Slippage Boosted Spectral Cleaning in a Seeded Free-Electron Laser

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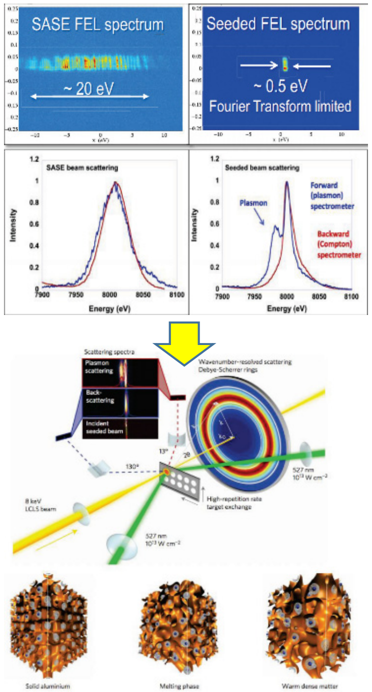
Outline

- Introduction
- External seeded FEL for fully coherent pulse generation
- Problems from the imperfections of the seed lasers and e-beams
- Slippage boosted spectral cleaning technique
- Experimental results
- Summary

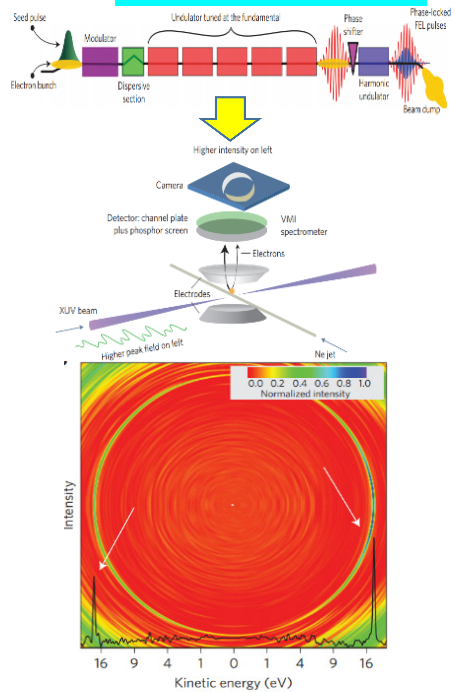
Applications of longitudinal coherent FEL

Self-seeding



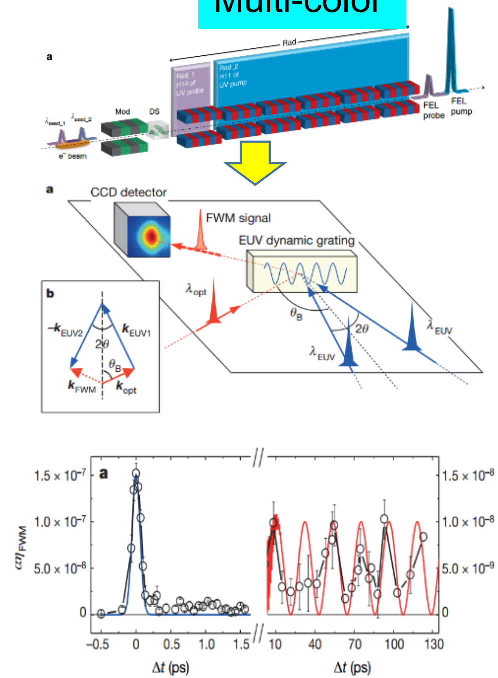
J. Amann et al., Nature Photonics, 2012.
L. Fletcher et al., J. Instrum,2013

External seeding



K. Prince et al., Nature Photonics, 2016.

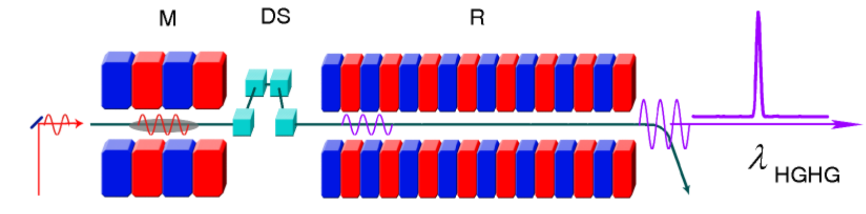
Multi-color



F. Bencivenga et al., Nature, 2015.

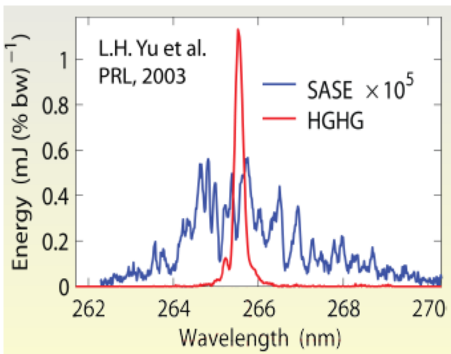
- User requirements for fully coherent, phase locked or multi-color radiation promote the development of fully coherent x-ray FEL.
- How to generate laser-like (stable and fully coherent) X-ray pulse becomes one of the main developing tendency of FEL.

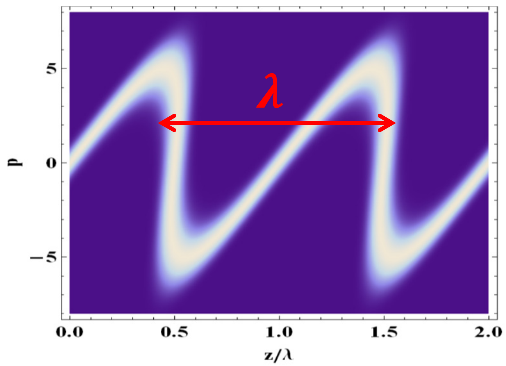
External seeded FELs (HGHG)

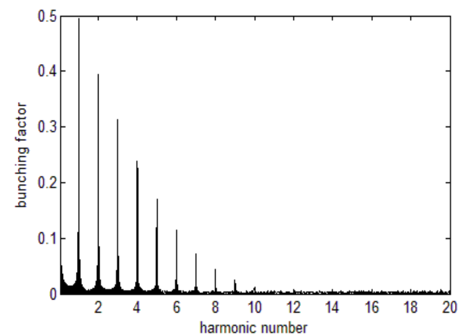


L. H. Yu, PRA (1991)

Cascaded HGHG:
L. H. Yu, I. Ben-Zvi, NIMA (1993)
J. Wu, L. H. Yu, NIMA (2001)
B. Liu et al. PRST-AB (2013)
E. Allaria, et al., Nat. photonics (2013)

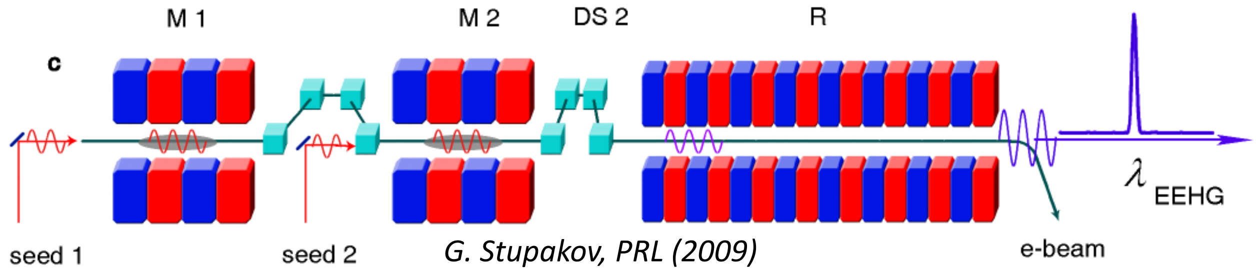






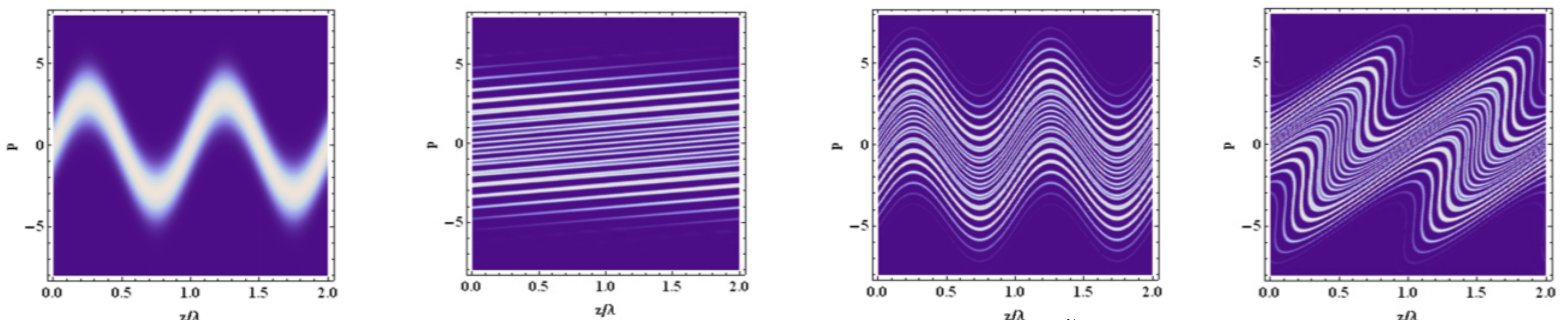
- Induced energy modulation at longer wavelength is changed into harmonic content after compression with a chicane.
- A selected harmonic is picked up with a succeeding undulator.
- Adopted by FERMI user facility / DCLS / SXFEL

External seeded FELs (EEHG)



G. Stupakov, PRL (2009)

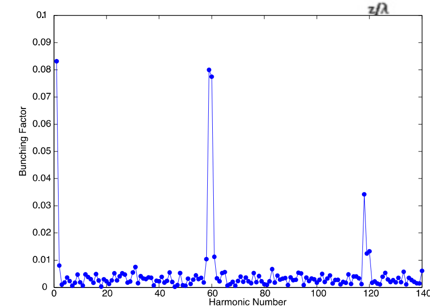
D. Xiang, G. Stupakov, PRAB (2009)



- over compression to generate energy bands
- spacing of bands defines harmonics

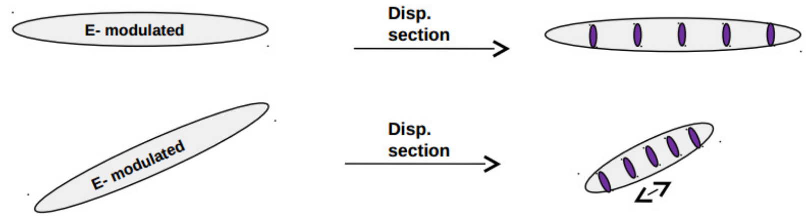
High efficiency for bunching

$$b_{\max} = \frac{0.39}{m^{1/3}}$$

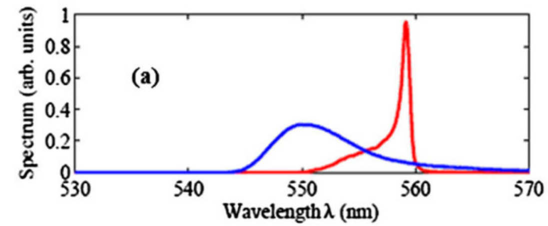


Limitations on the seeded FEL schemes at short wavelength

(1) Nonlinear energy chirps in the electron beam

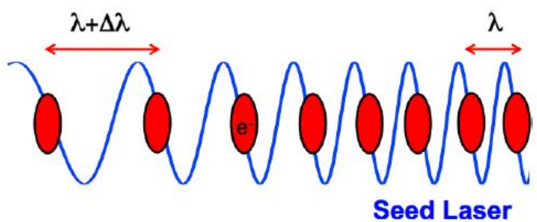


Wavelength shift and Bandwidth broadening



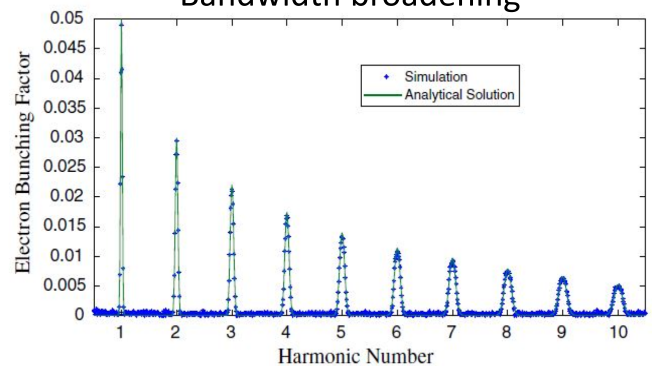
Courtesy Georgia Paraskaki

(2) Phase errors in the seed laser



D. Ratner et al., Phys. Rev. ST Accel. Beams 15 (2012) 030702.

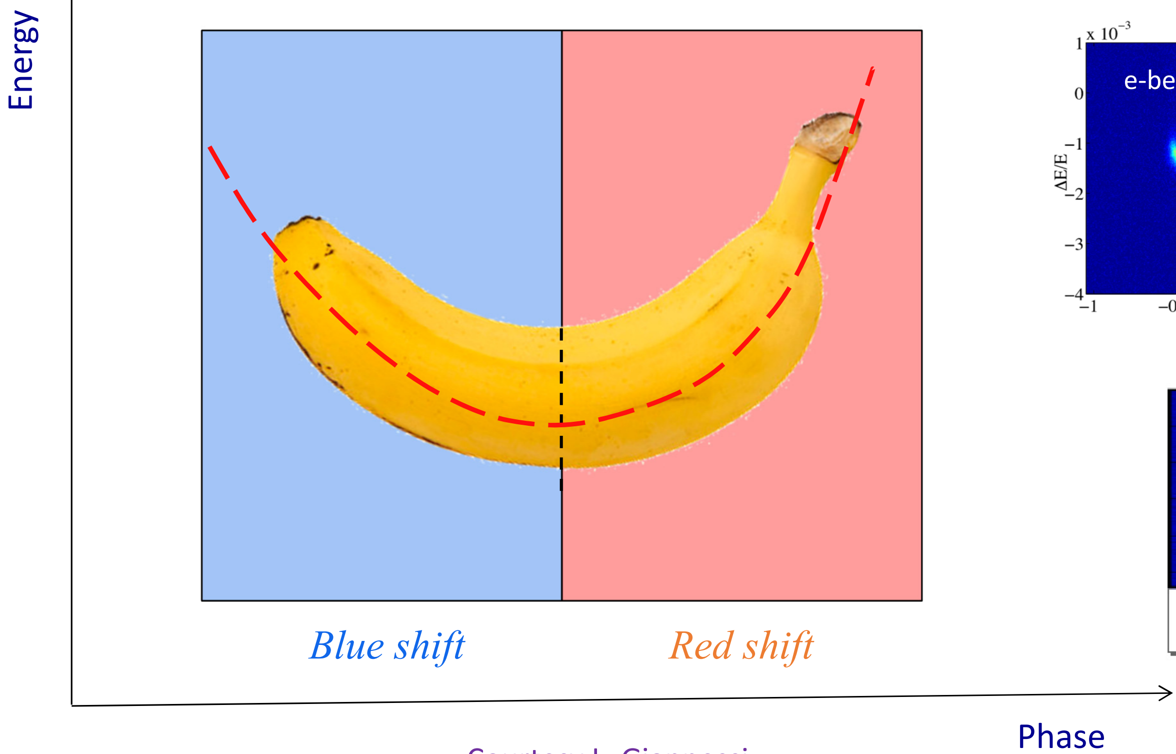
Bandwidth broadening

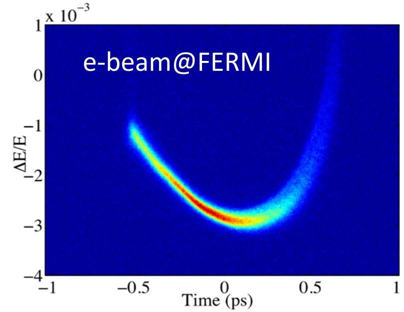


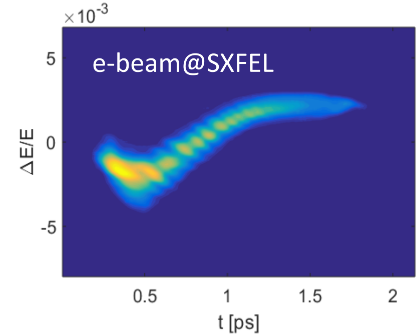
- The initial insignificant errors compared to the seed wavelength will be amplified by the harmonic up-conversion process and become large relative to a much shorter wavelength

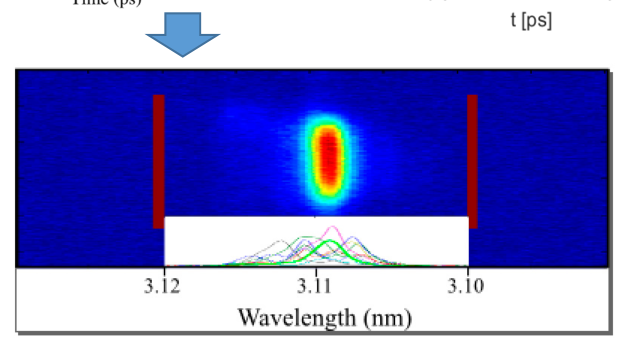
Problems from the imperfection of the electron beam

A quadratic energy chirp (or higher orders) in the e-beam phase space is one of the causes of frequency chirp & spectral broadening of the FEL pulses





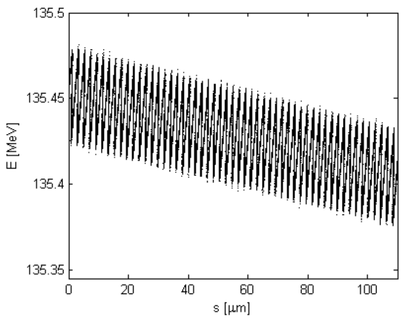




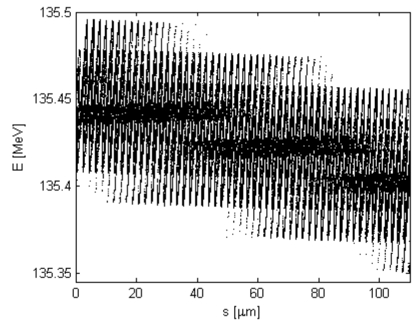
Courtesy L. Giannessi

EEHG is insensitive to the energy chirp in the e-beam

HGHG with chirped e-beam



EEHG with chirped e-beam



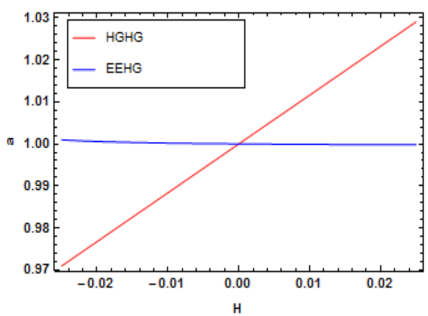
EEHG immune to energy chirp:

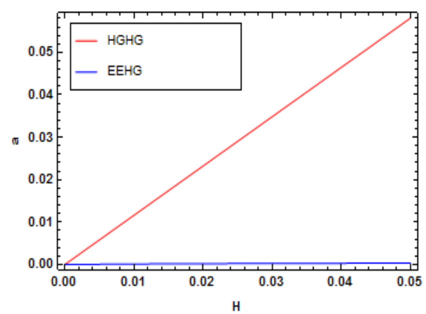
$$R_{56}^{(2)} = -\frac{n}{n+m} R_{56}^{(1)}$$

optimized condition for EEHG:

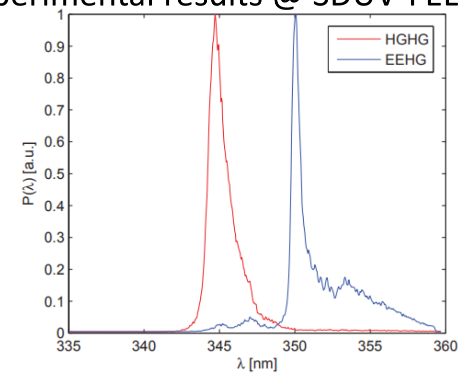
$$R_{56}^{(2)} = -\frac{n}{n+m} \left(R_{56}^{(1)} + \xi / n \right)$$

$$A_1 \left[J_{n-1}(A_1\xi) - J_{n+1}(A_1\xi) \right] = 2\xi J_n(A_1\xi)$$





Experimental results @ SDUV-FEL in 2011



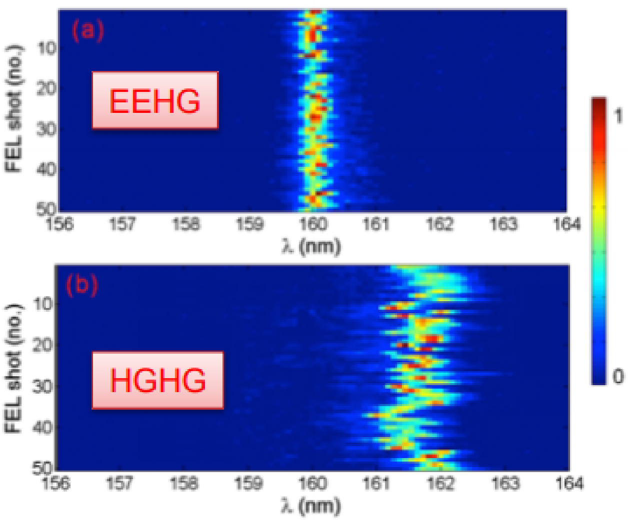
First proposed and demonstrated the condition that EEHG can be nearly immune to the beam energy chirp by properly setting the strengths of the chicanes:

[1] C. Feng, D. Wang and Z.T. Zhao, "Study of the energy chirp effects on seeded FEL schemes at SDUV-FEL." in IPAC 2012

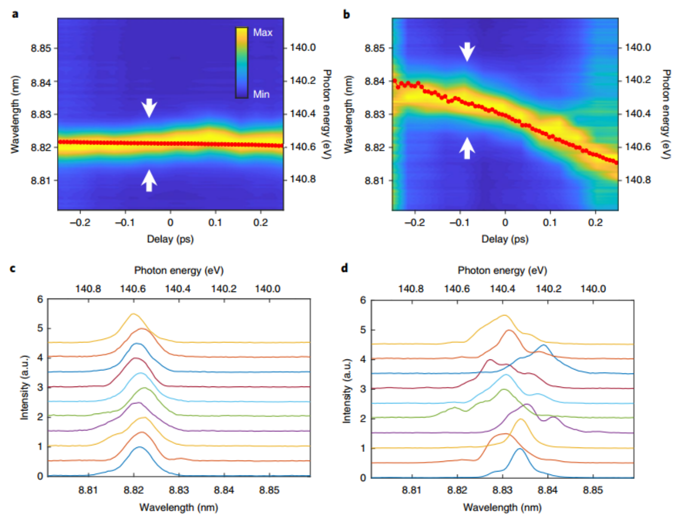
[2] Z.T. Zhao, et al., Nature photonics, 2012.

EEHG is insensitive to the energy chirp in the e-beam

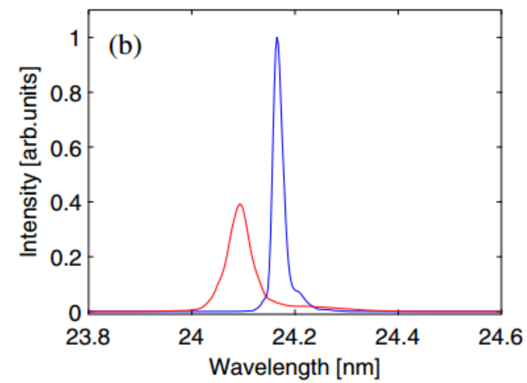
E. H, et al PRST-AB 17, 070702 (2014)



P.R. Ribič, et al Nat. Photon. (2019)

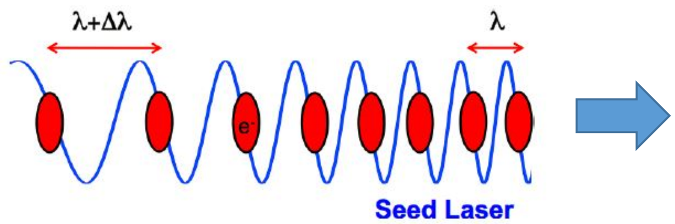


C. Feng, et al PRAB 22, 050703 (2019)

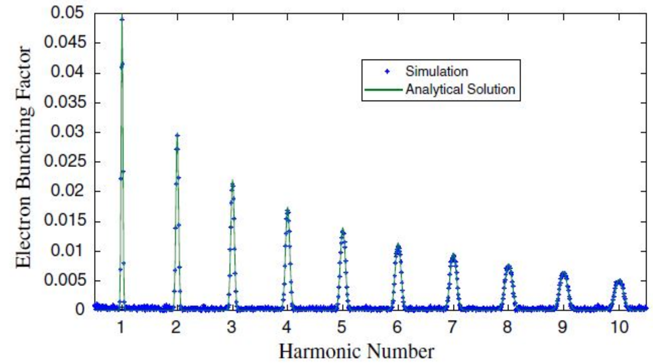


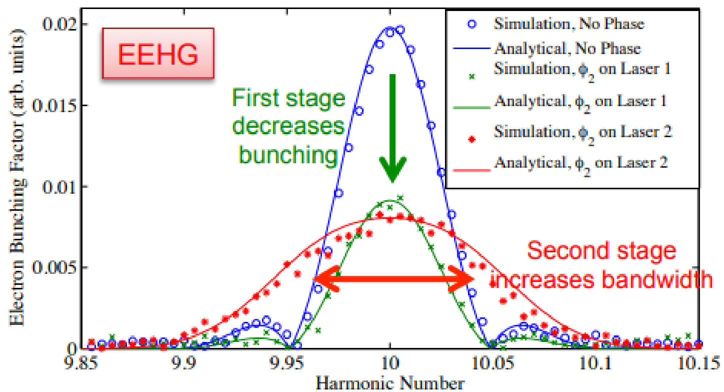
- ➢ These experimental results pave the way for seeding a x-ray FEL directly from an ultraviolet laser.
- ➢ But it is still a problem on how to mitigate the effect of the initial high order and random phase errors in the seed laser on the FEL output coherence.

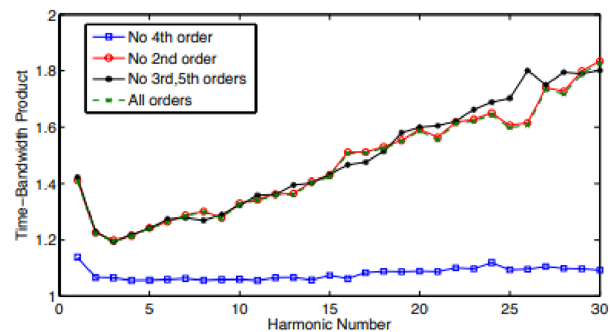
Problems from the imperfection of the seed laser



G. Geloni, V. Kocharyan, E. Saldin, arXiv:1111.1615v1.
G. Stupakov, SLAC-PUB-14639, Nov 2011
D. Ratner et al., Phys. Rev. ST Accel. Beams 15 (2012) 030702.

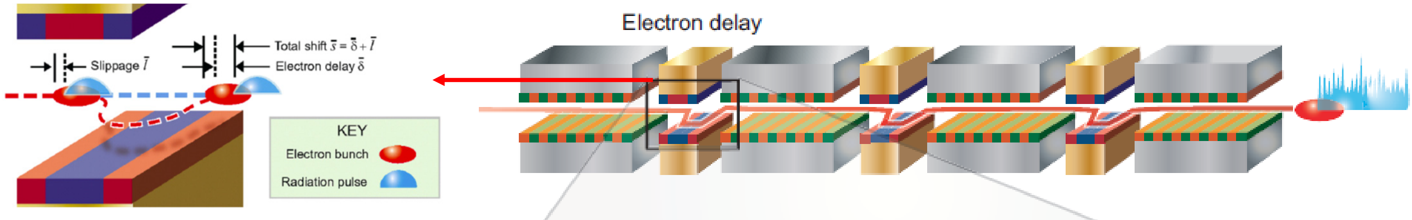




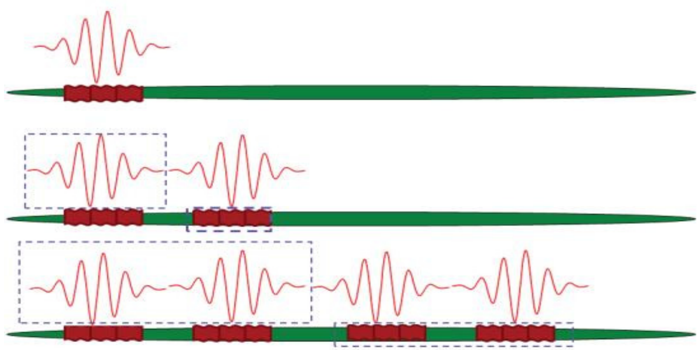


- The initial small phase errors of the seed laser will be amplified during the harmonic up-conversion process (time bandwidth product scales linearly with the harmonic order) and may eventually overwhelm the external seeding source at short wavelengths

Possible solutions



B. W. J. McNeil et al., PRL 110(2013) 134802



iSASE

J. Wu et al., IPAC 2013

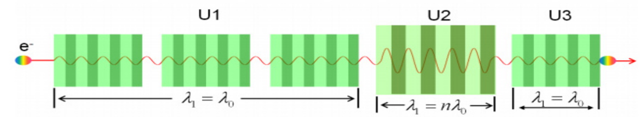


FIG. 2: Schematic layout of a pSASE FEL.

$$\frac{L_{1D}^{(n)}}{L_{1D}^{(1)}} = \left(\frac{A_1^2}{nA_n^2}\right)^{1/3},$$

$$A_n(K) = J_{(n-1)/2}\left(\frac{nK^2}{4+2K^2}\right) - J_{(n+1)/2}\left(\frac{nK^2}{4+2K^2}\right).$$

pSASE

D. Xiang et al., PRST-AB 16(2013)010703

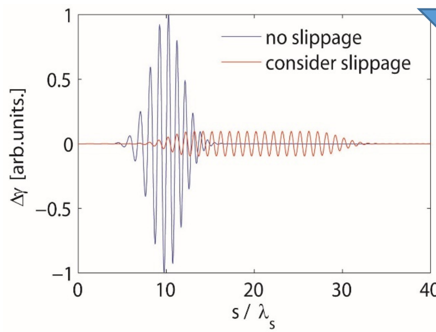
- Several techniques have been proposed to enhance the FEL slippage for a SASE FEL
- Provides an *in situ* method for communicating phase information over larger portions of the electron beam and improving the temporal coherence of the FEL

Possible solutions: enhance the slippage in the modulator

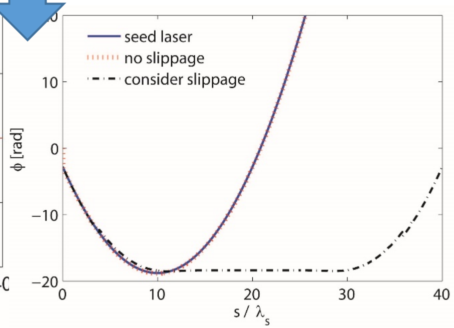
Considering the slippage effect
in the modulator

$$E(s,t) = E_0 e^{-[s-p(t)]^2/4\sigma_s^2} e^{i\{k_s[s-p(t)]+\alpha[s-p(t)]^2+\phi_0\}}$$

$$\gamma(s) = \int_0^{L_{mod}/c} \frac{e}{mc^2} E(s,t)\cdot \upsilon_x(t)dt$$

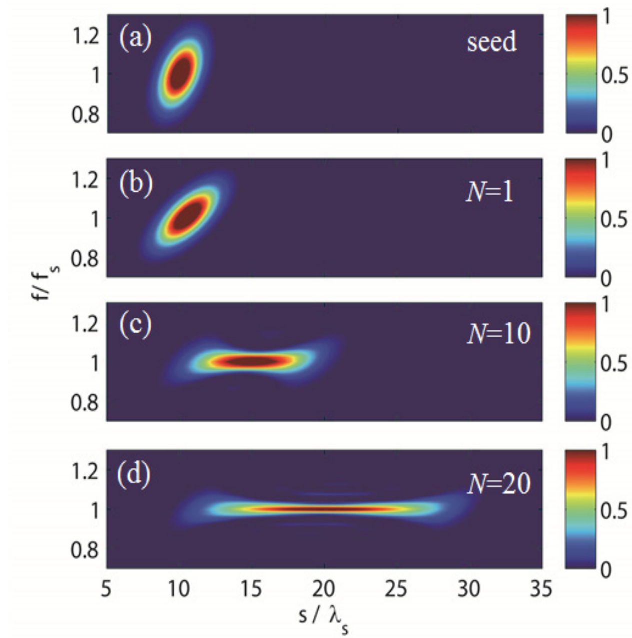


Energy modulation amplitude along the e-beam



Phase of the energy modulation along the e-beam

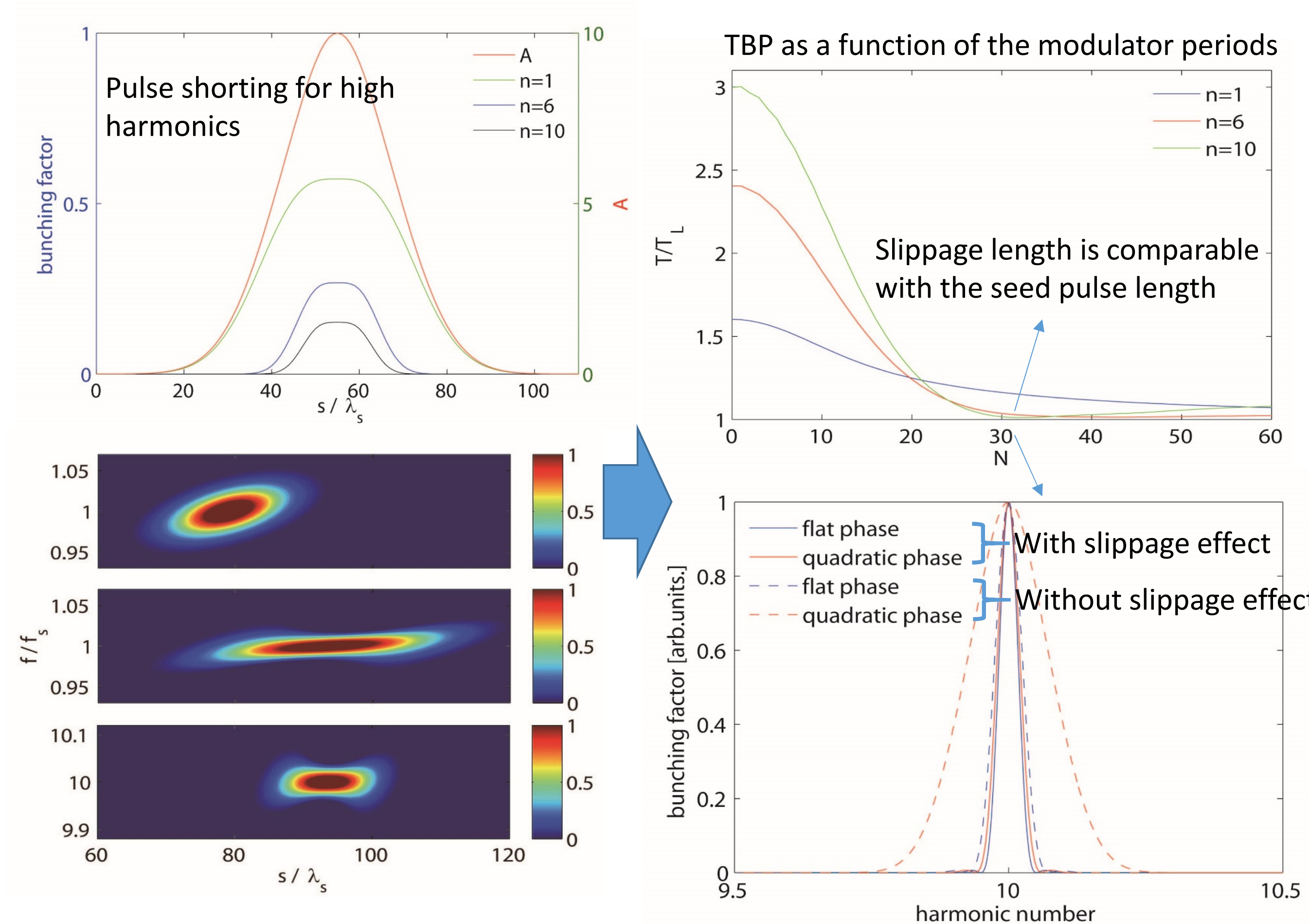
Wigner function



C. Feng, et al., PRST-AB 16 (2013) 060705.

- The seed laser wavelength is relative long, which results in a large slippage that we required.
- imperfection of the seed laser experienced by the electron beam can be significantly smoothed when the slippage length is comparable to the pulse length of the seed laser

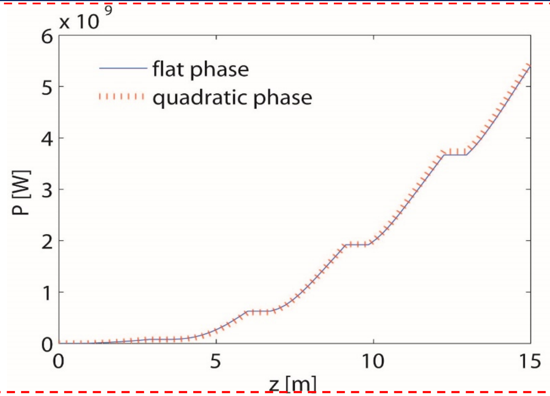
Simulations for HGHG with phase errors

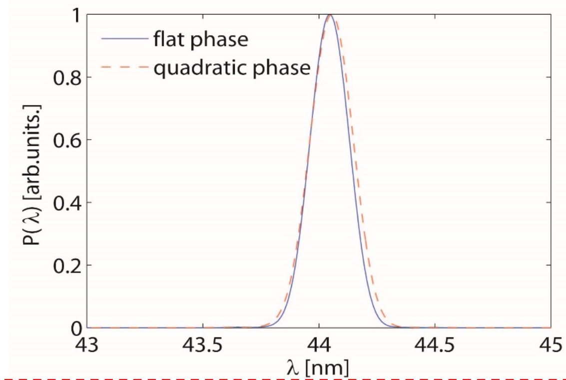


- The spectral chirp only appears in the lateral parts of the radiation pulse, which has negligible effects on the spectral bandwidth.
- the spectra are nearly the same for the flat and quadratic phase cases when the slippage effect is considered.

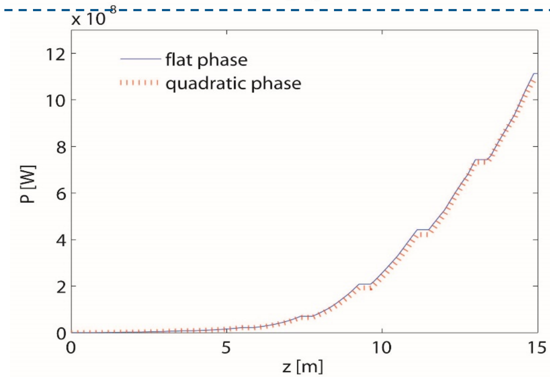
Simulations for HGHG and EEHG with phase errors

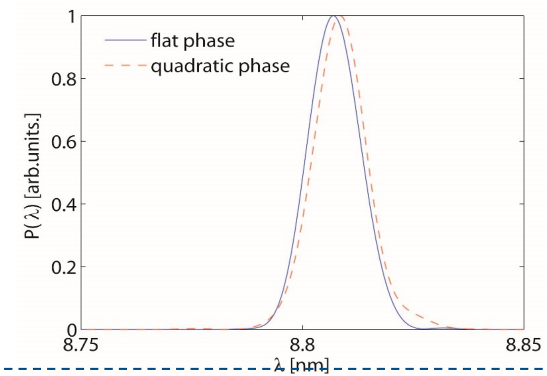
HGHG





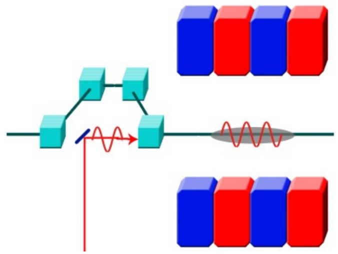
EEHG





- For both HGHG and EEHG, the slippage in the modulator is quite effective to mitigate the effect of the phase errors in the seed laser.
- Only central part of the modulation is suitable for harmonic generation, simulations show that the FEL pulse duration will not been stretched much when the slippage length is comparable with the seed pulse length.

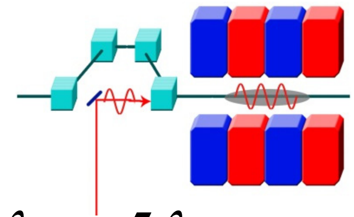
Enhance the slippage in the modulator with a sub-harmonic modulator



$$\lambda_m = \lambda_s$$

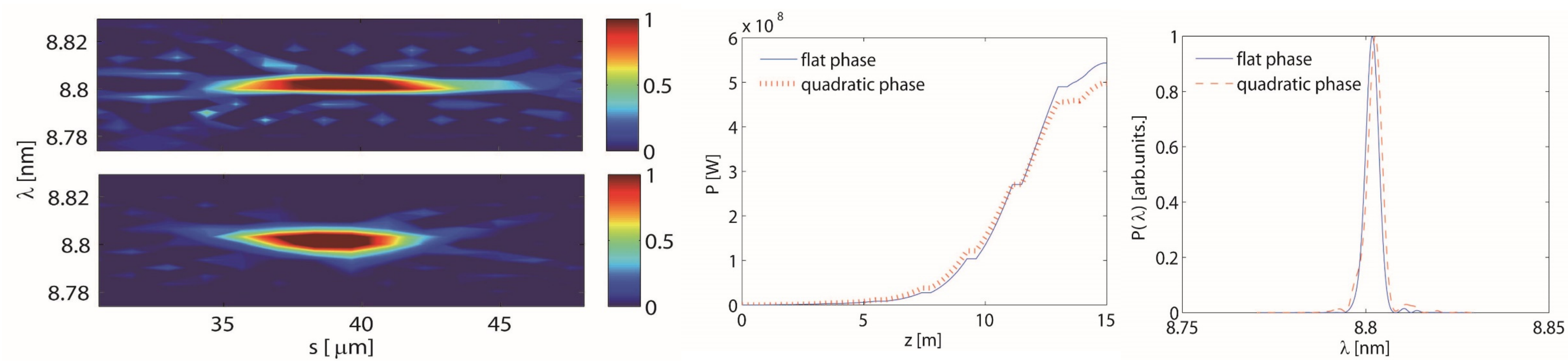
$$m\lambda_s = \frac{\lambda_u}{2\gamma_r^2}(1+K^2/2)$$

$$\lambda_m = m\lambda_s,\ m = 3, 5, 7, \ldots$$



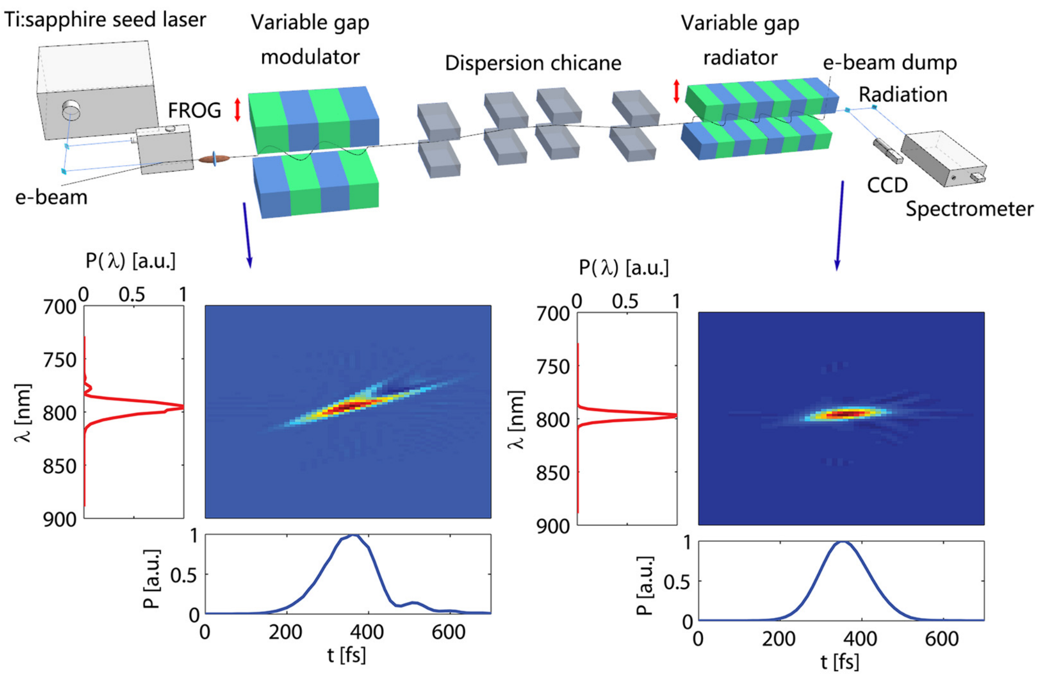
$$\lambda_m = 5\lambda_s$$

Simulation results with the parameters of the SXFEL



- Enlarge the slippage length by *m* times while still keeping the FEL interaction in the small-gain regime in the modulator.
- For a ~260 nm 100fs seed laser, a modulator with 30 periods and resonating at 5th sub-harmonic (1330 nm) will be sufficient to smooth the phase error

Proof-of-principle experiment setup

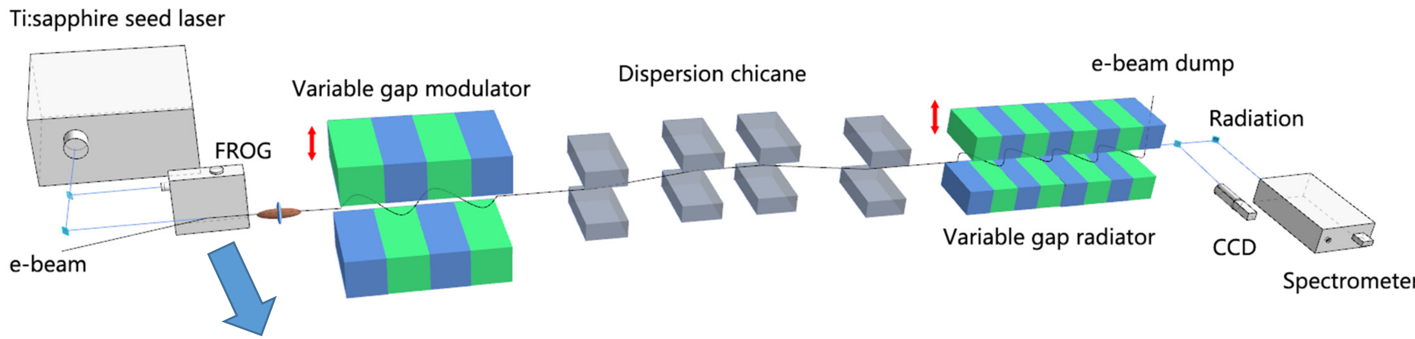


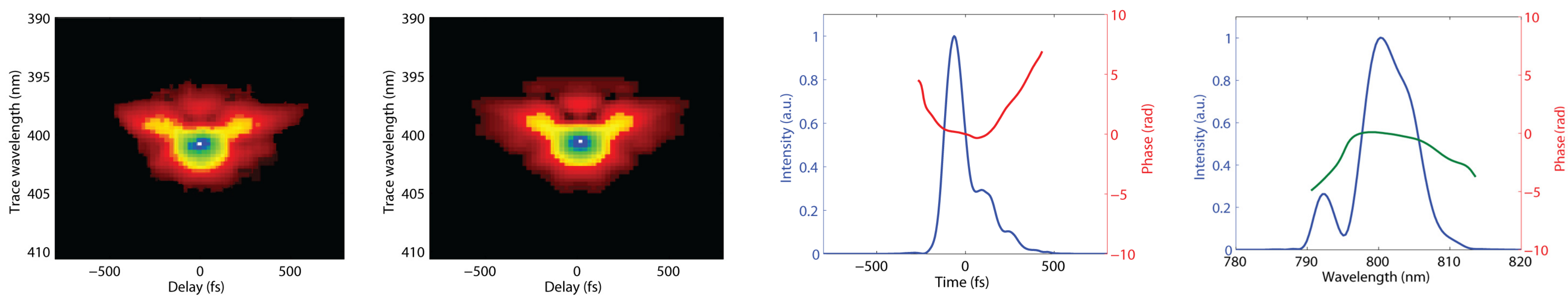
Electron beam	
Energy	148 MeV
Bunch length (without compression)	8.8 ps
Seed laser	
Wavelength	800nm
Pulse length	124 fs
Modulator	
Period	5 cm
Coverage	0.8-4 μm
Radiator	
Period	4 cm
Coverage	0.2-0.8 μm

- Performed for HGHG at SDUV-FEL.
- A FROG was used to detect the distribution of the seed laser, a CCD and a spectrometer were used to measure the properties of the radiation.

C. Feng, et al., Scientific reports 9 (2019): 6960.

Preparation of the seed laser with significant phase errors

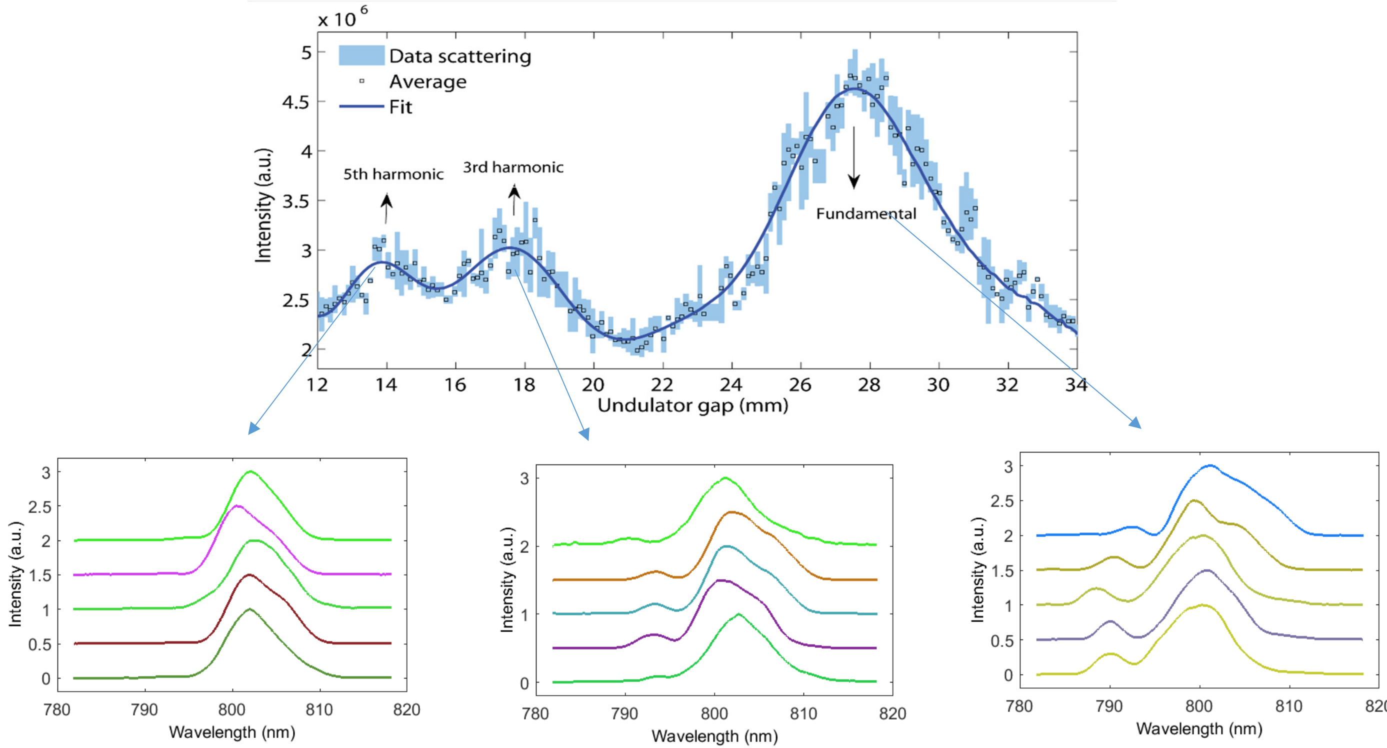




- The initial pulse length (close to Fourier-transform limit) is about 83 fs (FWHM)
- Large high order dispersions have been induced by tuning the position and angle of the second grating in the compressor of the Ti:Sa amplifier

Measurement results

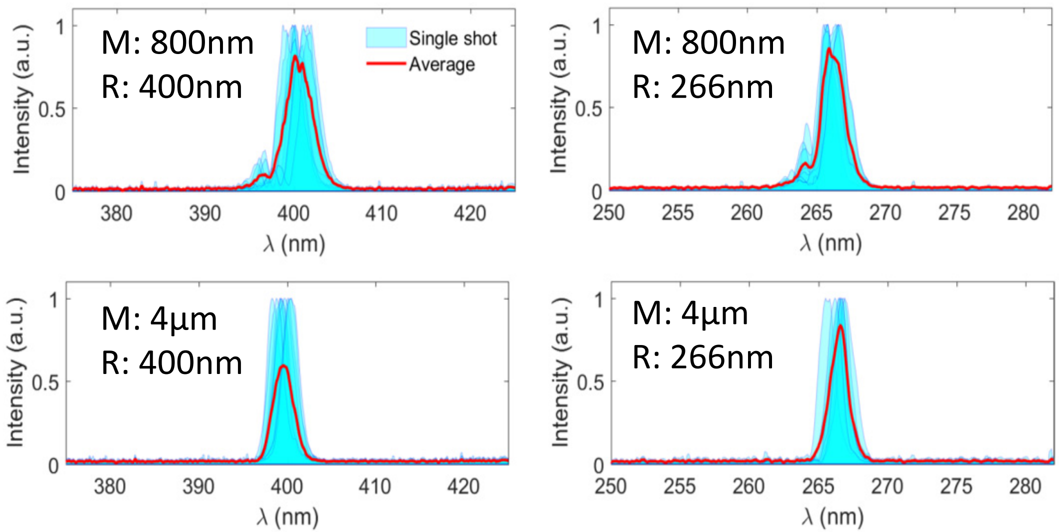
Scan the gap of the modulator and detect the radiation of CHG at 800 nm

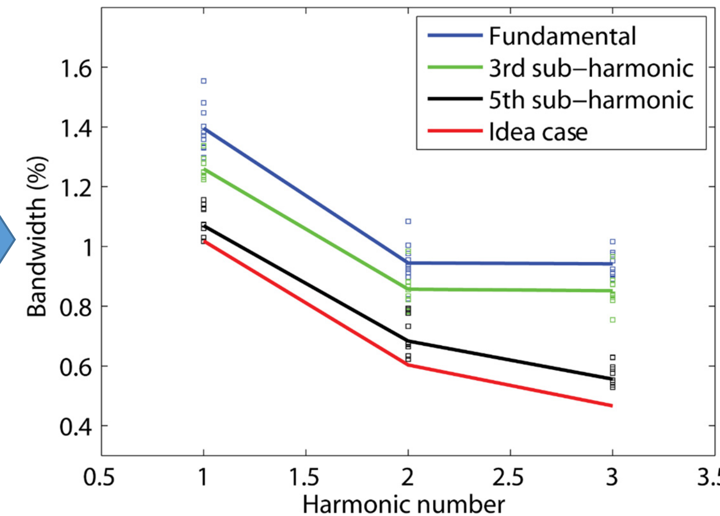


- ➢ Tree peaks appeared sequentially when the gap is tuned from 12 mm to 34 mm, corresponding to the resonant wavelengths of 800 nm (fundamental), 2.4 µm (3rd sub-harmonic) and 4 µm (5th sub-harmonic)
- ➢ The spectral sidebands are significantly reduced for longer resonant wavelength of the modulator

Measurement results

M: modulator R: radiator





- For higher harmonic radiation, the output bandwidth of CHG will be broadened mainly due to two efects: the natural pulse shortening and the phase error multiplication.
- The deviation between the experiment and simulation results becomes larger for higher harmonics due to the phase error multiplication.
- The spectral cleaning effect becomes significant when the modulator resonates at 4 μm, the average spectral bandwidths are quite close to those of the ideal case

Summary

- The realization of fully coherent and stable light sources at extreme ultraviolet to x-ray region has been a long standing challenge for high-gain FELs.
- For seeded FEL, the challenges and difficulties mainly comes from the imperfections of the electron beam and seed lasers. The e-beam energy chirp problem maybe relaxed by EEHG, The laser frequency chirp problem maybe relaxed by the proposed slippage boosted spectral cleaning technique.
- Theoretical and experimental results indicate the possibility of generating fully coherent x-ray radiation pulses by combining the EEHG with the slippage boosted spectral cleaning technique. Further experiments at x-ray wavelengths are needed.

Thank the operation staffs at SARI and SINAP for excellent support during the experiments. Thanks also go to D. Xiang and E. Hemsing for their help and useful comments.

Thanks very much for your attention!