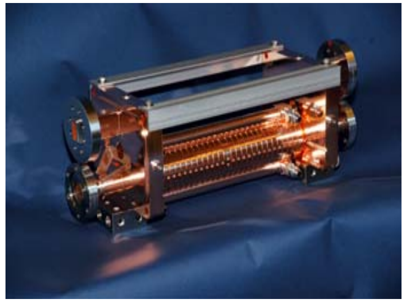


C-1

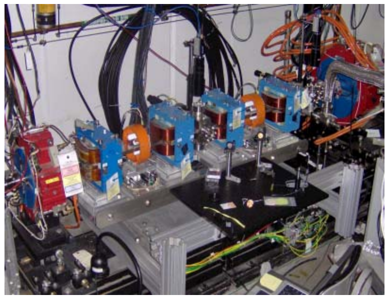


TCAV1

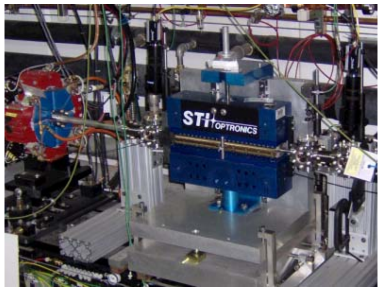
X2



TCAV2

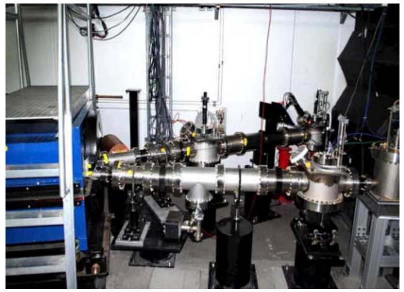


C1



U1

U2



spectrometer

Courtesy of D. Xiang, FEL11

2. EEHG experiments@SLAC

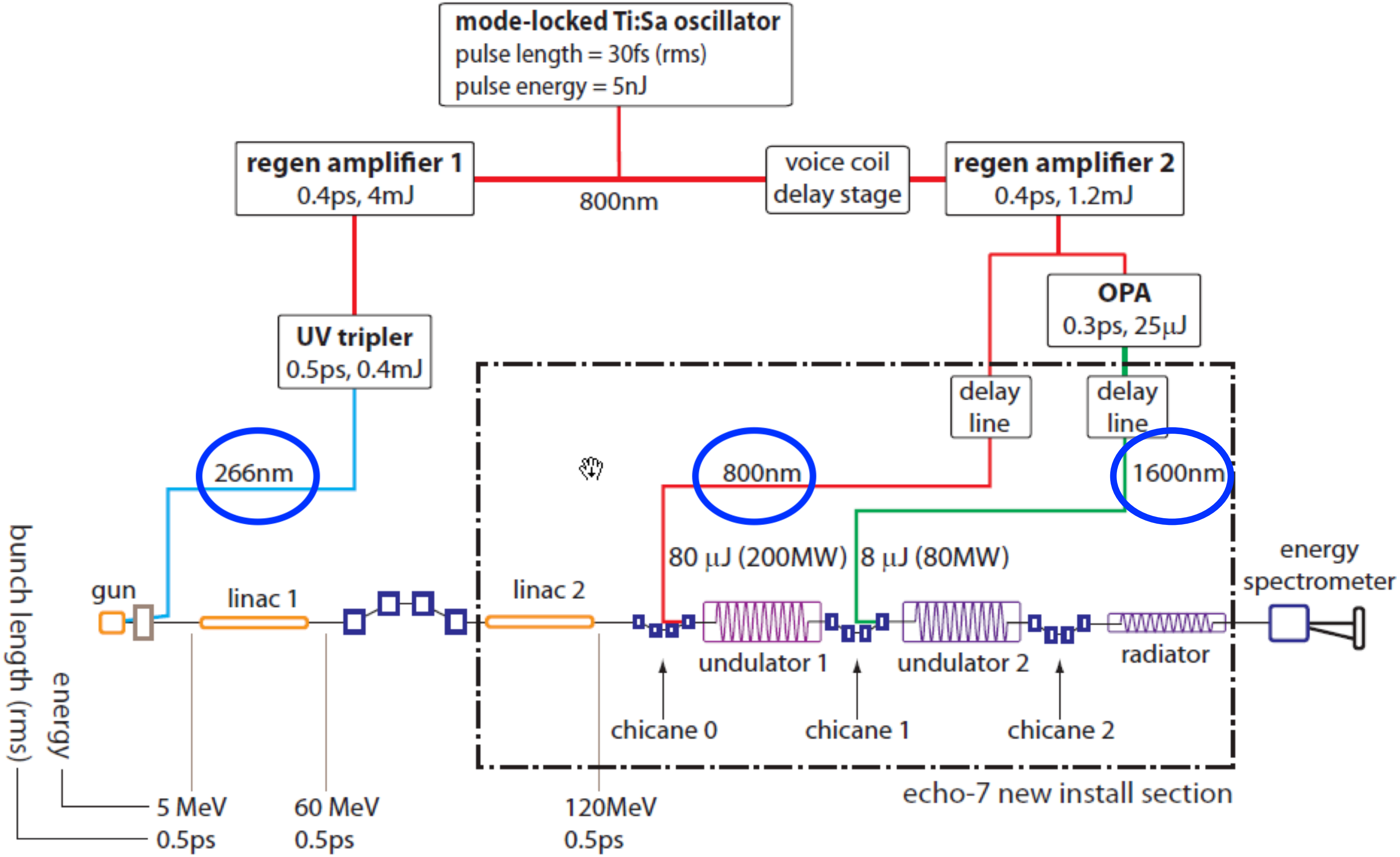
Main parameters of the EEHG experiment

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 $\times$3.3 cm
$N_p \times \lambda_u$ for U2	10 $\times$5.5 cm
$N_p \times \lambda_u$ for U3	10 $\times$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

Courtesy of G. Stupakov, IPAC10

2. EEHG experiments@SLAC - Laser system

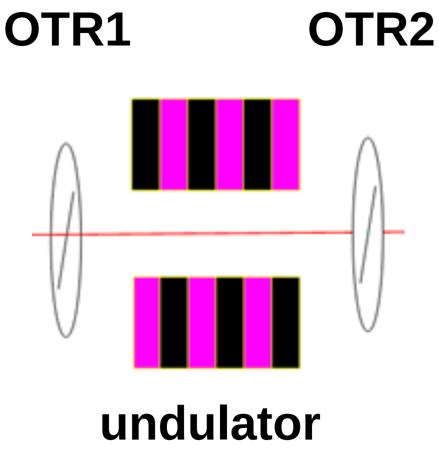
Long laser wavelength is chosen to avoid using in-vacuum UV spectrometer.



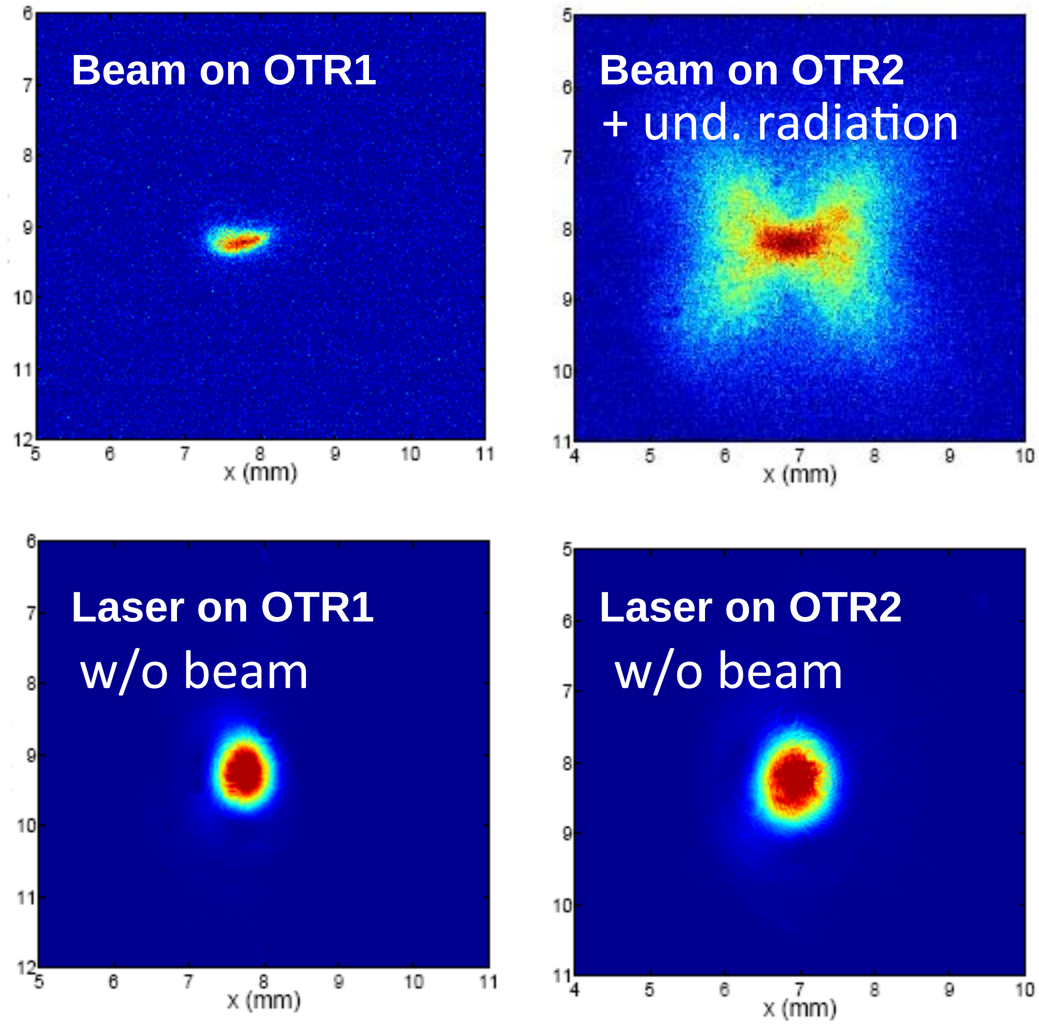
Courtesy of D. Xiang, PAC11

2. EEHG experiments@SLAC - Laser-beam interaction

Spatial overlap:



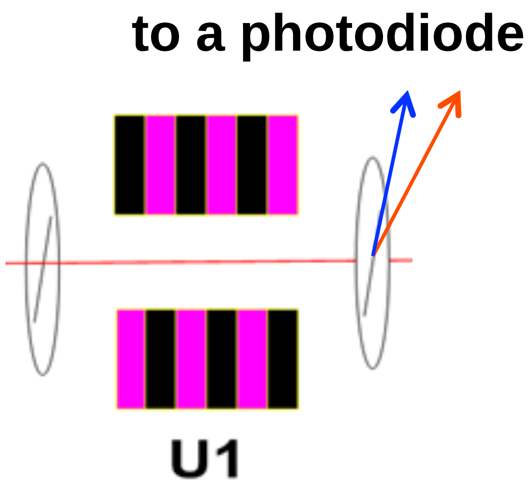
Beam-laser spatial overlap is achieved by steering the laser to the same position as the electron beam on the OTR screens upstream and downstream of the undulators

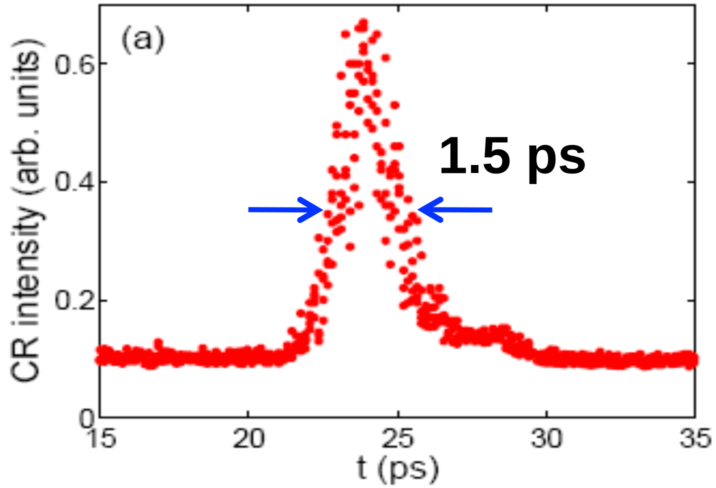


Courtesy of D. Xiang, PAC11

2. EEHG experiments@SLAC - Laser-beam interaction

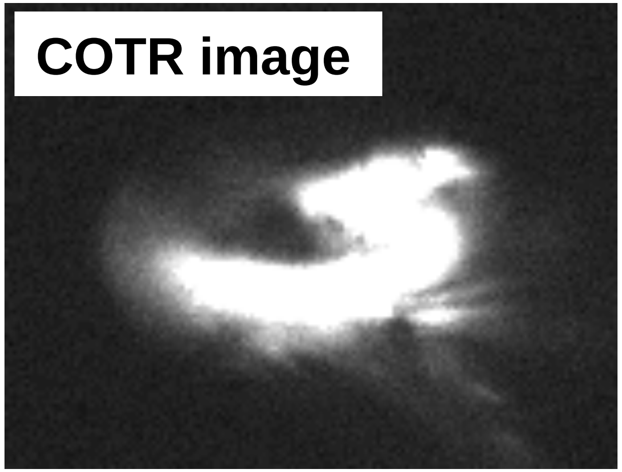
Temporal overlap:





COTR signal vs laser timing

- **The laser and undulator radiation are reflected out by the OTR screen and detected by a fast photodiode.**
- **Scan delay stage to finely adjust the laser timing until the COTR enhancement is observed.**

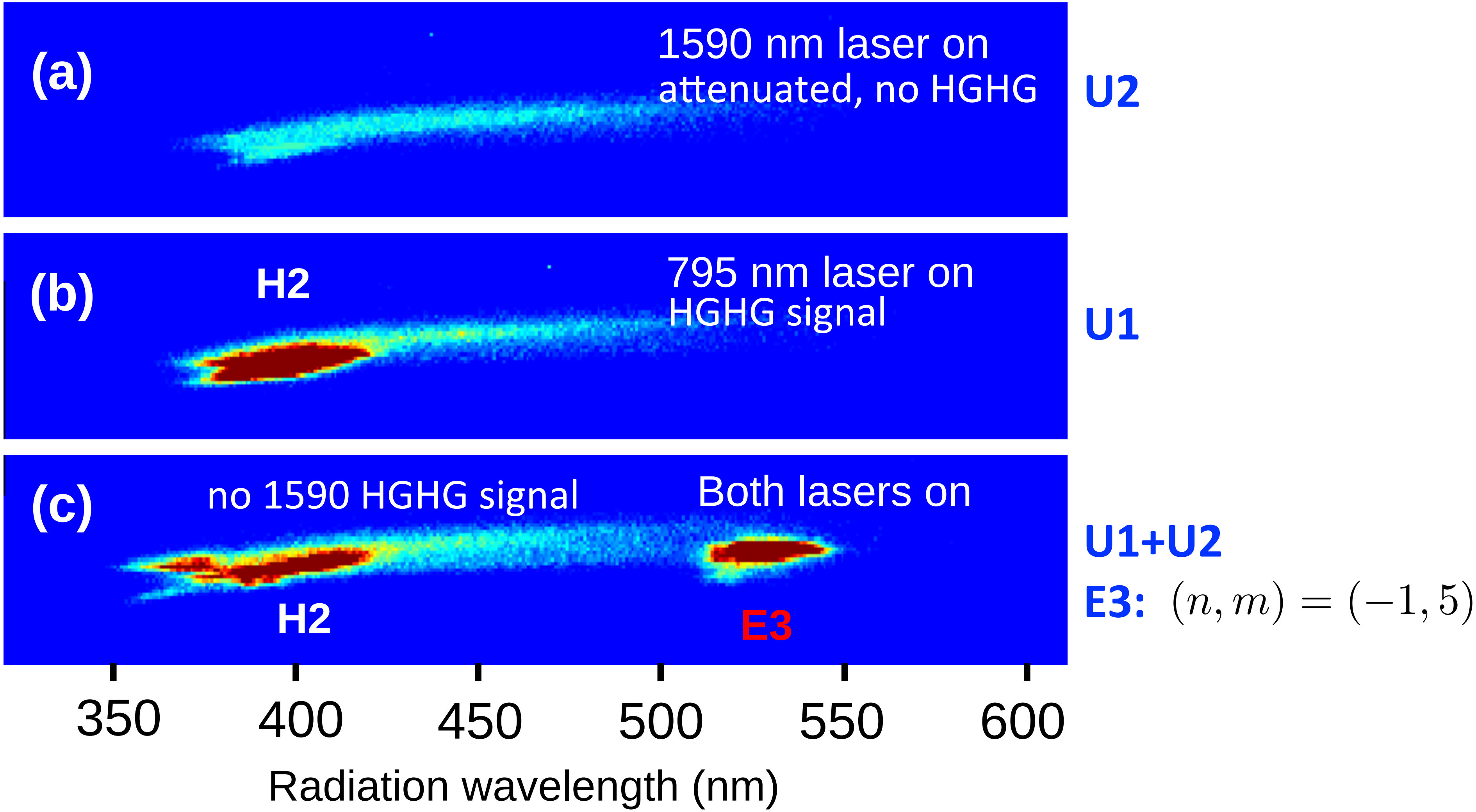


Courtesy of D. Xiang, PAC11

2. EEHG experiments@SLAC - Experimental results

First echo signal at the exit of U3 (optical lens, w/o TCAV):

$$k_E = nk_1 + mk_2$$

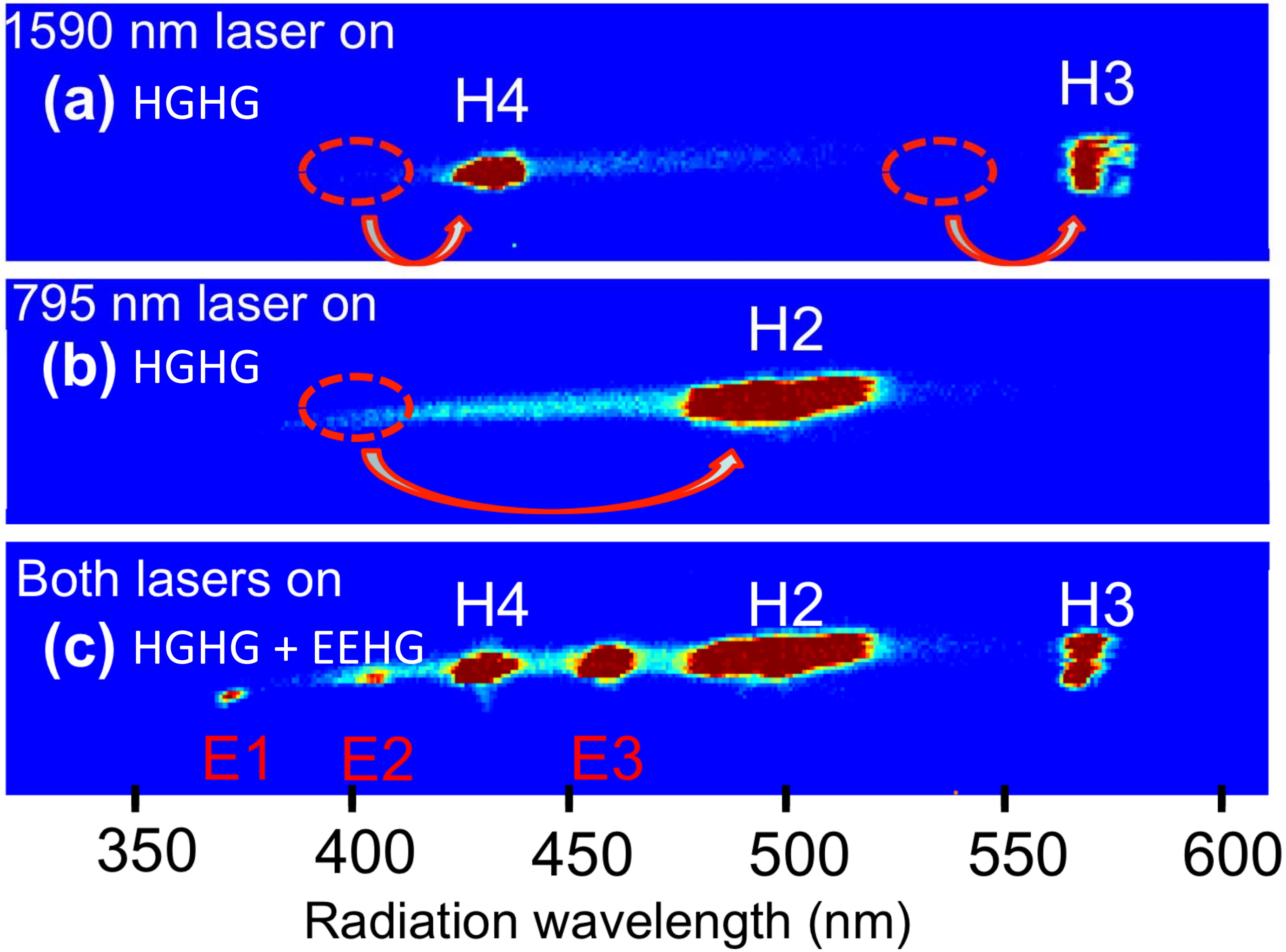


Courtesy of D. Xiang, PAC11
D. Xiang et al., PRL 105, 114801 (2010)

2. EEHG experiments@SLAC - Experimental results

Echo signal with energy chirp (optical lens, w/o TCAV):

$$k_E = nk_1 + mk_2 \qquad h = d\delta/dz = 33.4\ \mathrm{m}^{-1}$$



HGHG:

$$k_H = \frac{k_0}{1 + hR_{56}}$$

EEHG:

$$k_E(h) = \frac{nk_1 + (1 + hR_{56}^{(1)})mk_2}{1 + h(R_{56}^{(1)} + R_{56}^{(2)})}$$

E1: $(n, m) = (-5, 4)$

E2: $(n, m) = (-1, 6)$

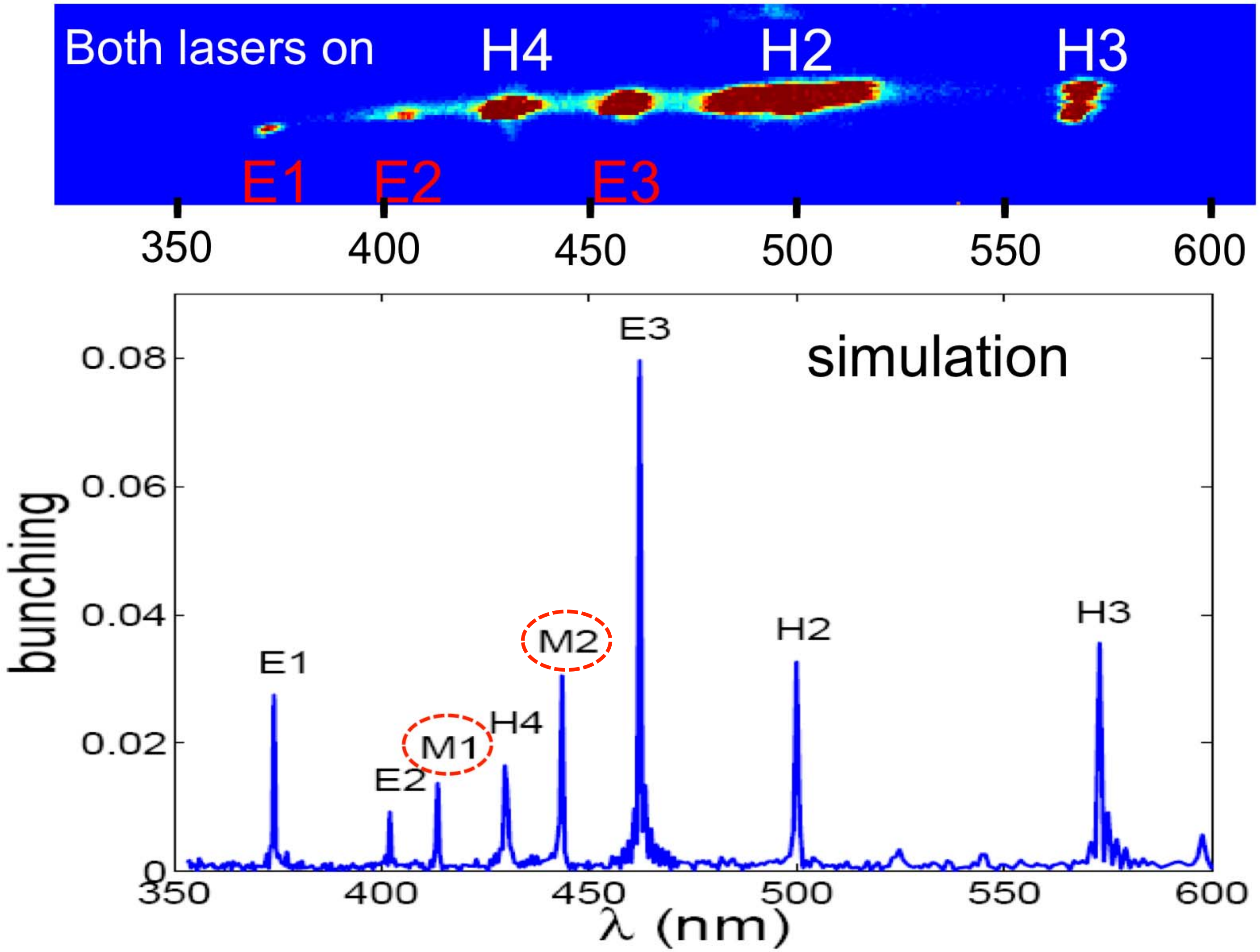
E3: $(n, m) = (1, 2)$

Courtesy of D. Xiang, PAC11

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

2. EEHG experiments@SLAC - Experimental results

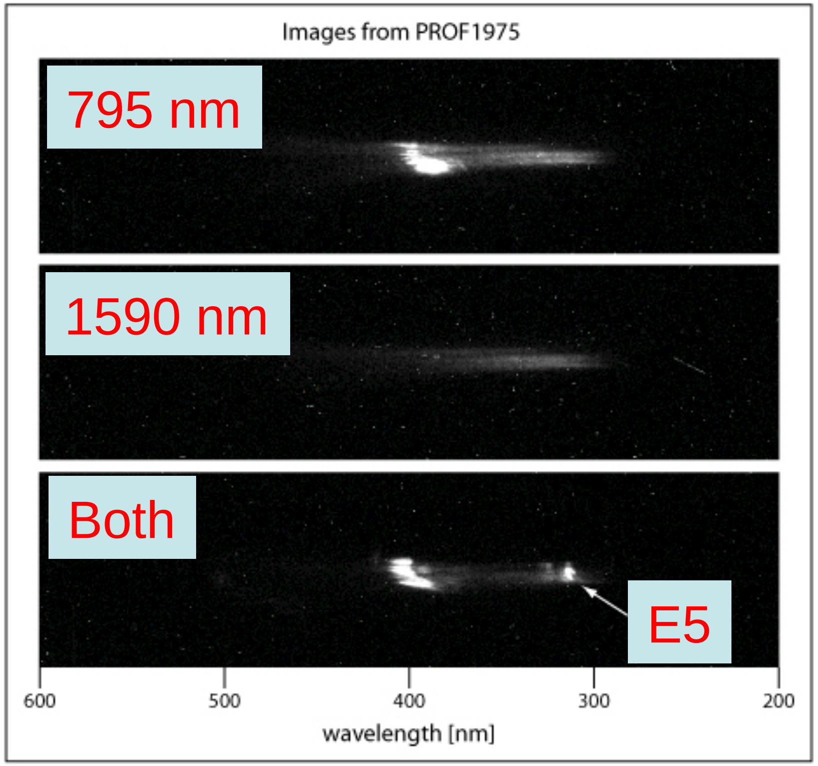
Good agreement with theory:

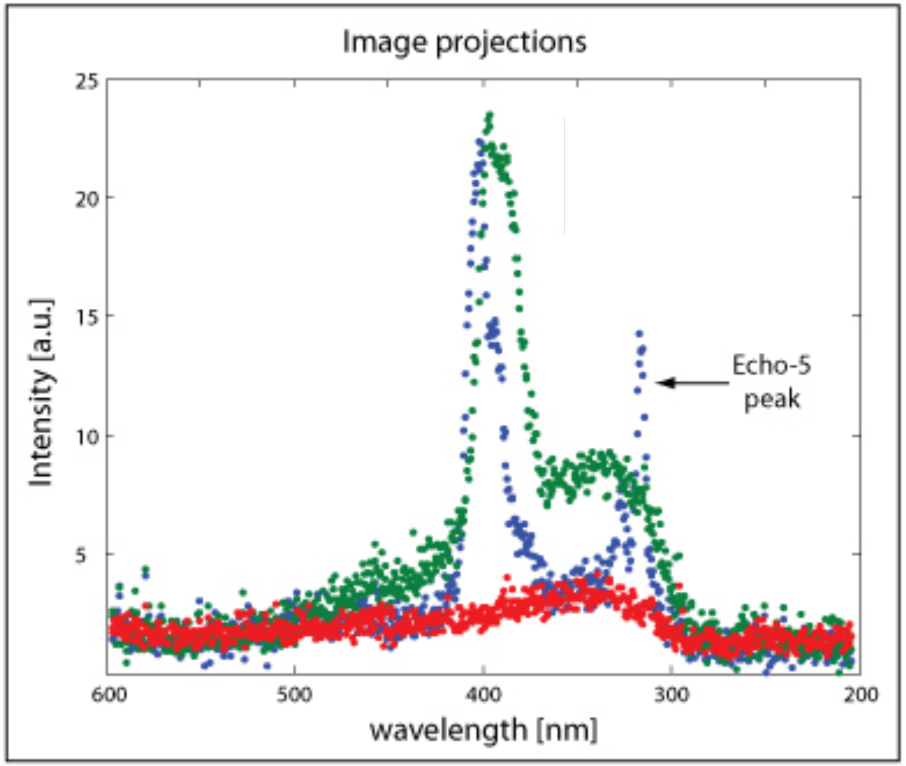


Courtesy of D. Xiang, PAC11
D. Xiang et al., PRL 105, 114801 (2010)

2. EEHG experiments@SLAC - Experimental results

5^{th} harmonic signal w/ optical lens replaced by UV lens:

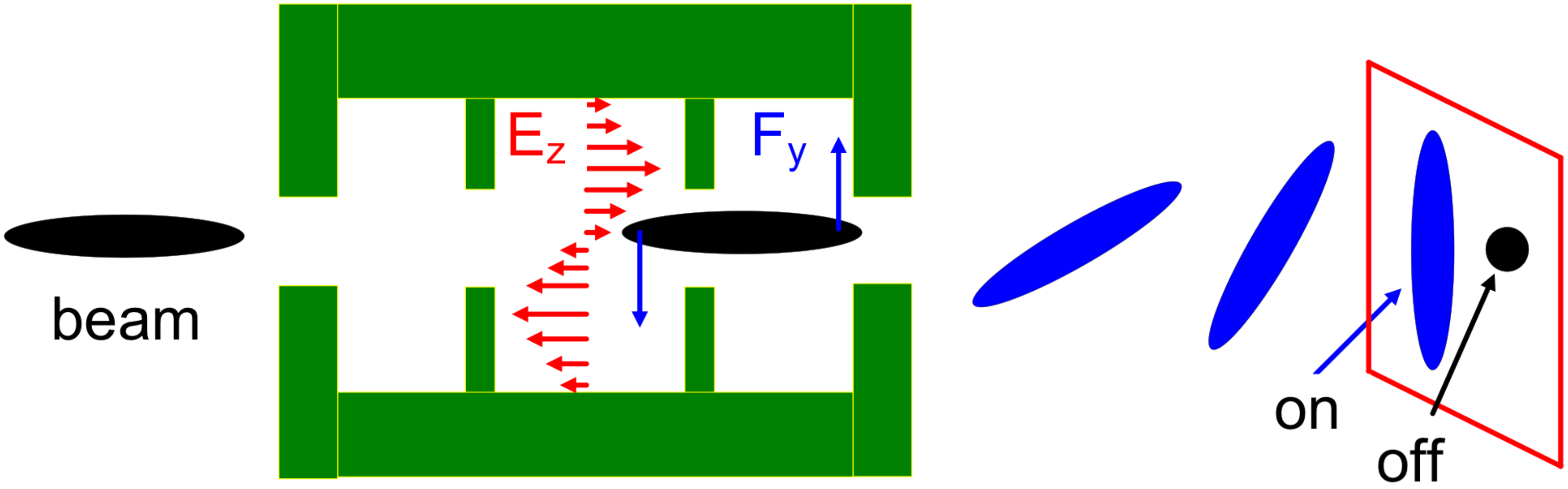




Courtesy of D. Xiang, PAC11

2. EEHG experiments@SLAC - Transverse cavity

Transverse deflection RF cavities are used to increase slice energy spread. EEHG is capable of generating high harmonics when the energy modulation is comparable to the slice energy spread.

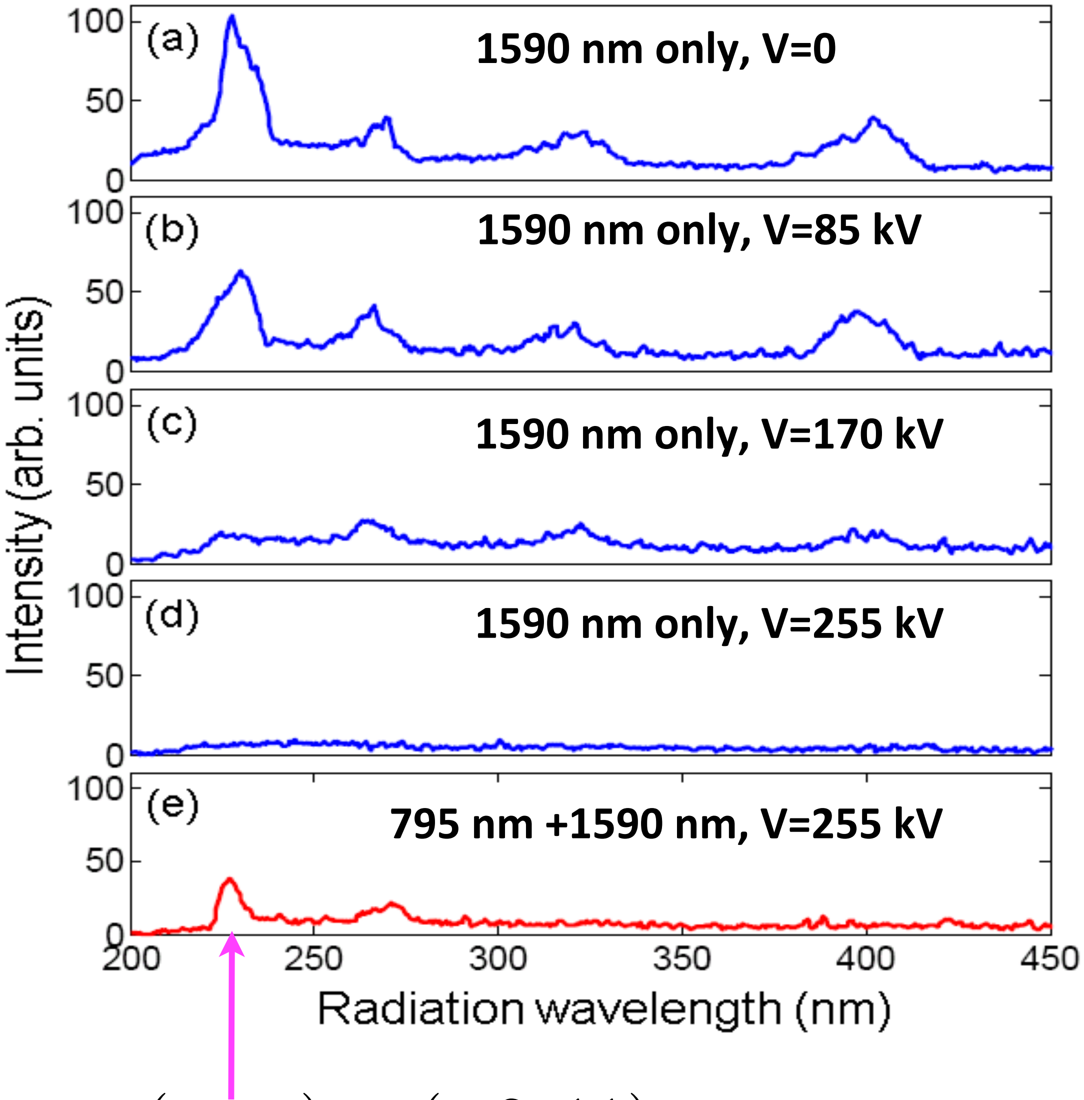


$$\delta = k\sigma_x \qquad k = \frac{2\pi eV}{\lambda_{RF} E}$$

Courtesy of D. Xiang, FEL11

2. EEHG experiments@SLAC - Experimental results

7th harmonic signal (w/ TCAV):



$$(n, m) = (-2, 11)$$

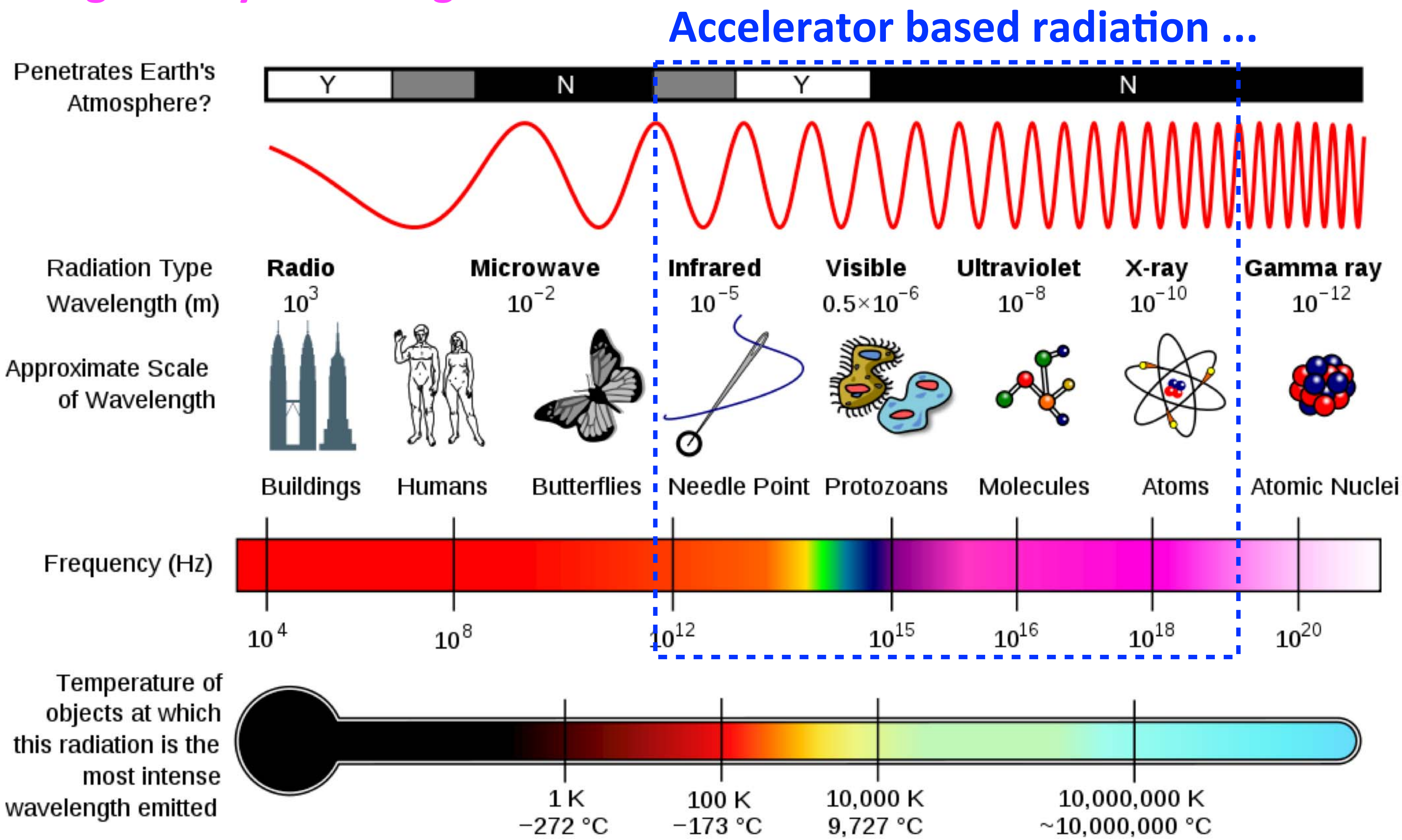
- **4th to 7th harmonics from HGHG suppressed with increased beam slice energy spread**
- **7th harmonic reappear with the first laser on, like an echo**
- **7th harmonic generated when energy modulation is about 2~3 times the beam slice energy spread**

Courtesy of D. Xiang, FEL11

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

3. Concerns of experimental design for ERL@KEK

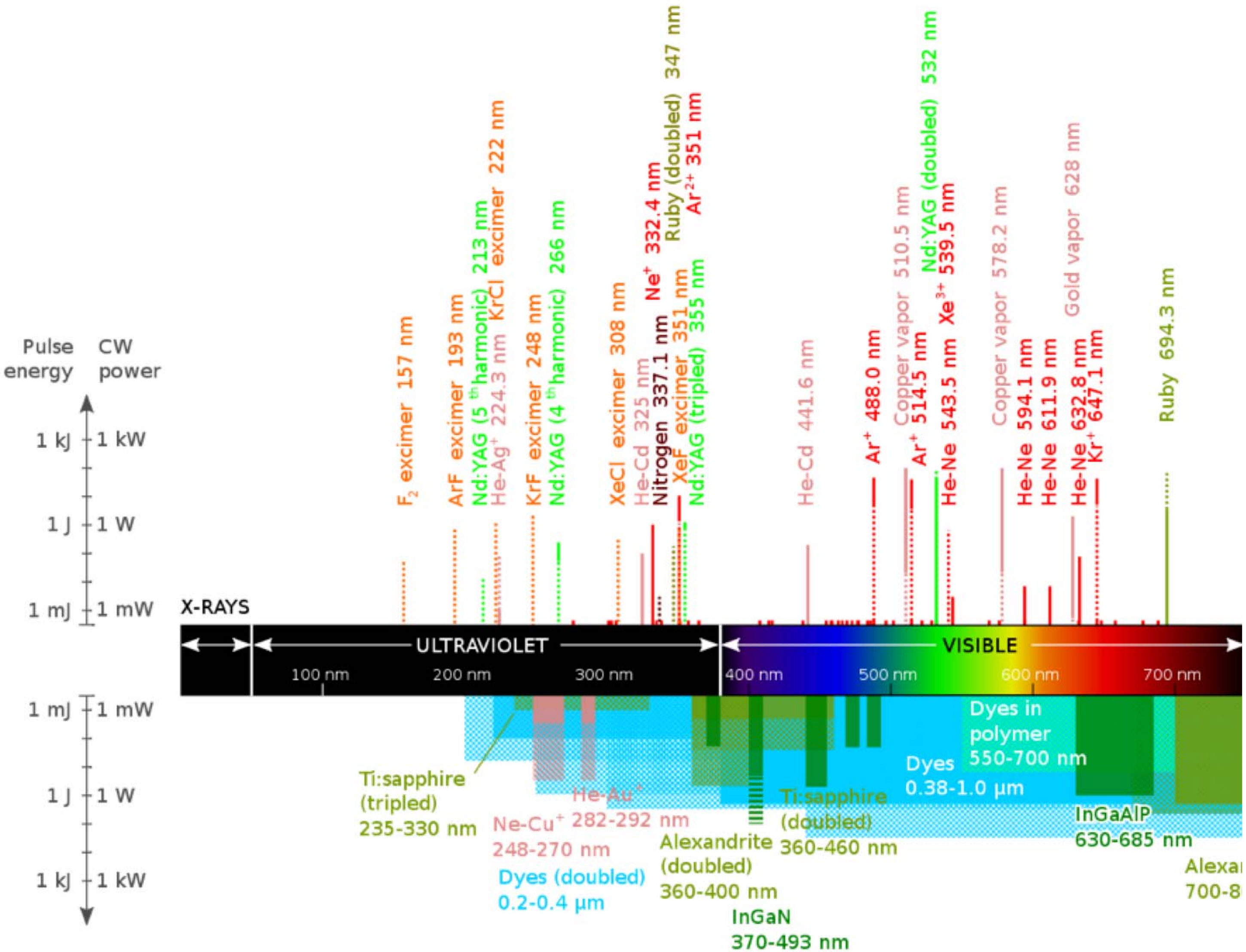
Target x-ray wavelength?



Source: http://commons.wikimedia.org/wiki/File:EM_Spectrum_Properties_edit.svg

3. Concerns of experimental design for ERL@KEK

Commercially available lasers:



Source: http://en.wikipedia.org/wiki/File:Commercial_laser_lines.svg

Courtesy of S. Kamada

3. Concerns of experimental design for ERL@KEK

- **Target x-ray wavelength: VUV? soft x-ray? hard x-ray?**

- **Commercially available UV lasers: $\gtrsim$200 nm**

- **EEHG promise: harmonic < 100 (Chicane strength, smearing effect, ...) ⇝ VUV or soft x-ray ($\gtrsim$2 nm)**

- **Beam parameters:**
  - **cERL@KEK: E=35/100 MeV, Q=77 pC, $\sigma_\delta=10^{-3}$, σ_z=0.6 mm**

  - **ERL@KEK: E=3 GeV, Q=77 pC, $\sigma_\delta=10^{-3}$, σ_z=0.1 mm**

3. Concerns of experimental design for ERL@KEK

➤ **Lattice design:**

Low beam energy: CSR and incoherent undulator radiation are not serious issues. Second-order effects (particles with different betatron amplitude have different path lengths) causes smearing of the fine structure and is a major concern.

➤ **Hardwares:**

To generate higher harmonics, good quality of photocathode, drive laser and chicanes are required.

➤ **Diagnostics and beam tuning:**

OTR(Optical Transition Radiation), Precise timing ...

➤ **Other factors:**

Misalignment of the quads, field errors of the dipoles, and the non-zero field integrals of the undulators. Tolerances can be set via simulations.

M. Dunning et al., IPAC10

4. Possible end-to-end simulations

➤ **Simulation tools for EEHG beam line:**
Chicane (CSR, ISR, IBS, etc.): ELEGANT
Modulator (Laser + undulator): need to develop new code (based on Ohmi-san's code)
Radiator (undulator): GENESIS

➤ **Issues to be investigated:**
Field errors, Beam energy chirp, CSR, ISR, IBS, Laser stability/ noise, Timing jitter, etc.
Advantages and challenges for ERL project ...

4. Possible end-to-end simulations

EEHG option for FLASH II:

Table 3 The main parameters of EEHG setup for FLASH II

Harmonic number	20	40	60
Seed laser wavelength	262nm	262nm	262nm
Seed laser power	1.2GW	1.5GW	1.5GW
Seed laser radius	0.6mm	0.6mm	0.6mm
Modulator period	0.1m	0.1m	0.1m
Modulator length	0.4m	0.4m	0.4m
Modulator K	4.2031	6.1753	7.5984
R56(1)	1.08mm	2.86mm	5.25mm
R56(2)	0.0576mm	0.0730mm	0.0888mm
Beam energy	0.7GeV	1.0GeV	1.22GeV
Radiator period	29mm	29mm	29mm
Radiator K	1.1793	1.1793	1.1793
Radiation wavelength	13.1nm	6.55nm	4.37nm

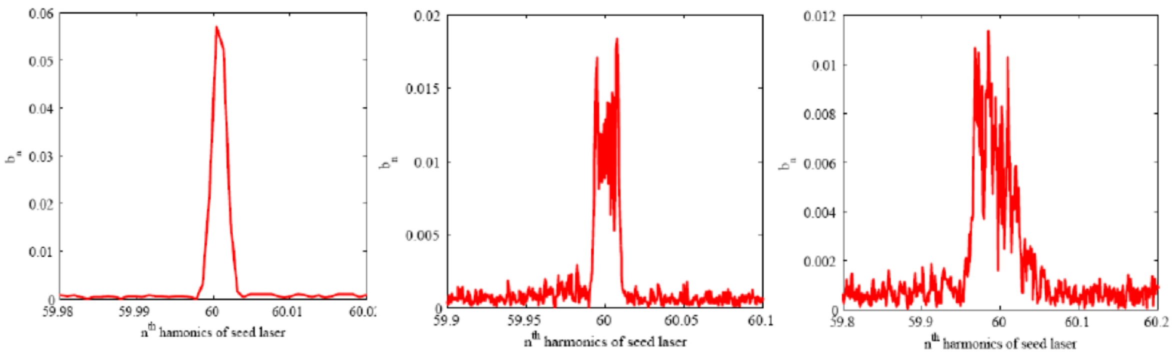
Table 1 The main beam parameters of FLASH II

Beam energy	0.7 / 1.0 / 1.22 GeV
Normalized emittance	1.5 mm-mrad
Slice energy spread	0.2 MeV
Peak current	1.25 / 2.5 kA
Bunch charge	1 nC
Beam size in Modulator	60 um

Table 2 The main parameters of the 1st chicane in EEHG option for FLASH II

Dipole length	0.4 m
Dipole field	0 ~ 0.5 T
Drift between the 1st/2nd and 3rd/4th dipole	2.0 m
Drift between the 2nd and 3rd dipole	0.4 m

60th harmonic EEHG for FLASH II



Without CSR *1.25kA, with CSR* *2.5kA, with CSR*

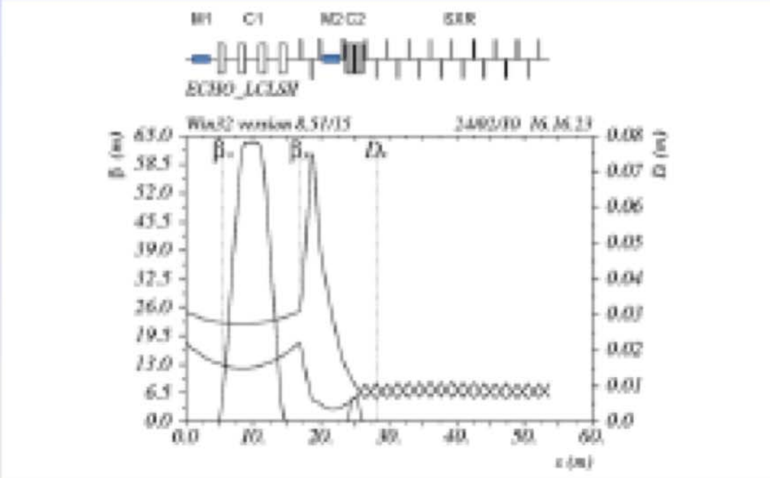
Courtesy of H. Deng, FEL Beam Dynamics Meeting, DESY, Dec.06, 2010; arXiv:1103.0112v2

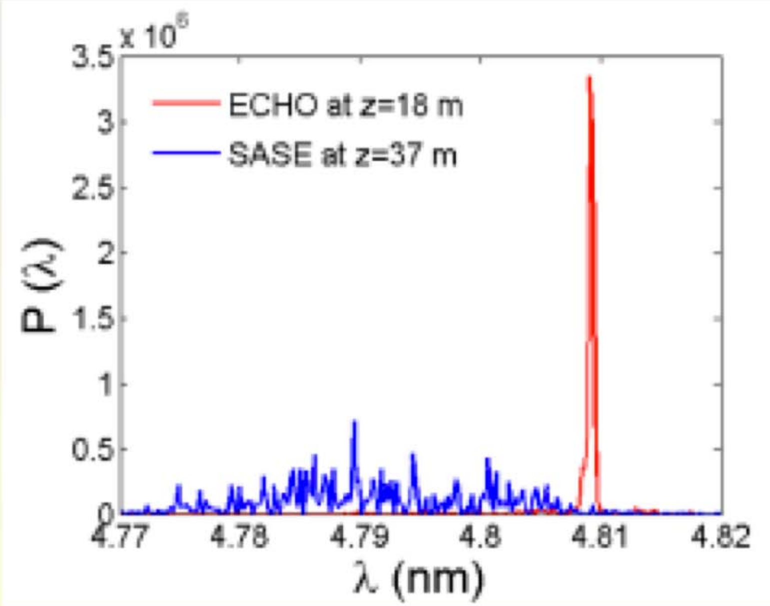
4. Possible end-to-end simulations

EEHG option 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.



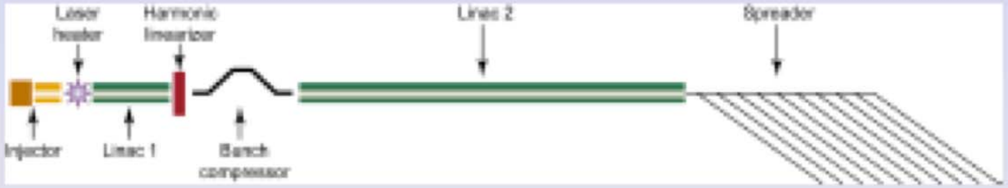


Courtesy of G. Stupakov, KEK, Nov. 05, 2010

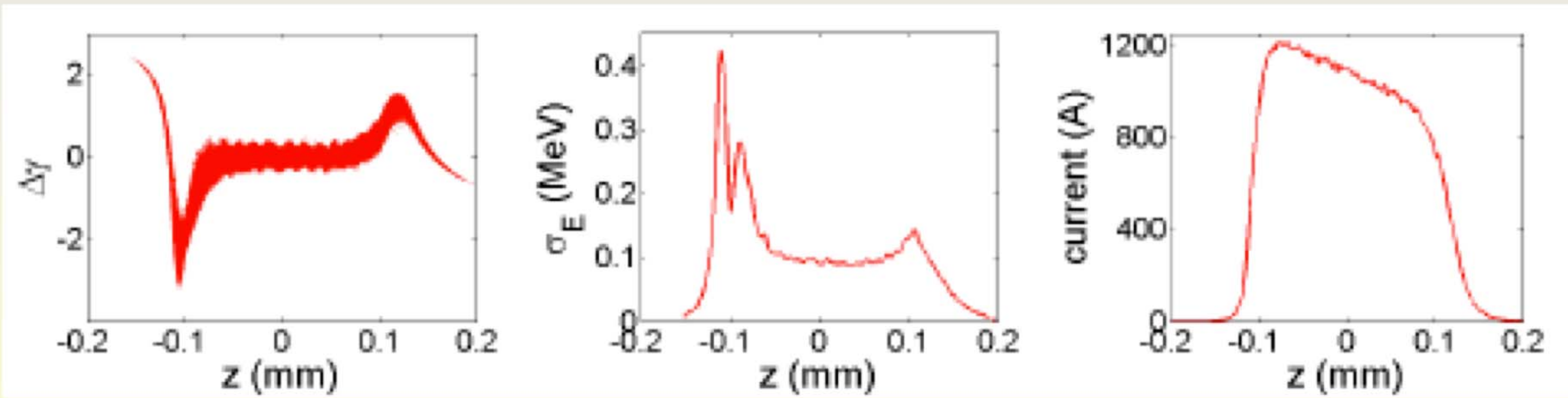
4. Possible end-to-end simulations

EEHG option for LBNL soft x-ray FEL:

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.

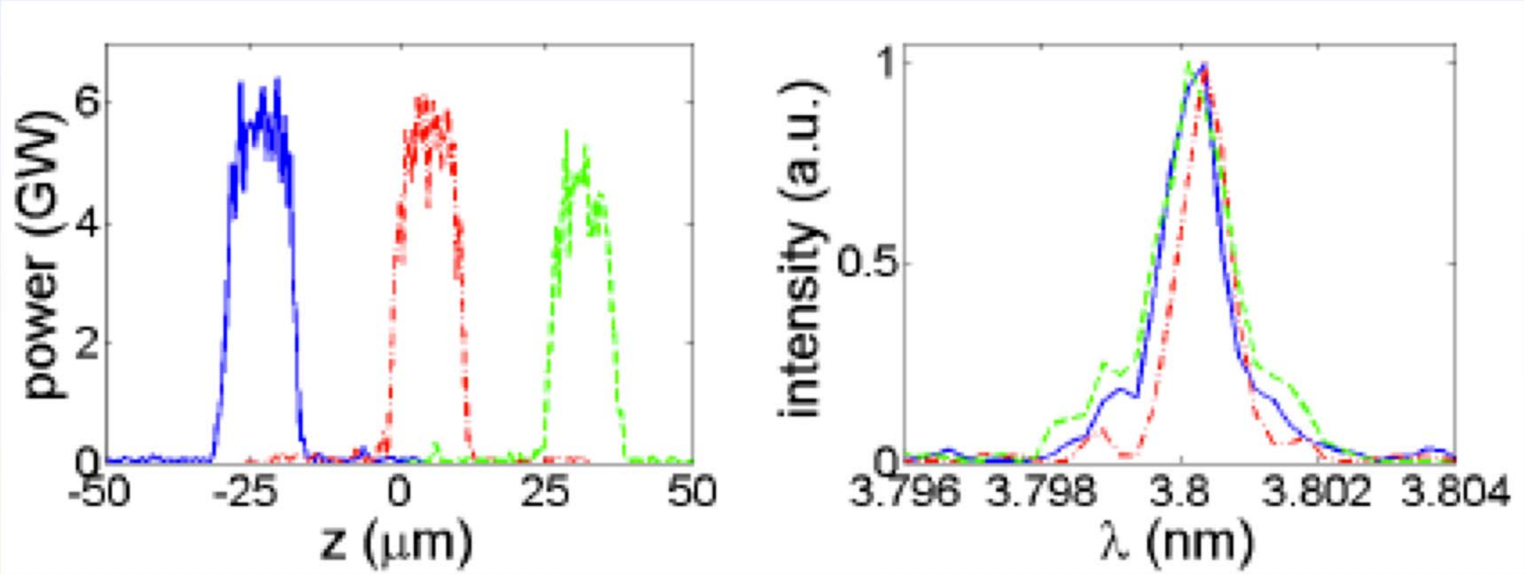


Courtesy of G. Stupakov, KEK, Nov. 05, 2010

4. Possible end-to-end simulations

EEHG option 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.

Courtesy of G. Stupakov, KEK, Nov. 05, 2010

5. Summary

- Proof-of-principle experiments@SLAC verified the EEHG theory. The performance of echo experiments is limited by the NLCTA injector system and beam timing jitter.

- EEHG seems to be promising for generation of harmonics up to 40-100. Seed wavelength ~200 nm ⇝ FEL wavelength ~a few nm. (G. Stupakov)

- Goals, advantages and challenges for Echo experiment@ERL are to be identified. Target x-ray wavelength ⇝ Lattice design ⇝ End-to-end simulation ⇝ Optimize FEL performance and tolerance studies.