Overview of Seeded FELs and Harmonic Generation

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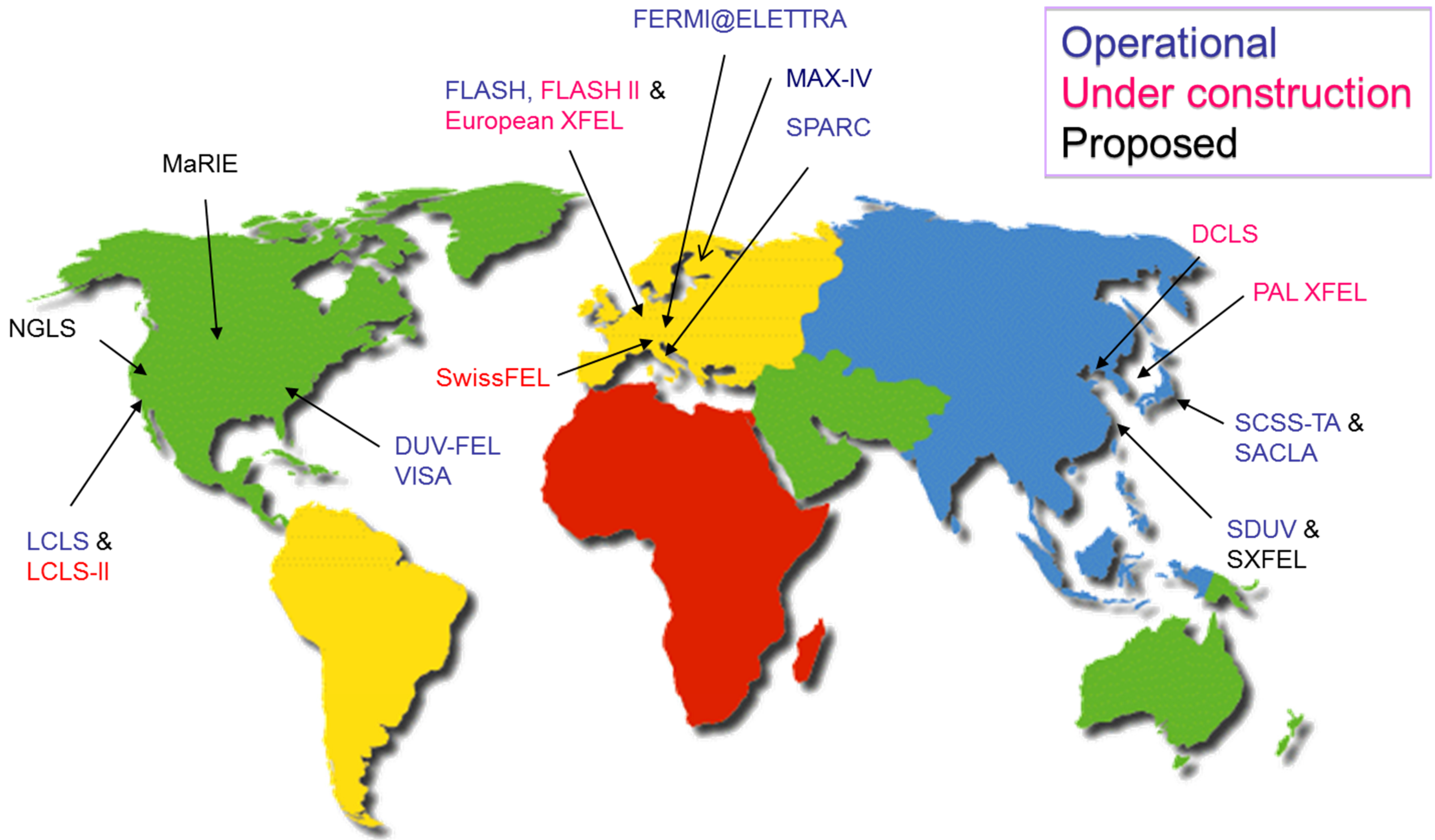
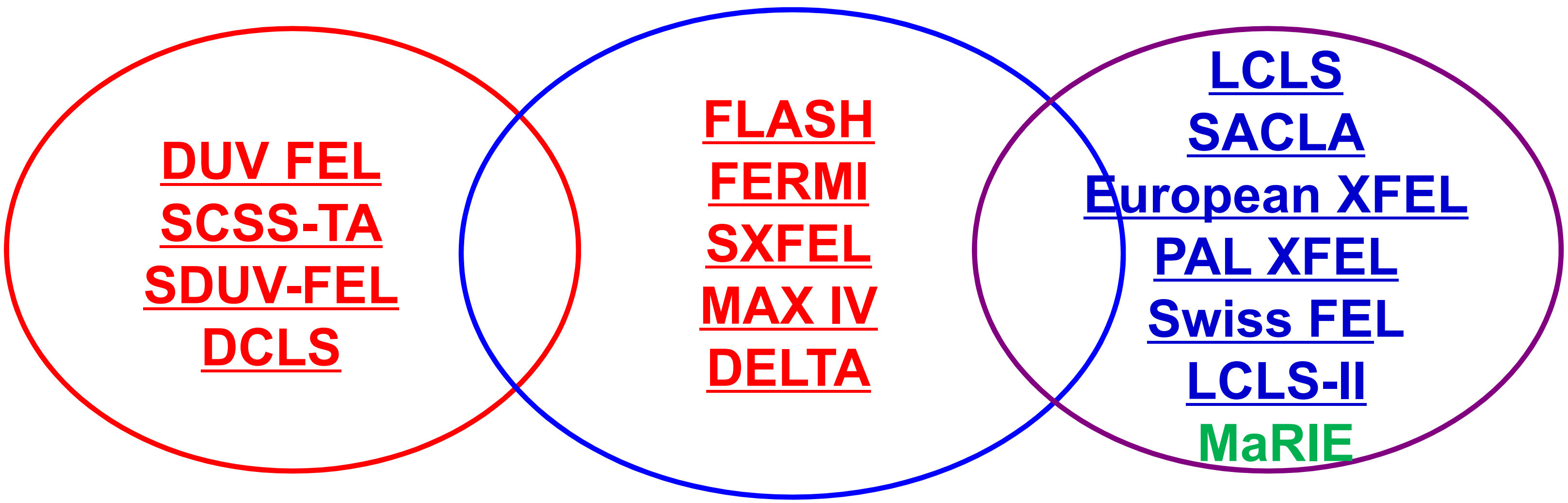
Outline

- Introduction & background
- Seeded FEL facilities
- Seeded FEL schemes and experiments
- Proposed novel schemes
- Summary

Worldwide XFELs

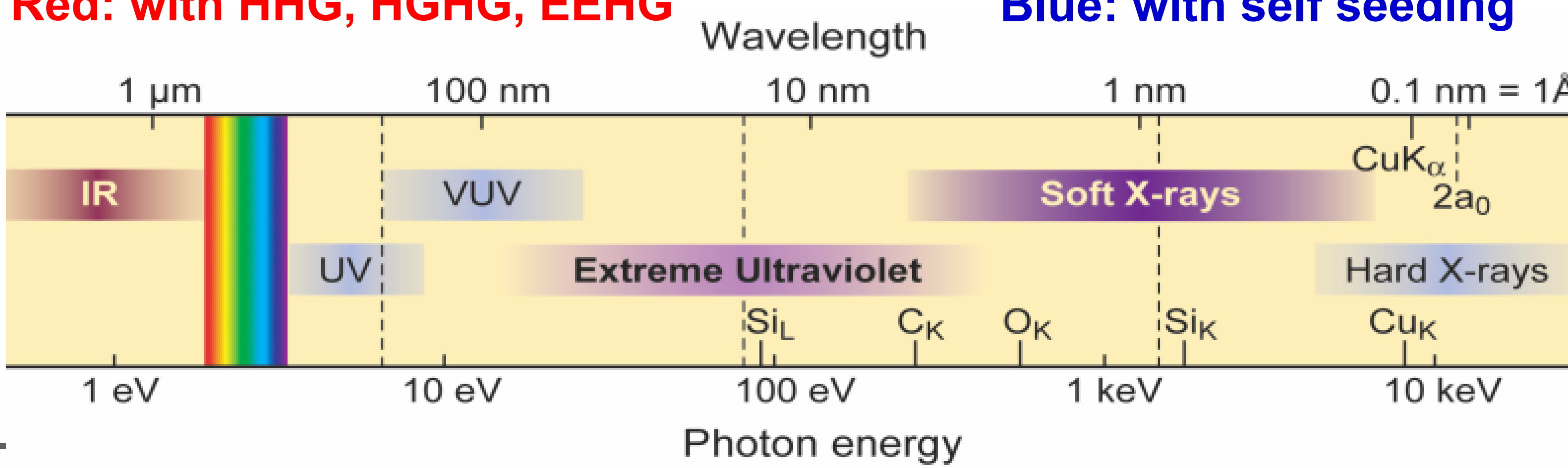


Worldwide FELs



Red: with HHG, HGHG, EEHG

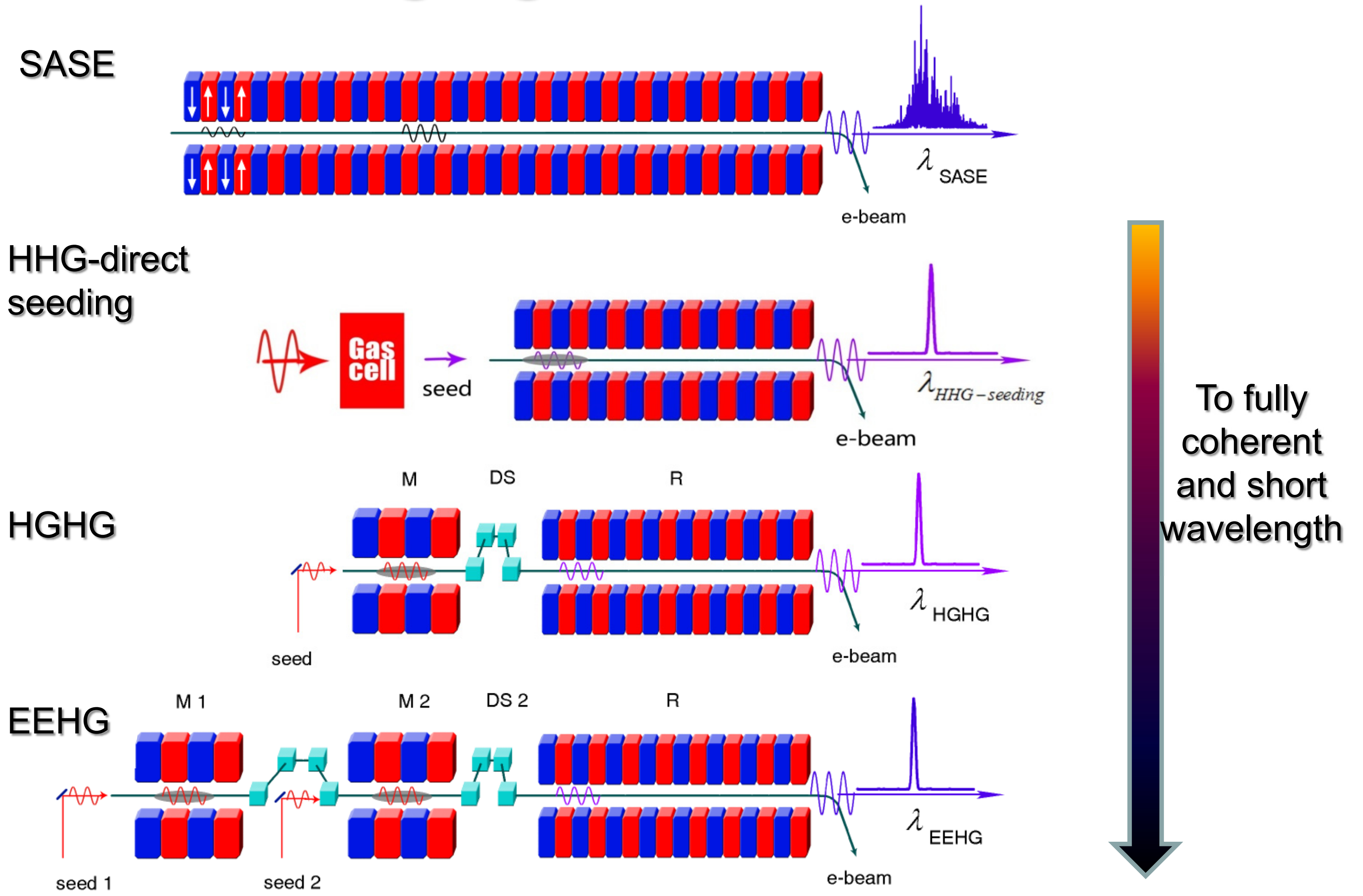
Blue: with self seeding



Seeded FEL facilities

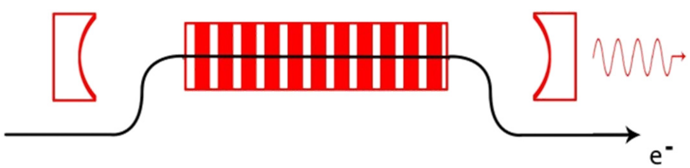
Seeded FEL schemes

High-gain FELs

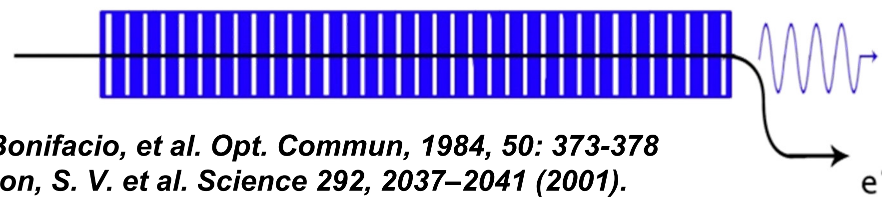


SASE and Self-seeding

Oscillator

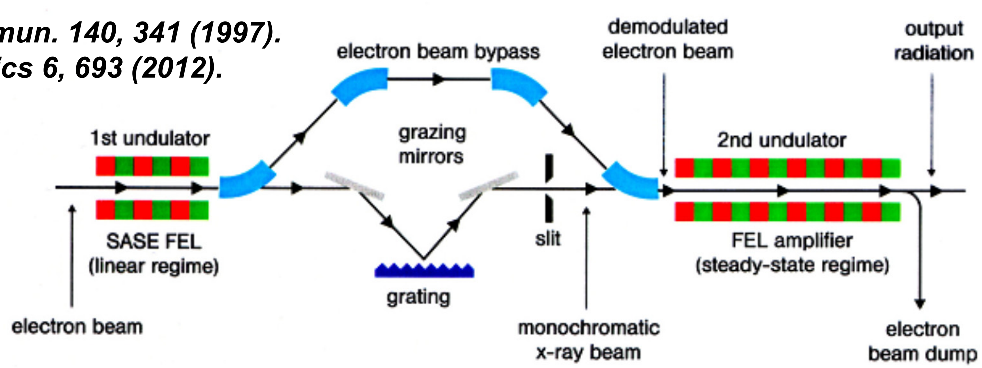


SASE



R. Bonifacio, et al. Opt. Commun, 1984, 50: 373-378
Milton, S. V. et al. Science 292, 2037–2041 (2001).
P. Emma et al., Nat. Photonics 4, 641 (2010).

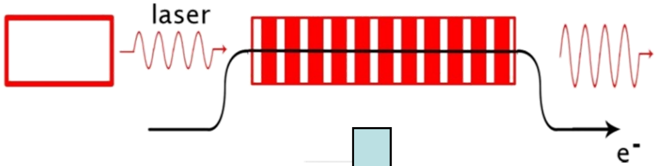
J. Feldhaus et al., Opt. Commun. 140, 341 (1997).
J. Amann et al., Nat. Photonics 6, 693 (2012).



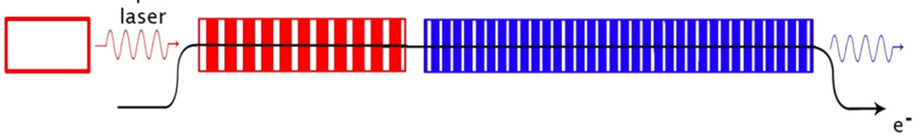
Self-seeding

Seeded FEL schemes (with external seeding source)

Amplifier

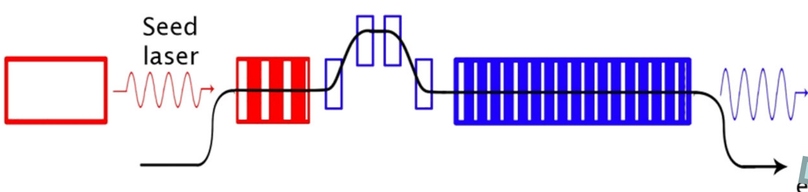


Two wiggler



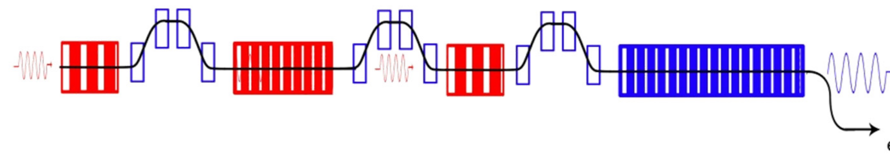
R. Bonifacio, et al. Nucl. Instrum. Methods A 296,787 (1990).

HGHG



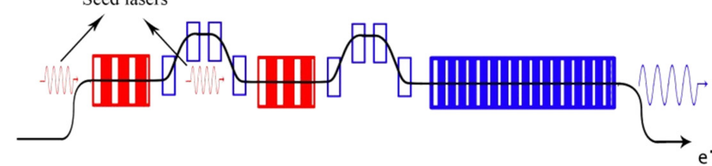
L. H. Yu. Phys. Rev. A, 1991, 44: 5178-5193
L. H. Yu, et al., Science 289, 932 (2000).

Cascaded HGHG



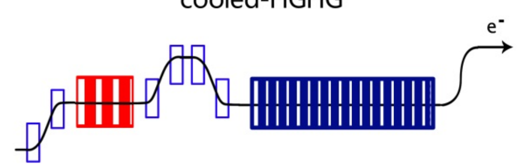
Yu L H, Ben-Zvi I. Nucl Instr Meth A, 1997, 393: 96–99
B. Liu, et al. Phys. Rev. ST Accel. Beams 16, 020704 (2013).
L. Giannessi, Synchrotron Radiation News, 2013, 26:1, 48.

EEHG



G. Stupakov, Phys. Rev. Lett. 102, 074801 (2009).
Z. T. Zhao, et al., Nat. Photonics 6, 360 (2012).

cooled-HGHG



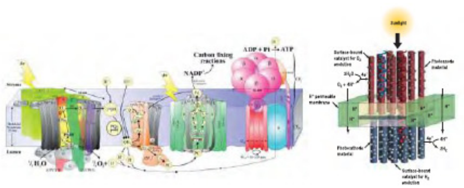
H. Deng, C. Feng. Phys. Rev. Lett. 111, 084801 (2013)

Advantage of seeded FELs

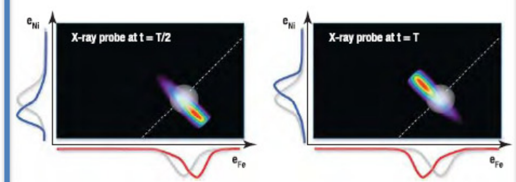
- Improve the longitudinal coherence and brilliance
- Improve stability of pulse energy and central wavelength (**In principle**)
- Increase FEL efficiency with undulator taper(**In principle**)
- Generation and control of ultra-short pulse length
- Natural synchronization of the FEL pulse to the seed laser (**In principle**)
- Reduction of saturation length.

Broad range of science enabled by seeded FELs

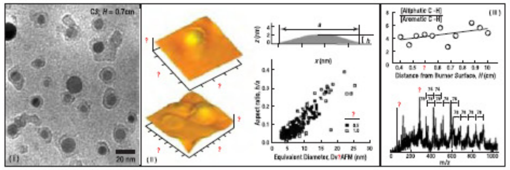
Natural and Artificial Photosynthesis



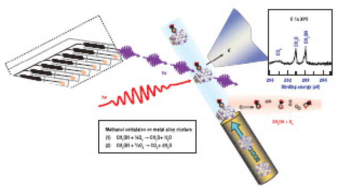
Fundamental Charge Dynamics



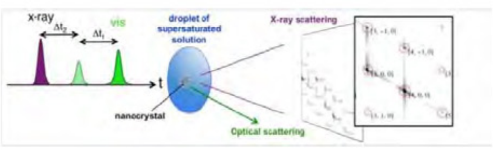
Advanced Combustion Science



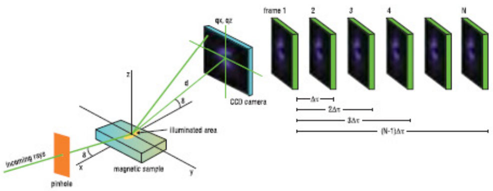
Catalysis



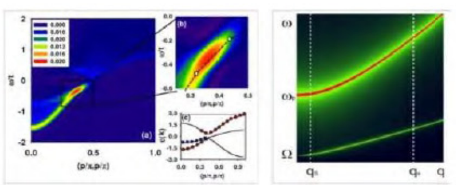
Nanoscale Materials Nucleation



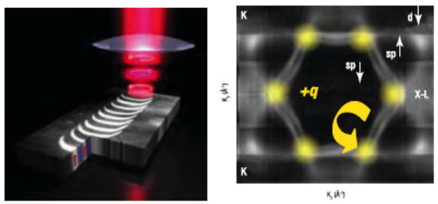
Dynamic Nanoscale Heterogeneity



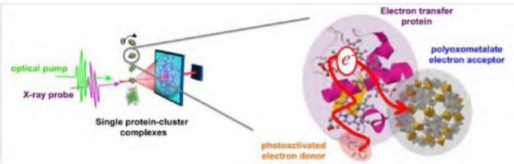
Quantum Materials



Nanoscale Spin and Magnetization



Bioimaging: Structure-to-Function

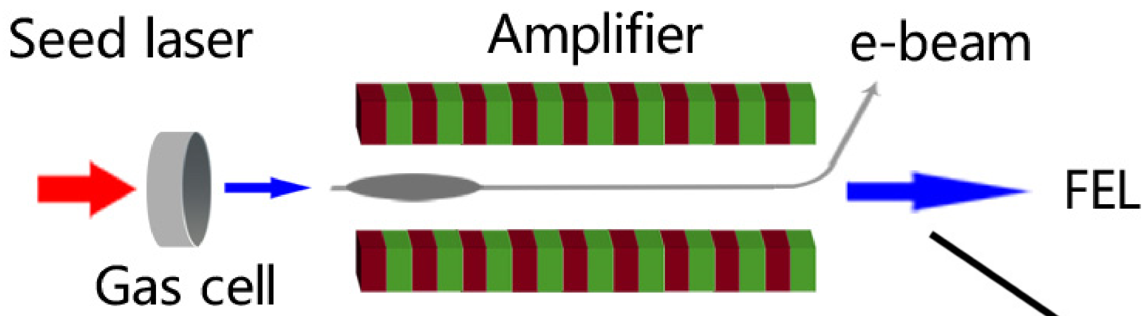


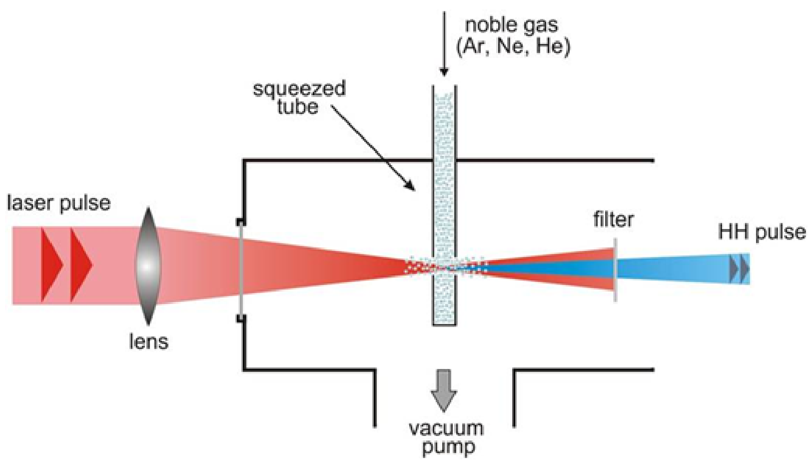
B. Schoenlein, 2011

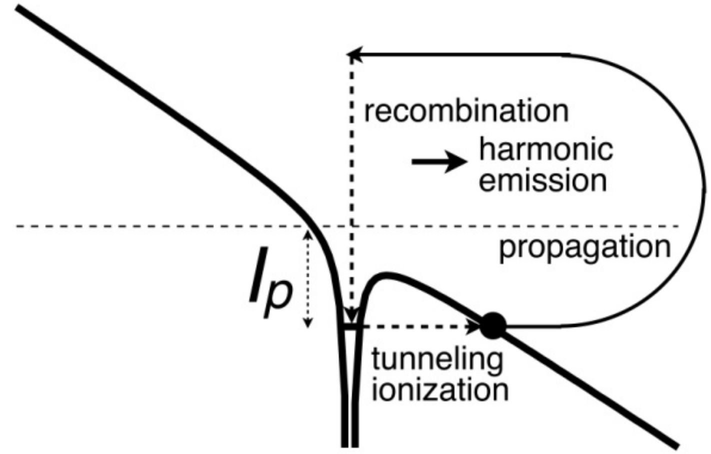
Seeding sources

- A short wavelength laser, e.g. HHG (UV-VUV)
  - FEL works as an amplifier. (direct seeding)
- A free electron laser (IR-X-ray)
  - Radiation from a FEL is used as a seed for another FEL (self seeding, oscillator, …)
- An external conventional laser (visible to UV)
  - Electron beam manipulation for high-harmonic generation. (CHG, HGHG, EEHG, cooled-HGHG,…)

HHG direct seeding





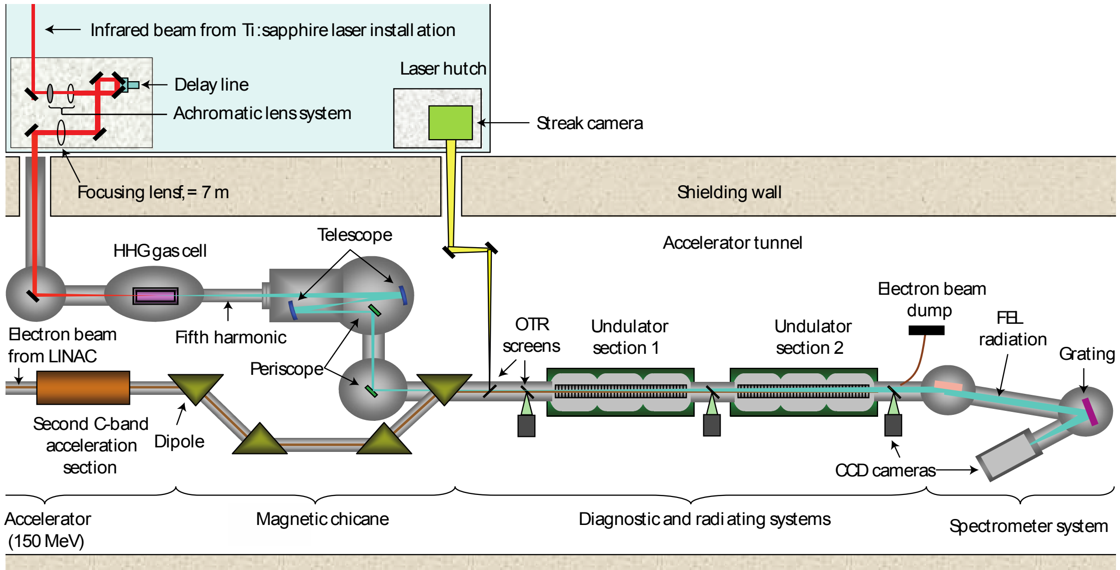


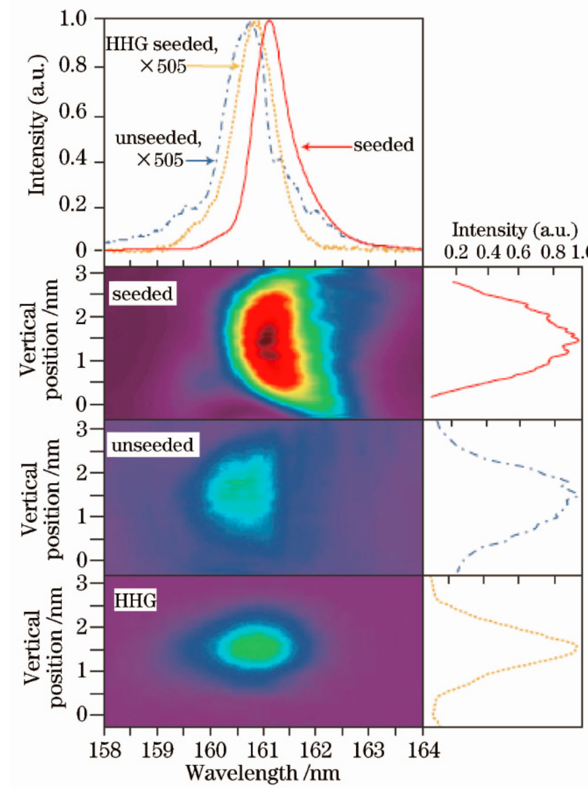
- 3 step process in noble gases
- High energetic photons, phase locked to drive laser
- Coherence properties inherited from drive laser
- Limited to short pulses due to ionization of gas

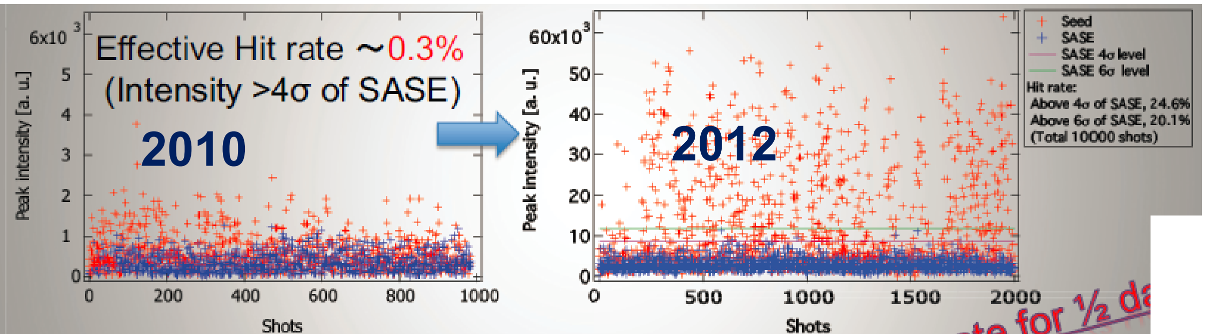
Key technologies of HHG directing seeding:

- HHG with short wavelength
- Increase the efficiency of HHG to overcome shot noise
- Overlap of the HHG seeding pulse and electron bunch

HHG direct seeding @ SCSS







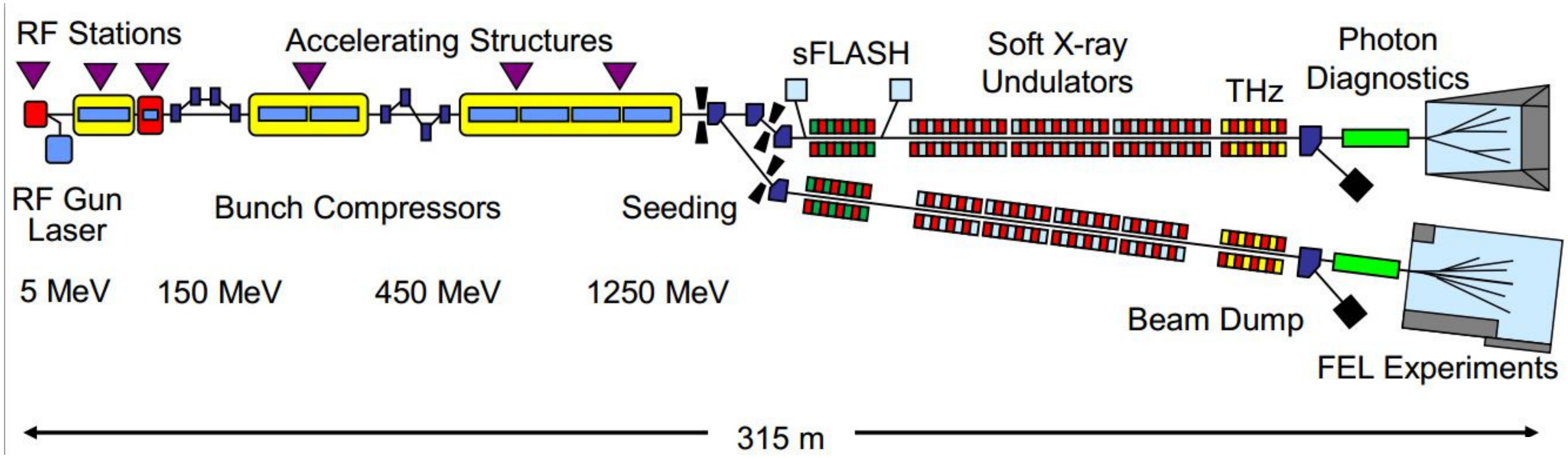
- Seeded FEL output was 1.3 μJ
- The seeding operation was only obtained less than 10 minutes.

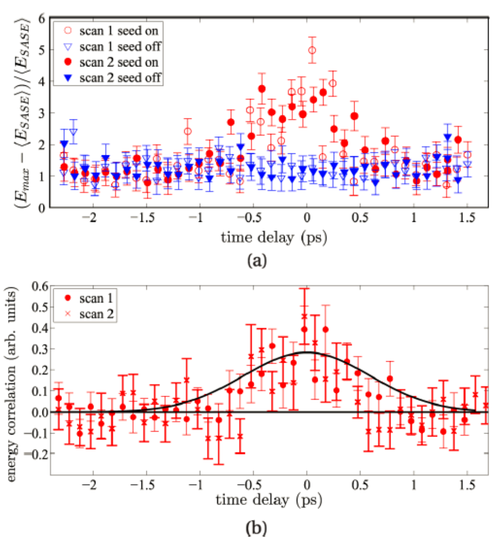
~30% effective hit rate for ½ da
Up to 20 μJ

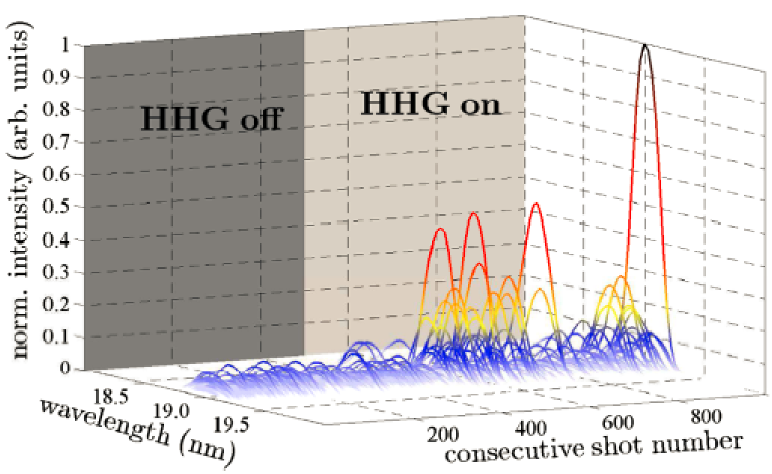
- First POP-experiment of HHG-direct-seeding has been performed at SCSS.
- Stable operation at 61.5 nm
- Contrast ratio was improved more than 5 times.

G. Lambert et al, Nature Physics Vol. 4 (2008) 296 H. Tomizawa, et al, FEL13, THOANO01

HHG direct seeding @ sFLASH





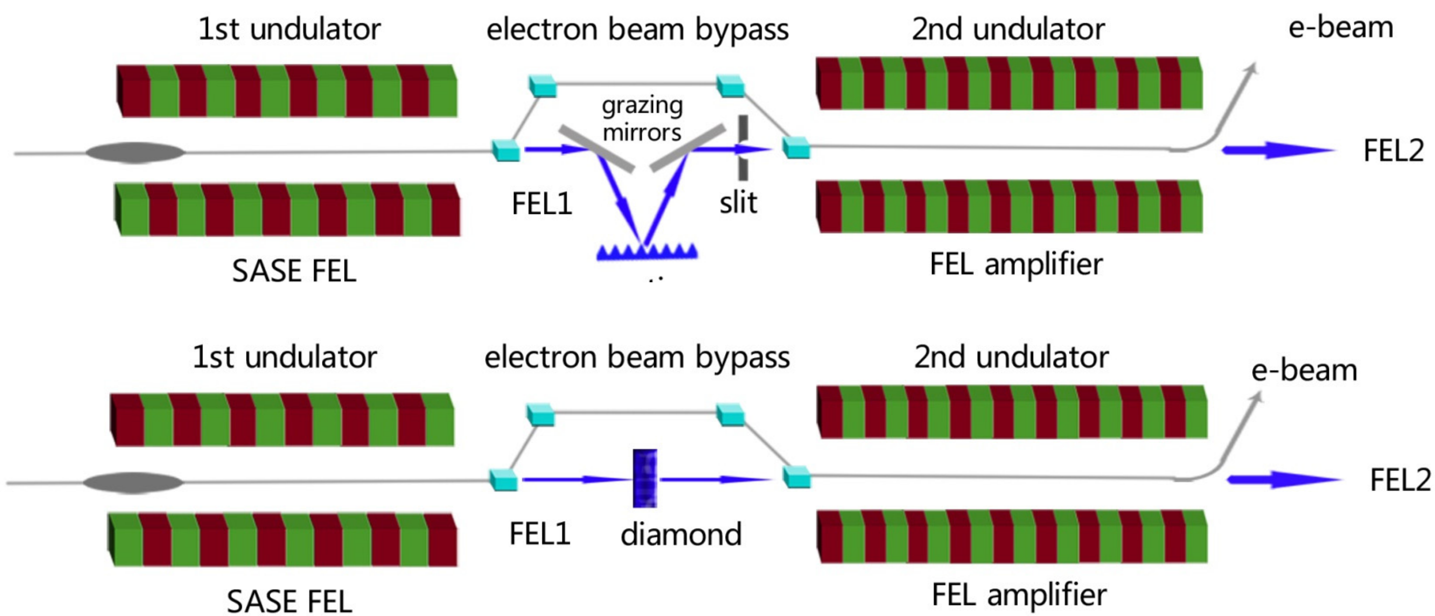


- Seeding at 38 nm (21st harmonic of the seed).
- Radiation at both 38.2nm and 19.1nm
- GW-level coherent radiation is generated
- Power contrast approx. 30

J. Boedewadt et al., Phys. Rev. Letters 111 (2013), 114801.

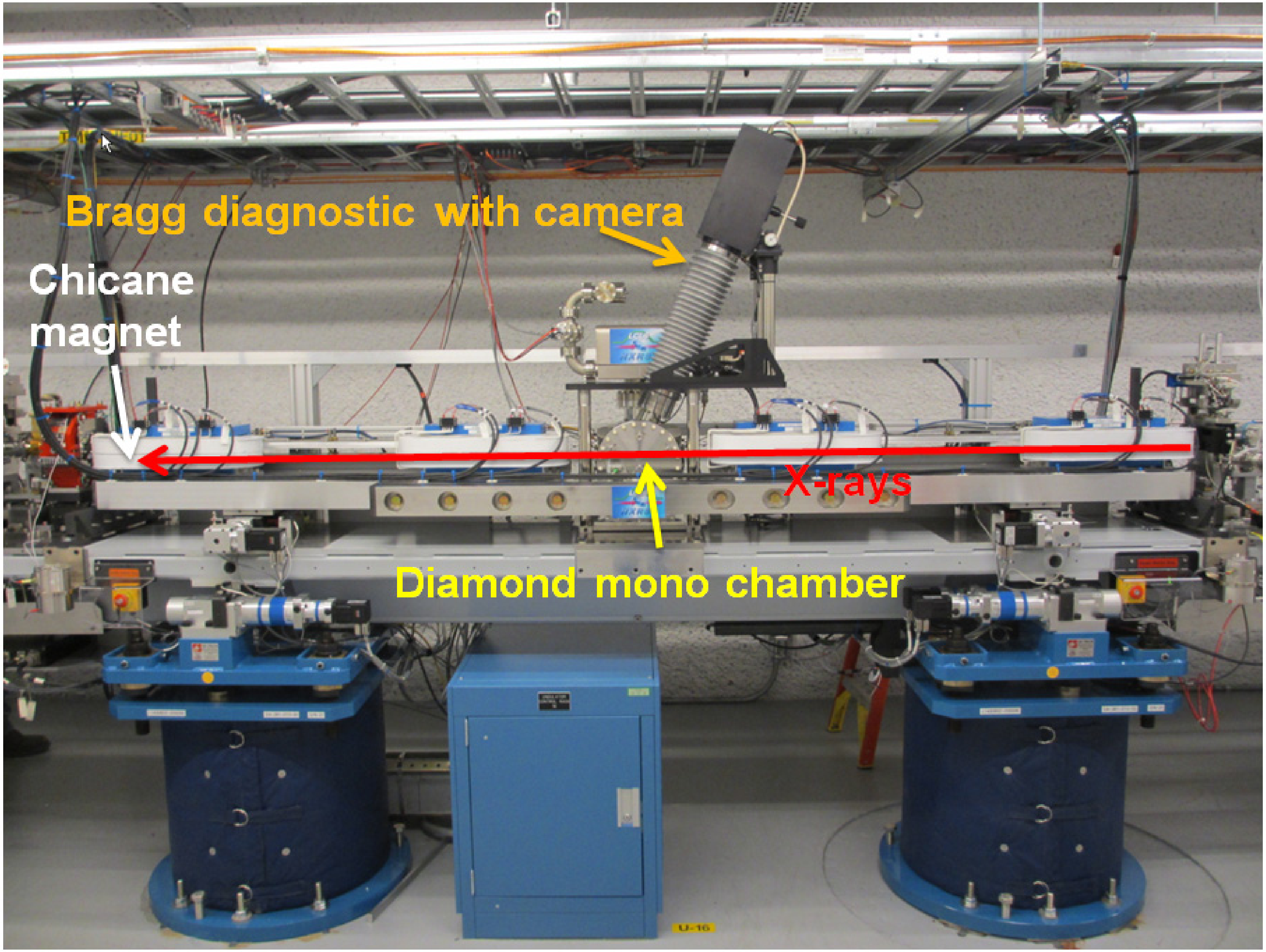
Seeded FEL experiments

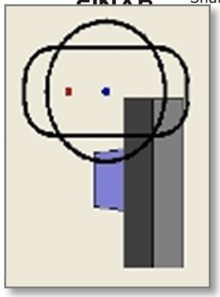
Self-seeding



- Basic Idea:
- 1st stage operates as SASE FEL, but far from saturation
- Radiation is filtered, introducing longitudinal coherence
- Delay of radiation field is matched with delay electron beam with a magnetic chicane. The chicane removes also any induced bunch, removing the imprint of SASE in the bunch
- Beam and radiation are overlapped in a second stage, operating as an FEL amplifier.
- First proposed for soft X-ray FEL FLASH [J. Feldhaus et al, Opt. Comm 140 (1997) 341] but never realized due to the strong delays in the photon and electron path.
- Idea brought up again for hard X-ray [G. Geloni, Jour. Of Modern Optic 58:16 (2011) 1391], using the transmission around the stop band of a Bragg reflection (see next slide).
- More compact design for soft X-ray [Y. Feng, LCLS] makes self-seeding feasible for longer wavelength

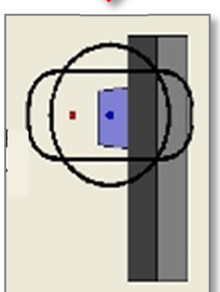
Self-seeding @ LCLS



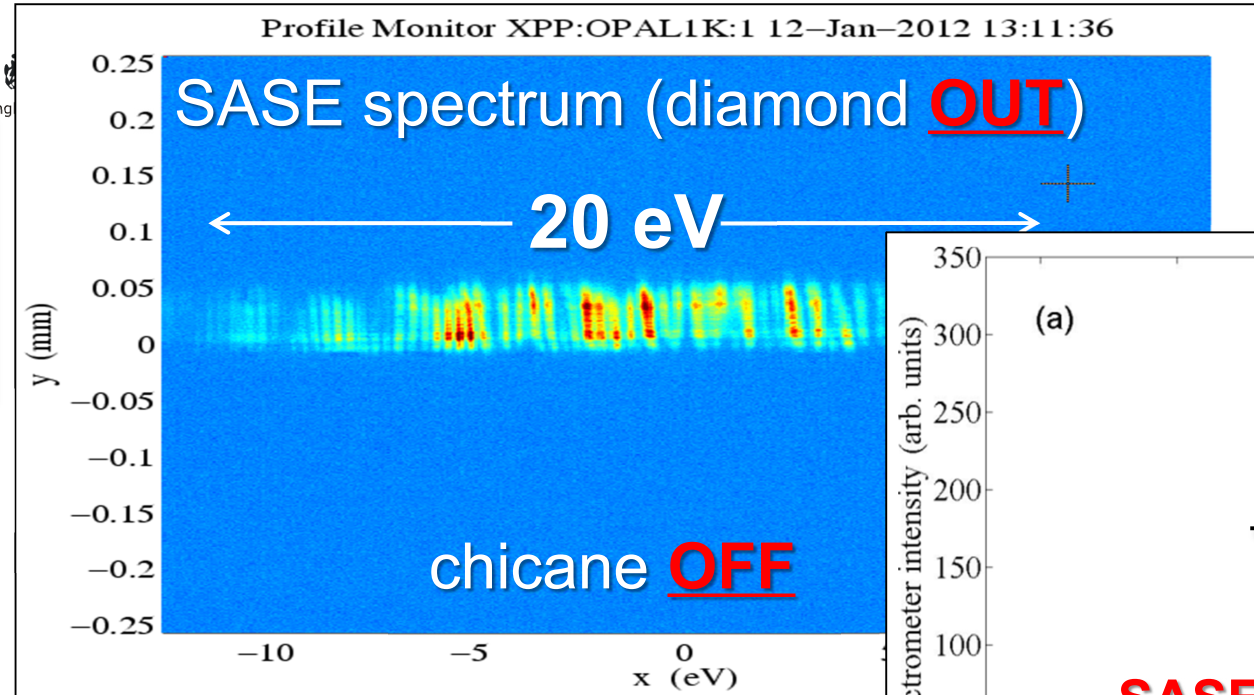


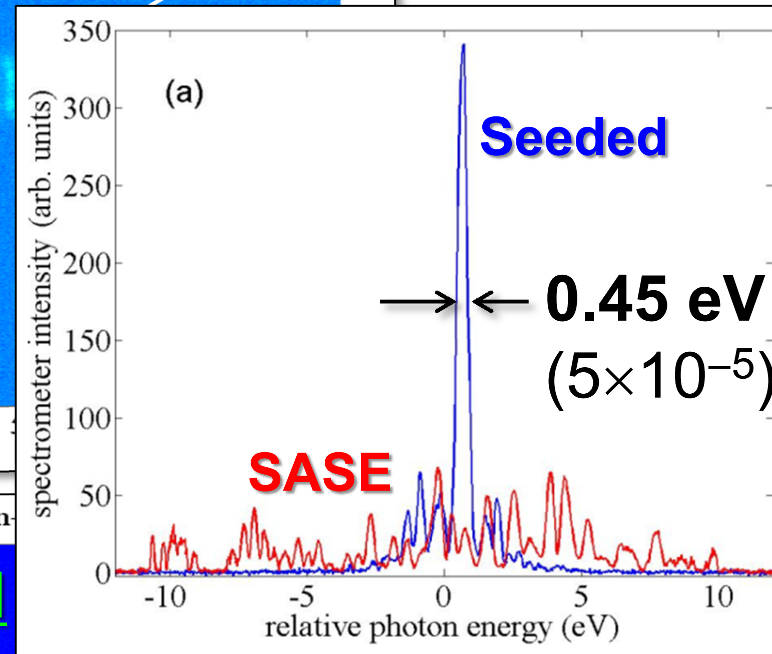
SASE

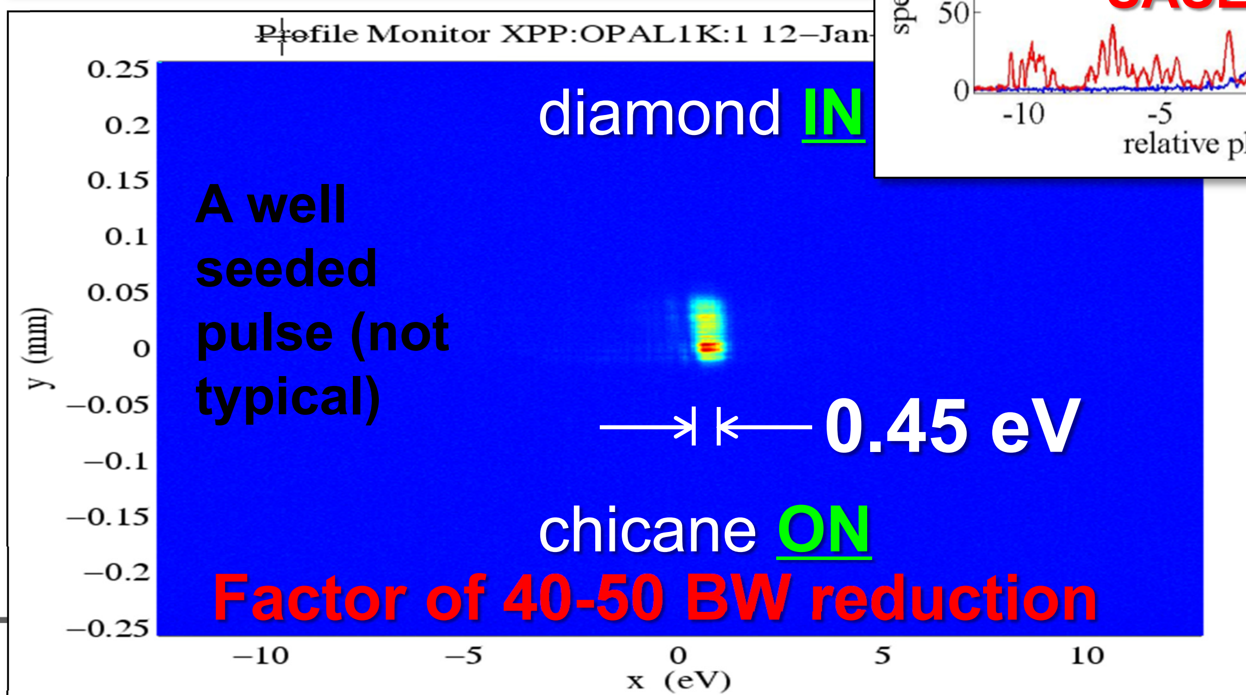
insert diamond & turn on chicane



seeded



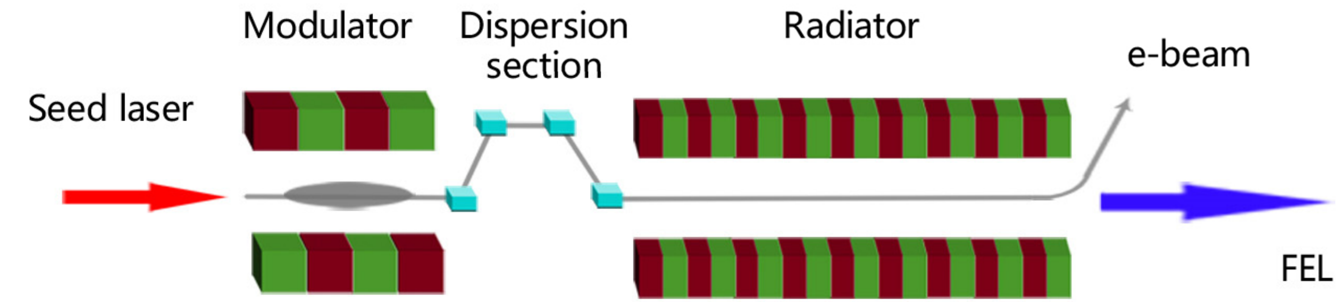


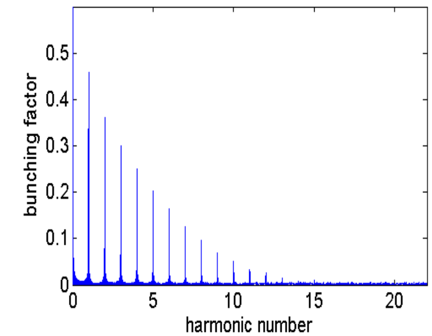


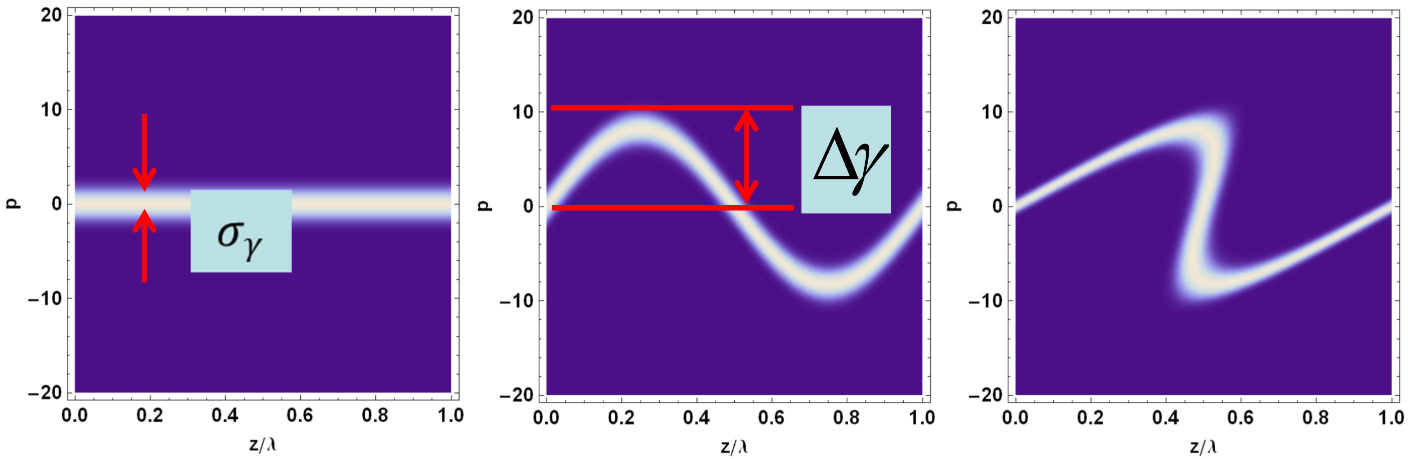
Relatively large shot-to-shot pulse energy fluctuations due to the energy jitter

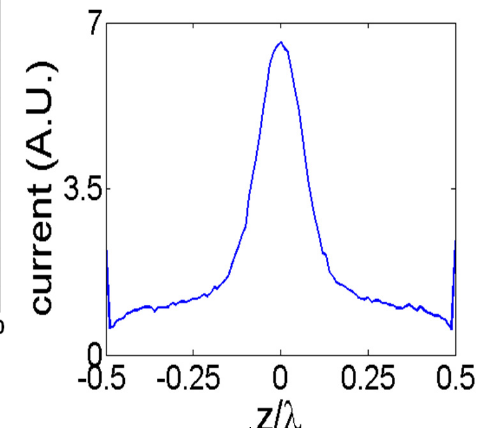
J. Amann et al., Nature Photon., 2012

HGHG and CHG









Energy modulation $A = \Delta\gamma / \sigma_\gamma$

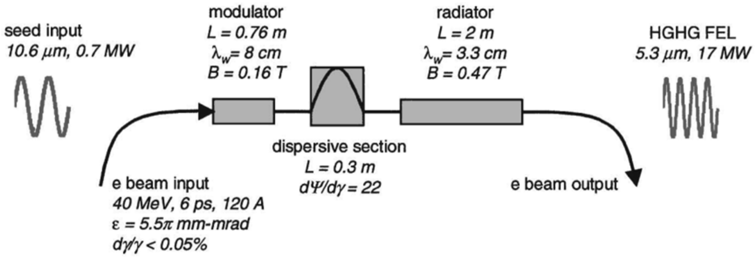
Dispersion strength $B = R_{56} k_1 \sigma_\gamma / \gamma$ ⇒ ***Bunching factor*** $b_k = J_k(kAB)\exp(-\frac{1}{2}k^2 B^2)$

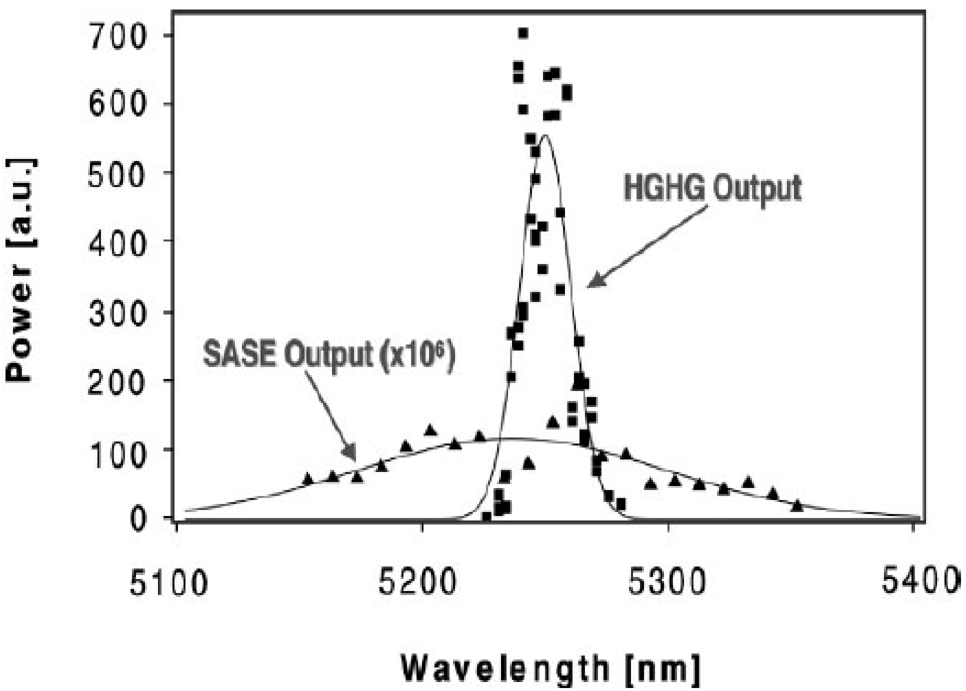
- In order to reach nth harmonic, the energy modulation amplitude should be n times larger than the initial energy spread, which prevents the possibility of reaching short wavelength in a single stage.

HGHG experiments @ BNL

Proof-of Principle Experiment (SDL)

L. H. Yu, et al., Science 289, 932 (2000).





First UV HGHG (DUV-FEL)

L.H. Yu, et al., Phys. Rev. Lett. 91, 074801 (2003).

X.J. Wang, et al., Proc. of FEL 2006.

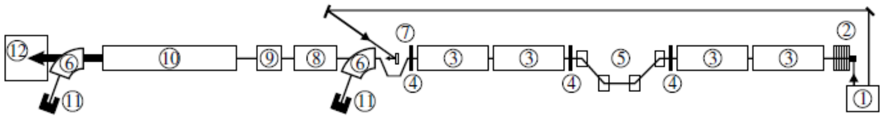
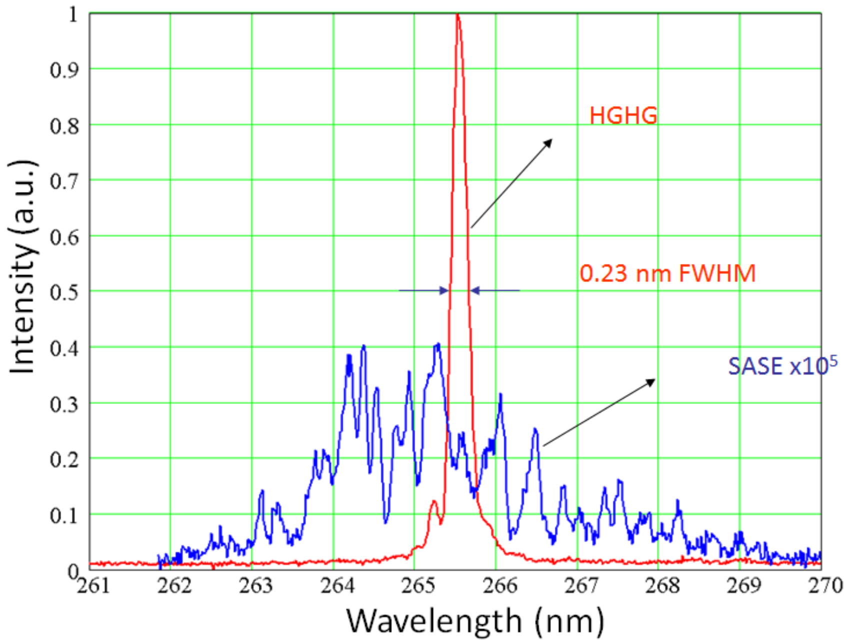
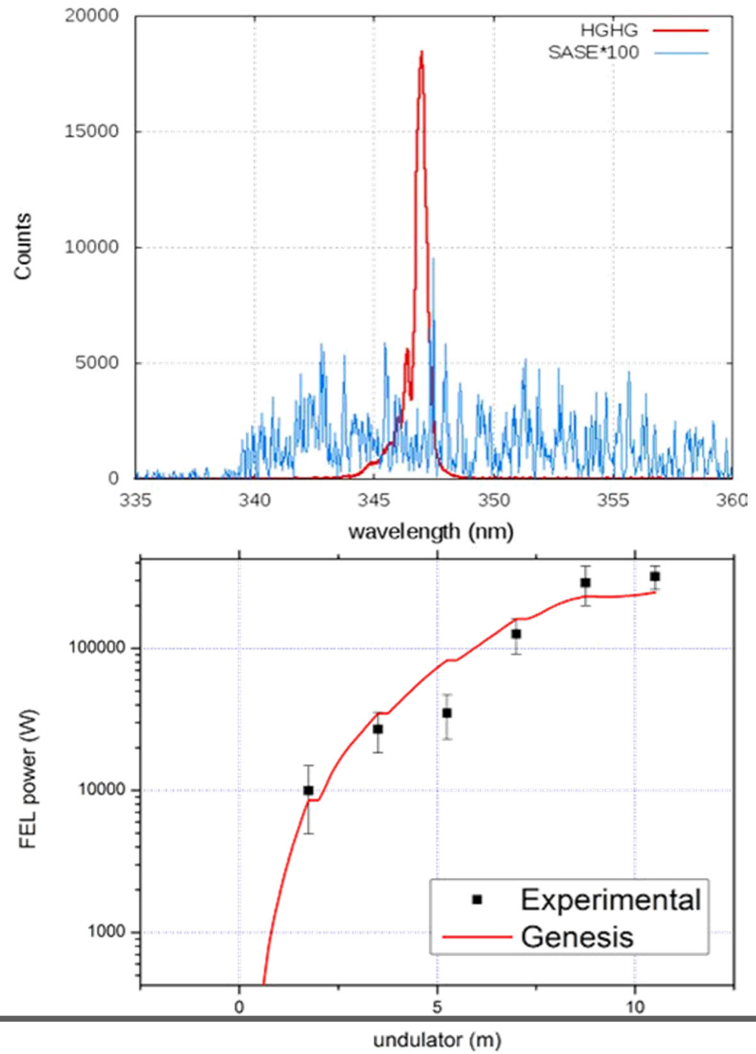


FIG. 1. The NSLS DUV FEL layout. 1: gun and seed laser system; 2: rf gun; 3: linac tanks; 4: focusing triplets; 5: magnetic chicane; 6: spectrometer dipoles; 7: seed laser mirror; 8: modulator; 9: dispersive section; 10: radiator (NISUS); 11: beam dumps; 12: FEL radiation measurements area.

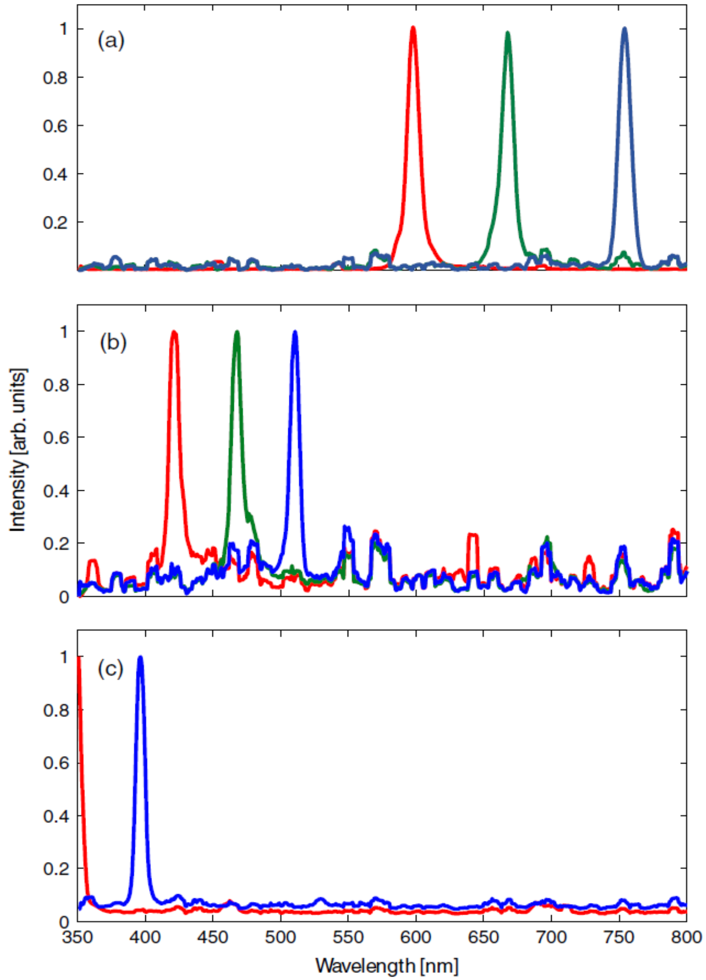


HGHG experiments @ SINAP

HGHG saturation at 3rd harmonic

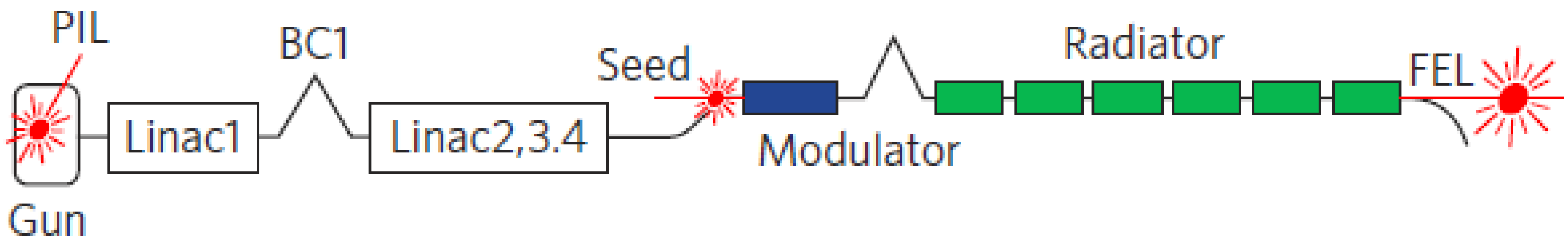


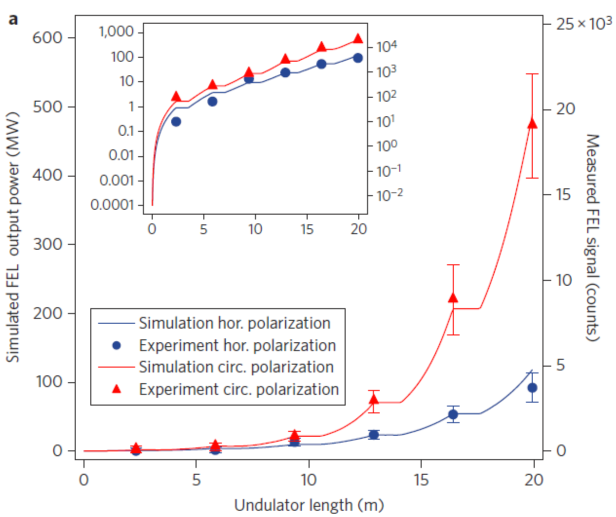
Wide tunable HGHG

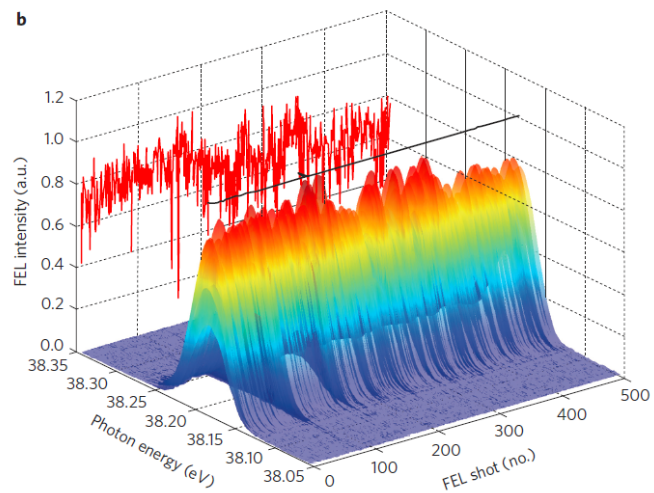


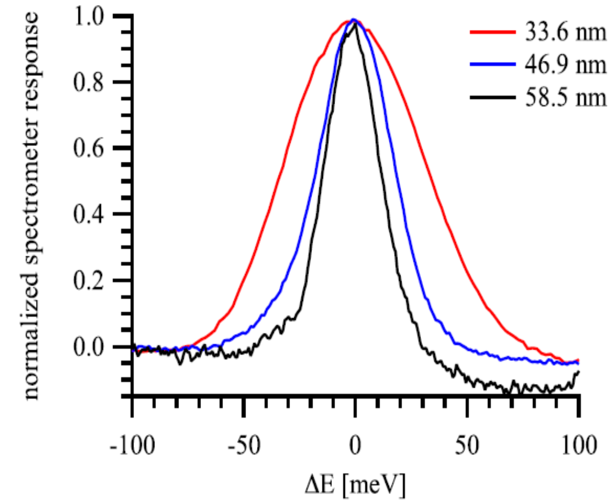
B. Liu, et al. Phys. Rev. ST Accel. Beams 16, 020704 (2013).

HGHG experiments @ FERMI







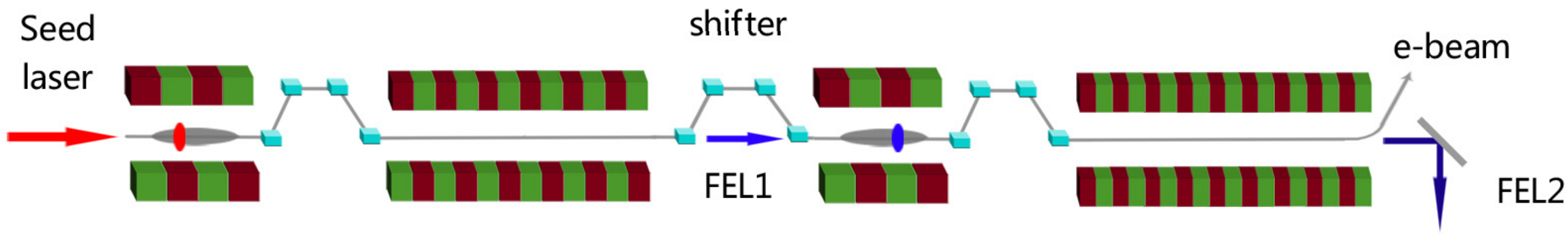


- Radiation at 13th harmonic of the seed (20 nm). 15th harmonic radiation signal was also clearly observed
- Nearly transform-limit bandwidth, normalized poton-energy stability is of the order of 7e-5(rms)

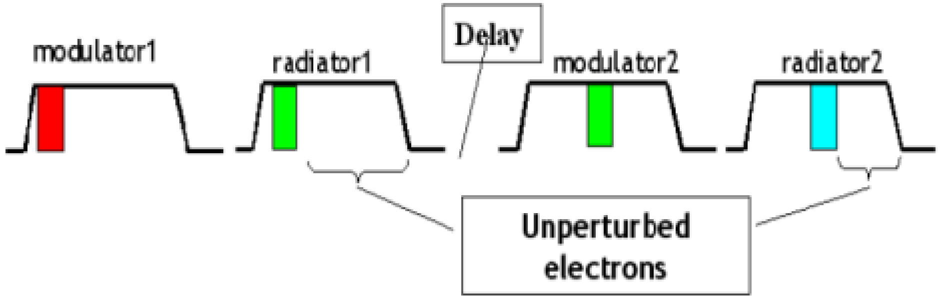
E. Allaria et al, Nature Photonics. 6 (2012) 699

E. Allaria et al, New. J Physics. 14 (2012)

Cascaded HGHG

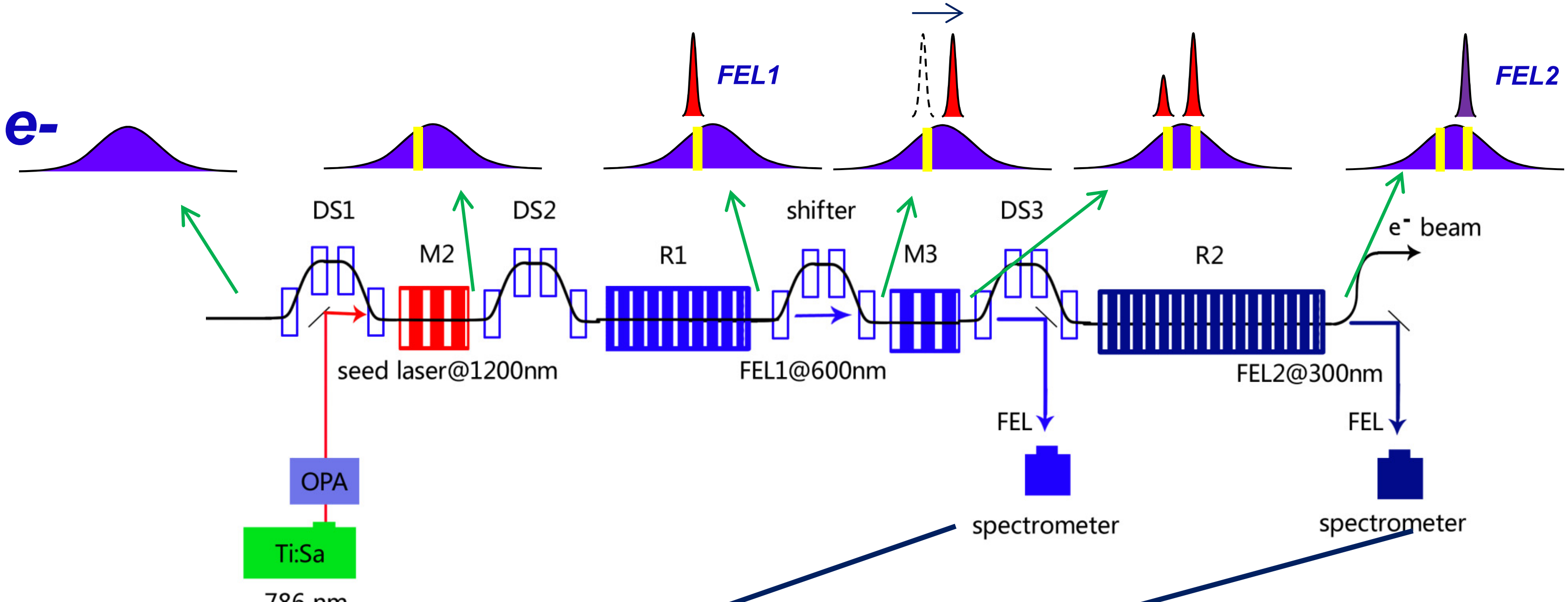


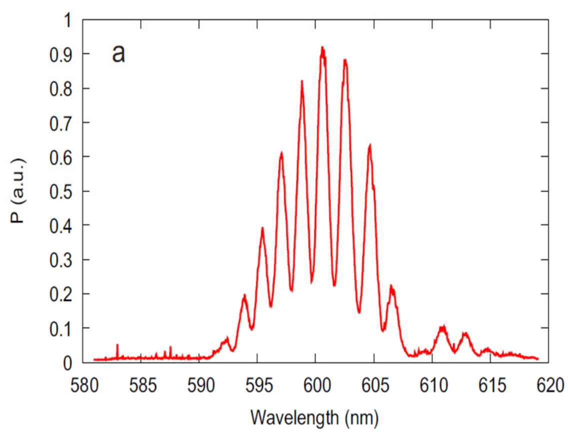
Fresh bunch technique

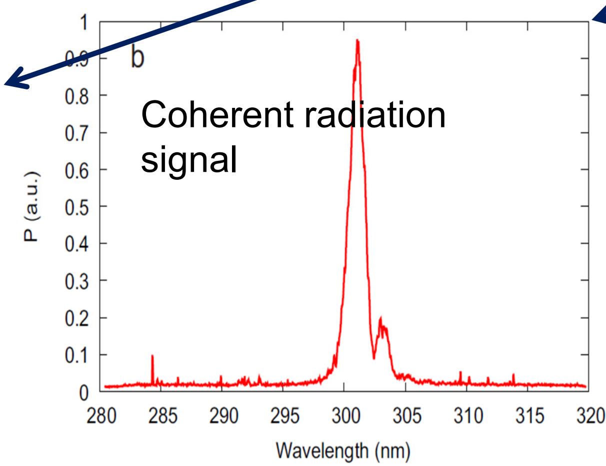


- Extend the HGHG to x-ray region.
- The coherent radiation from the previous stage works as the seed laser of the following stage.
- The electron bunch is divided into several parts for different stages with the "fresh bunch" technique.

cascaded HGHG experiment @ SINAP



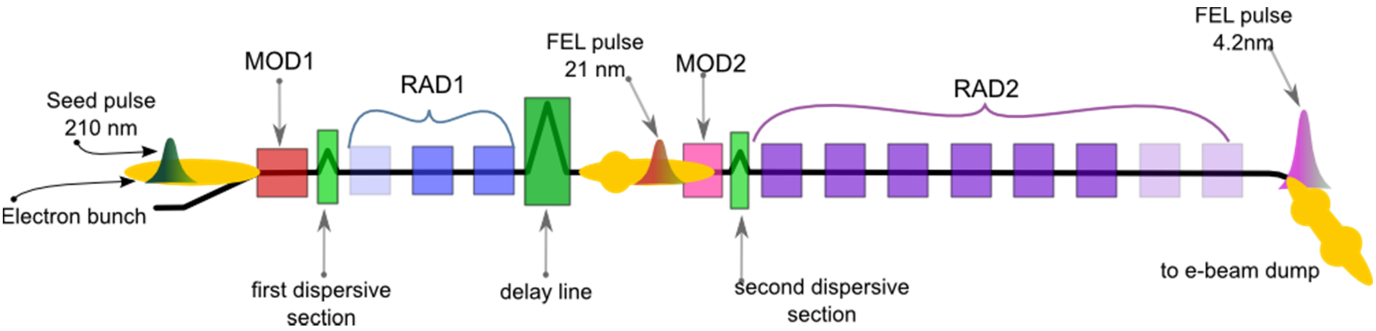


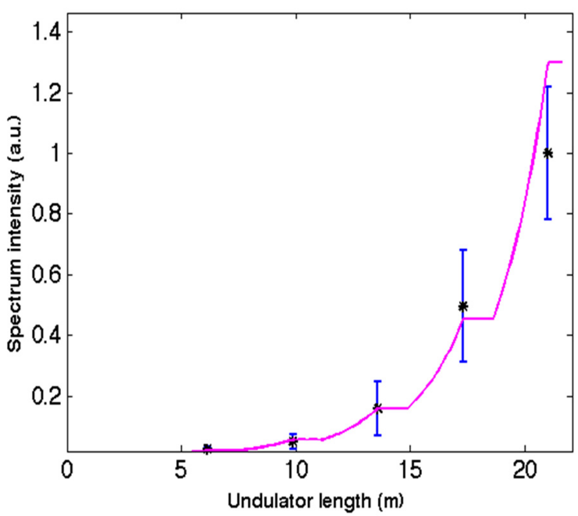


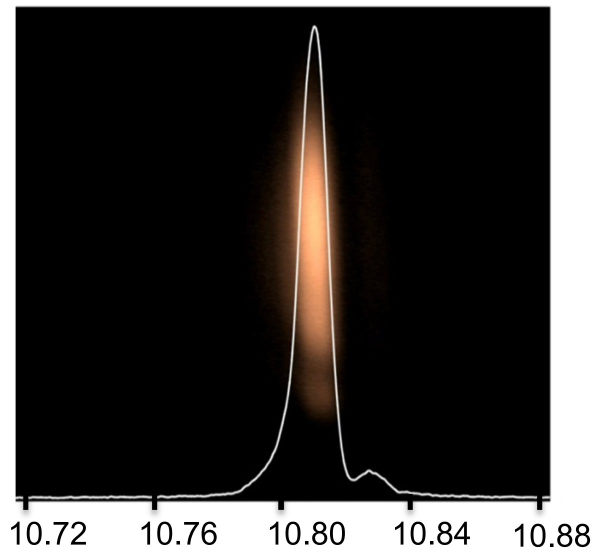
- The harmonic up-conversion number is 2*2.
- The interference pattern of the spectrum has been clearly seen.

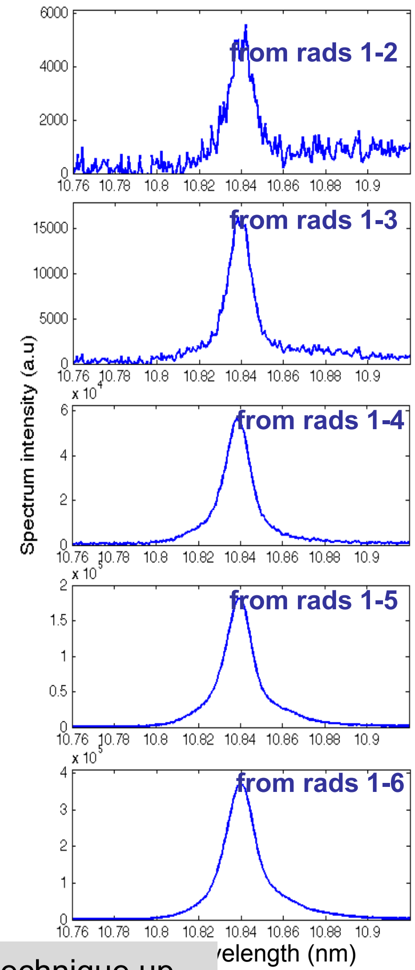
B. Liu, et al. Phys. Rev. ST Accel. Beams 16, 020704 (2013).

cascaded HGHG experiment @ FERMI



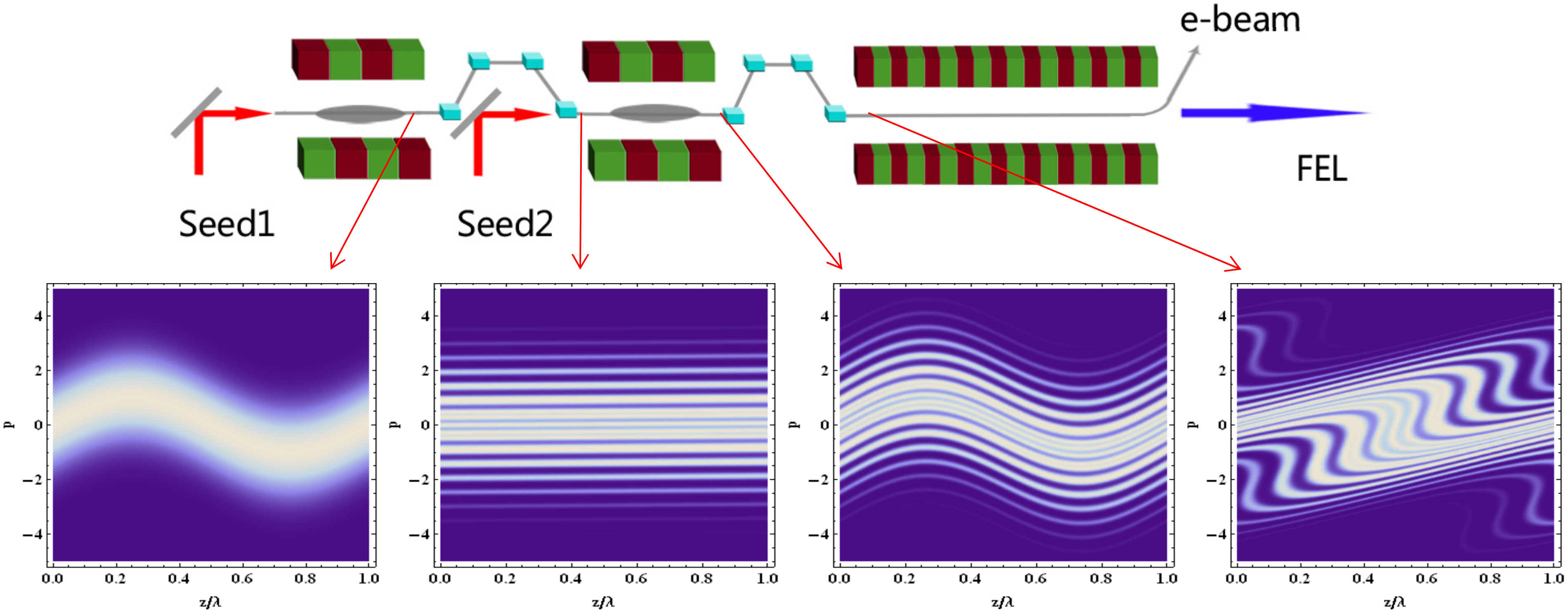






- A two stage harmonic generation FEL has been successfully operated with the fresh bunch technique up to a final harmonic upshift ratio exceeding 50.
- FEL output pulse energies of ~10 μJ or greater has been achieved down to 5.2 nm.
- Coherent emission levels of 1 μJ down to 4.0 nm has been generated in the cascade configuration.

Echo enabled harmonic generation



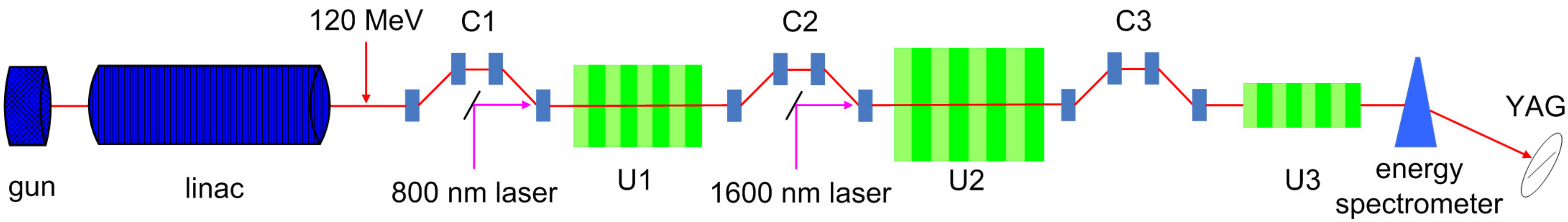
High efficiency for bunching

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

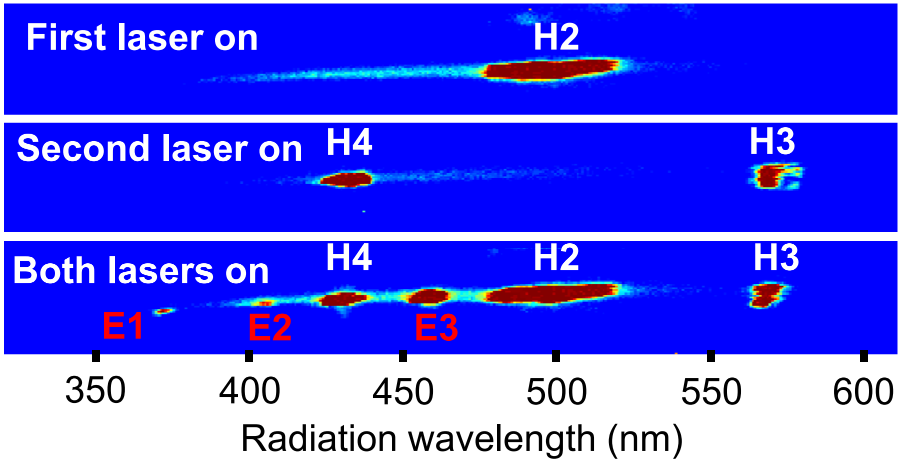
Basic Idea:

- 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

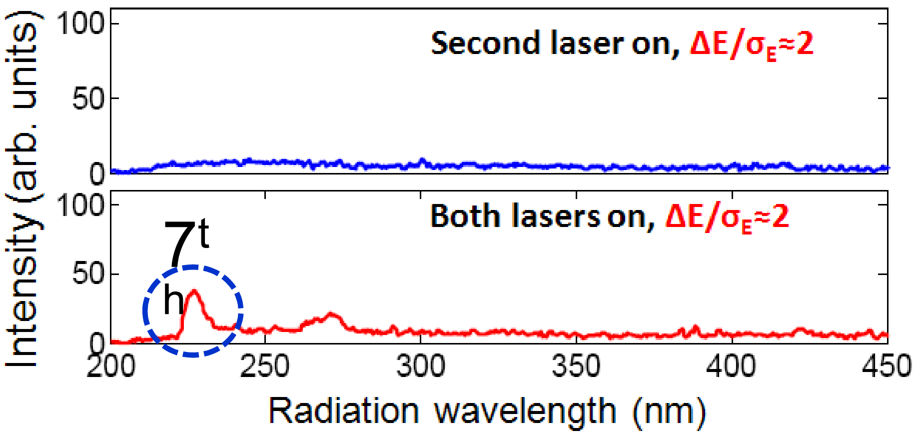
EEHG experiments @ SLAC NLTCA



☞ 2010



☞ 2011



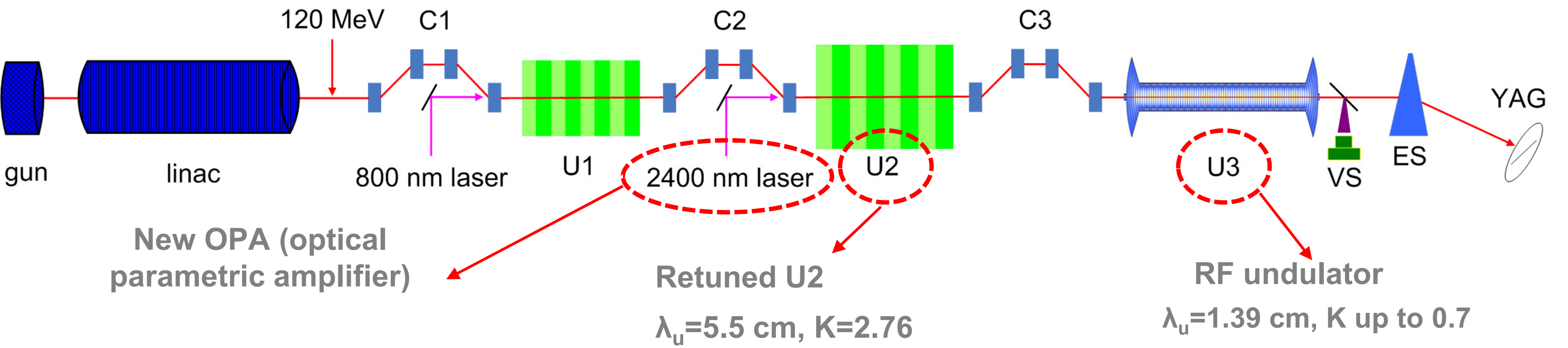
- EEHG at the 4th harmonic: $\Delta E/\sigma_E \approx 80$
- Phase space correlation can be preserved

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

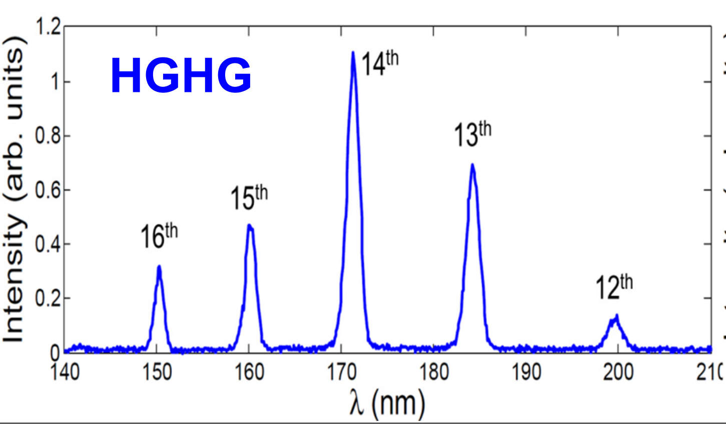
- EEHG at the 7th harmonic: $\Delta E/\sigma_E \approx 2$
- n >> $\Delta E/\sigma_E$

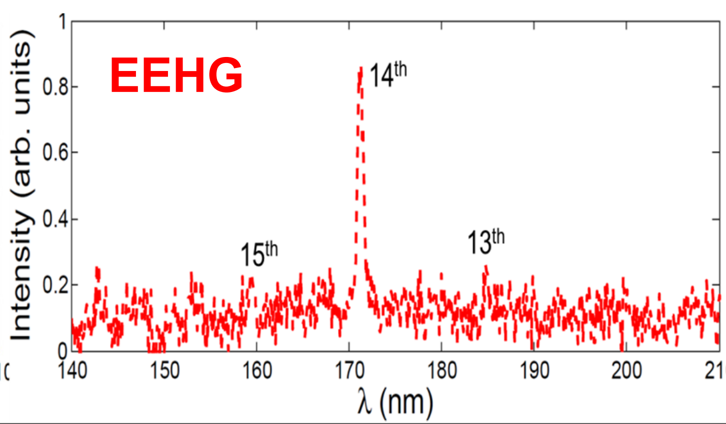
Xiang *et al., PRL 108, 024802* (2012)

Upgraded EEHG beam line at SLAC's NLCTA for higher harmonic generation



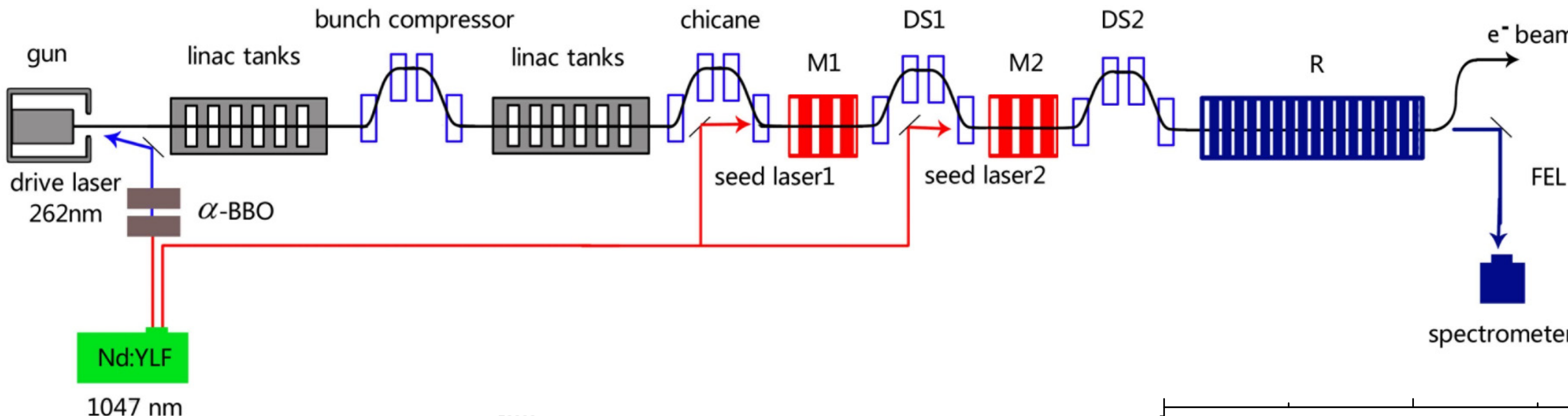
- $R_{56}^{(1)}$=5.91 mm, $R_{56}^{(2)}$=1.37 mm

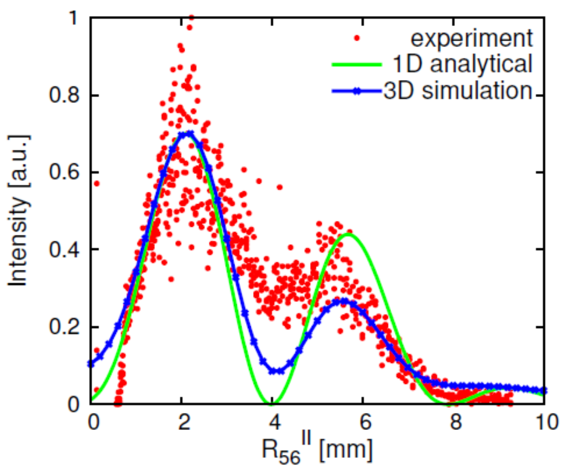




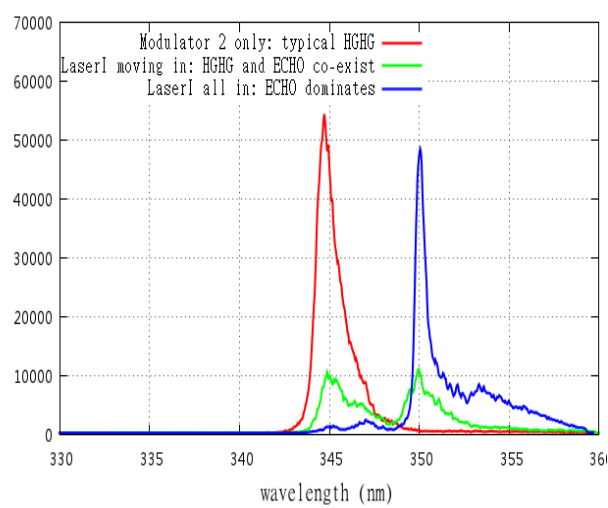
- HGHG signal is 10 times larger than EEHG
- EEHG has smaller bandwidth

EEHG experiments @ SINAP

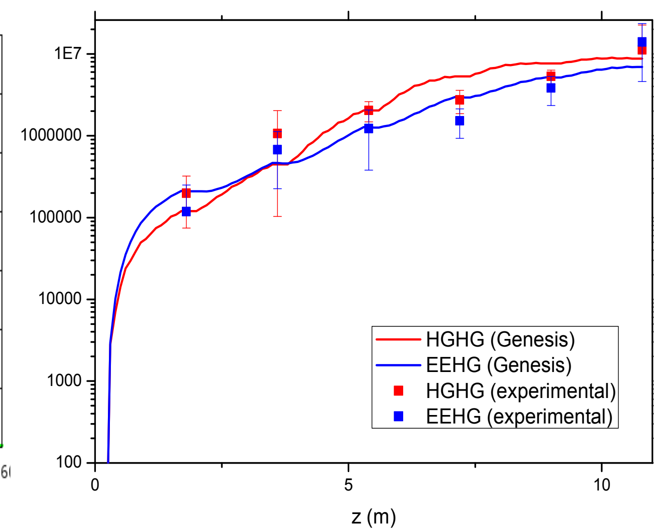




"Double-peak" structure when scanning R56



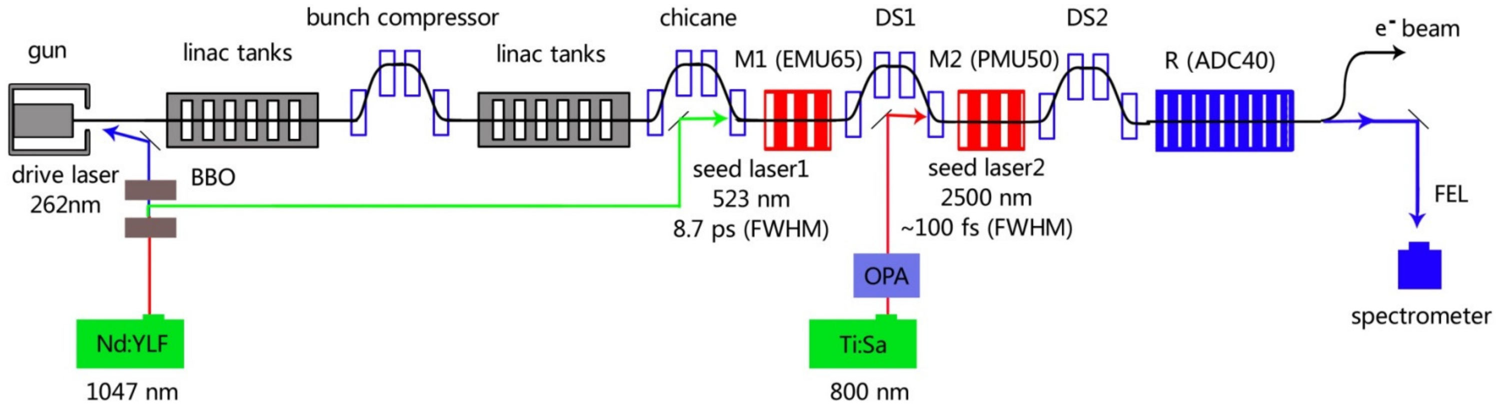
Distinguish of EEHG from HGHG by using the energy chirp

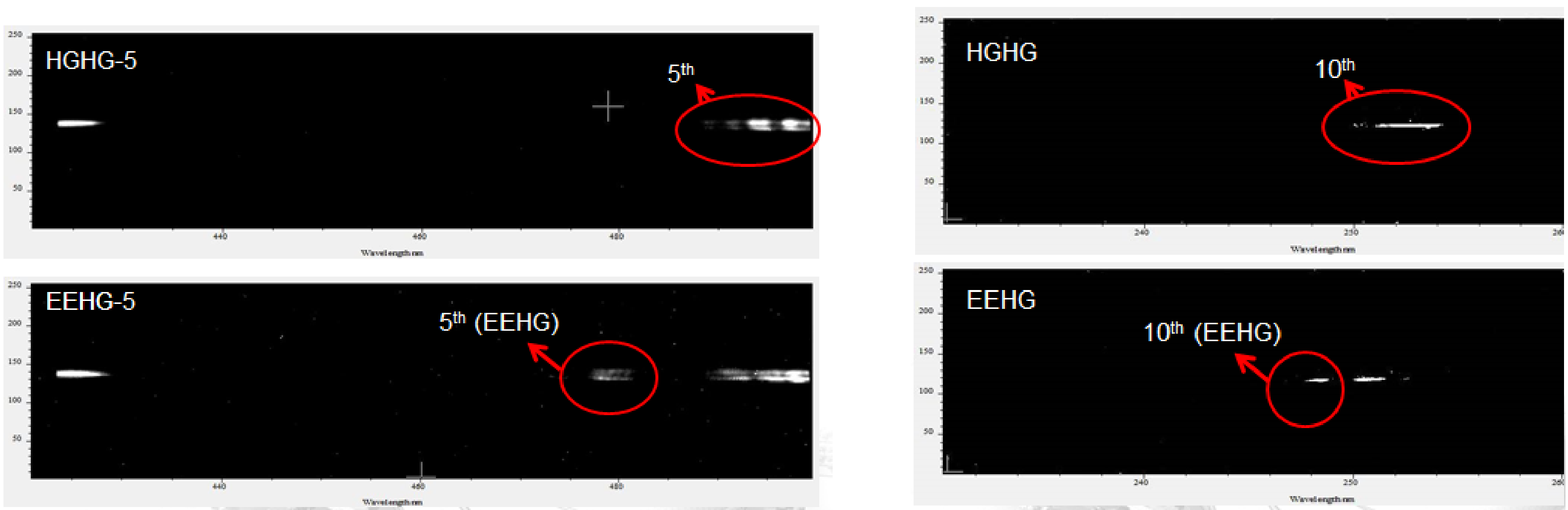


First lasing of EEHG at 3rd harmonic

Z. T. Zhao et al., Nat. Photonics 6, 360 (2012).

EEHG experiments @ SINAP

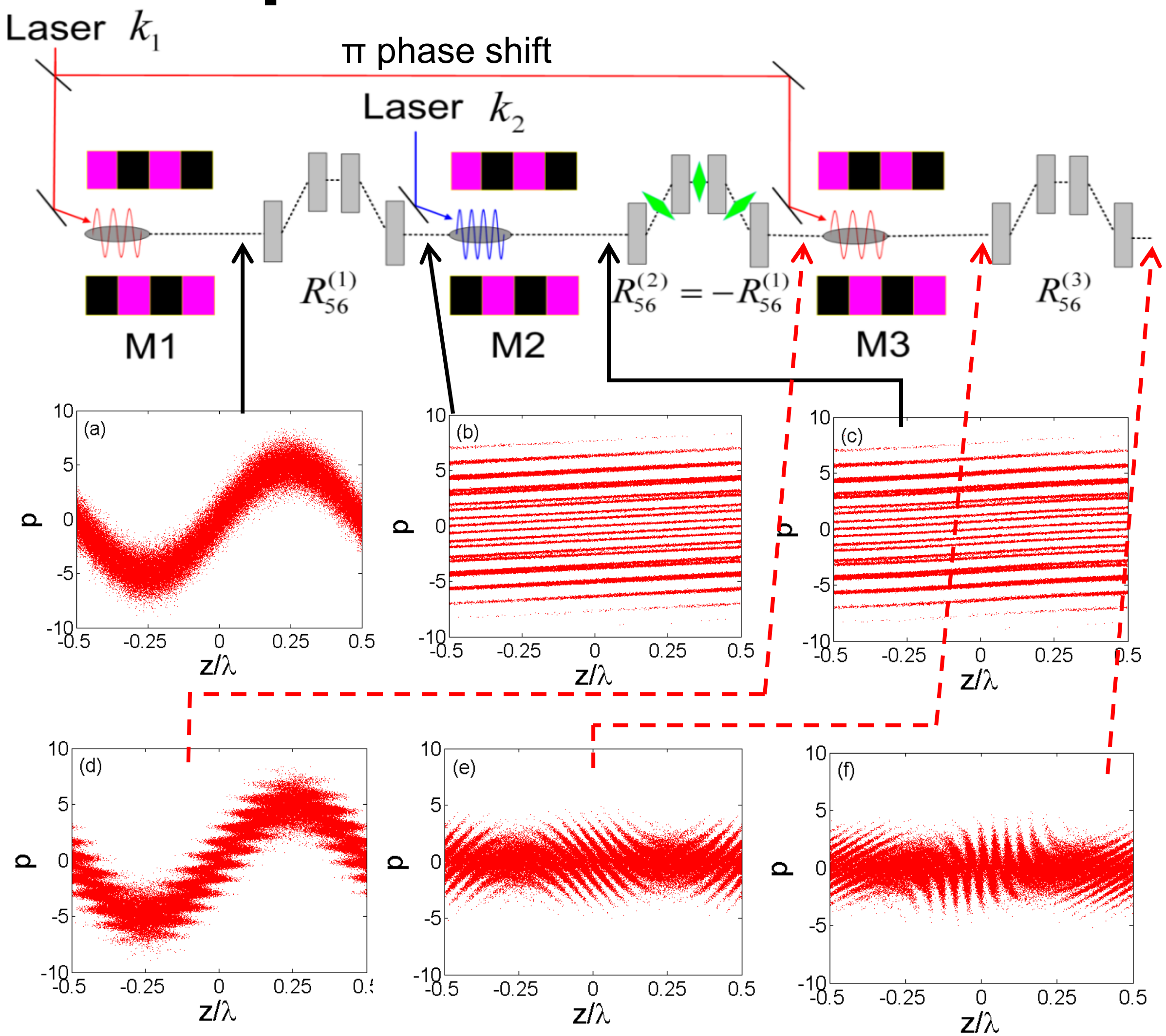




- The two seed wavelengths are different, which results in the different output wavelength of HGHG and EEHG.
- 4-10th harmonic signal of HGHG and EEHG have been observed at SDUV-FEL.

Z.T. Zhao, FEL13, THOANO04

A Triple Modulator-Chicane (TMC) scheme



- Bunch decompression in chicane 1 to split phase space (EEHG)
- Small modulation in M2 (HHG)
- Bunch compression in chicane 2 (CHG)
- Modulation in M2 compressed and superimposed on modulation from M1 (CHG)
- Modulation in M3 to cancel modulation in M1 (HGHG silencer)

- ❑ Ultrahigh harmonics can be generated while keeping energy spread growth negligible
- ❑ Suited for seeding with HHG source because only small energy modulation is needed in M2

D. Xiang and G. Stupakov, New Journal of Physics, 2011

A TMC-seeded FEL at 1 nm

Main parameters

$$A_1 = \Delta E_1/\sigma_E \qquad B_1 = R_{56}^{(1)} k\sigma_E/E \qquad A_2 = \Delta E_2/\sigma_E \qquad B_2 = R_{56}^{(2)} k\sigma_E/E$$

E=2.4 GeV, σ_E=150 keV

~100 MW UV laser at 200 nm in M1 and M3 to generate 450 keV energy modulation

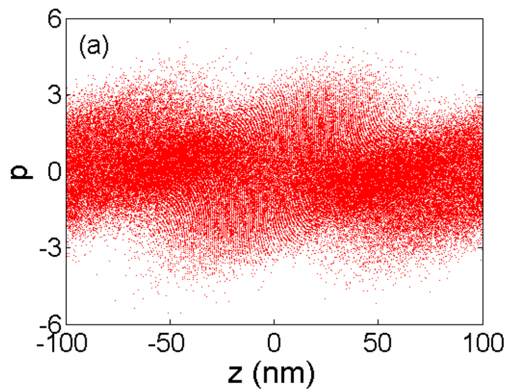
~100 kW HHG seed at 20 nm in M2 to generate 15 keV energy modulation

R_{56} for the 3 chicanes: 3.3 mm, -3.3 mm, 0.16 mm

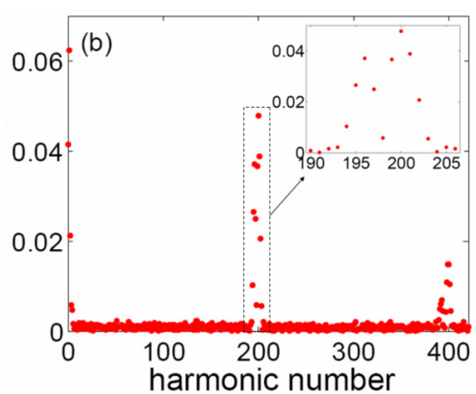
Energy spread growth ~ 40%

Tolerances

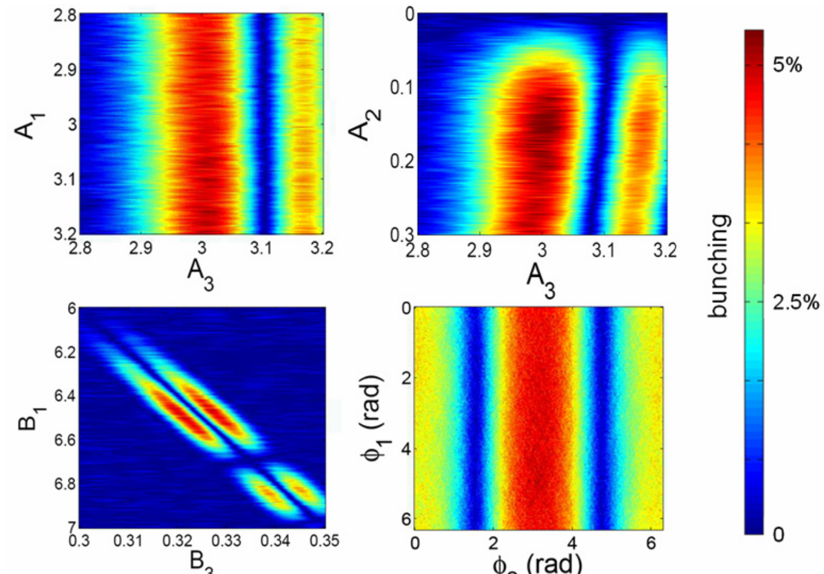
- UV Laser power fluctuation < 4%
- NOT sensitive to HHG power fluctuation
- UV Laser phase jitter < π /4



Phase space



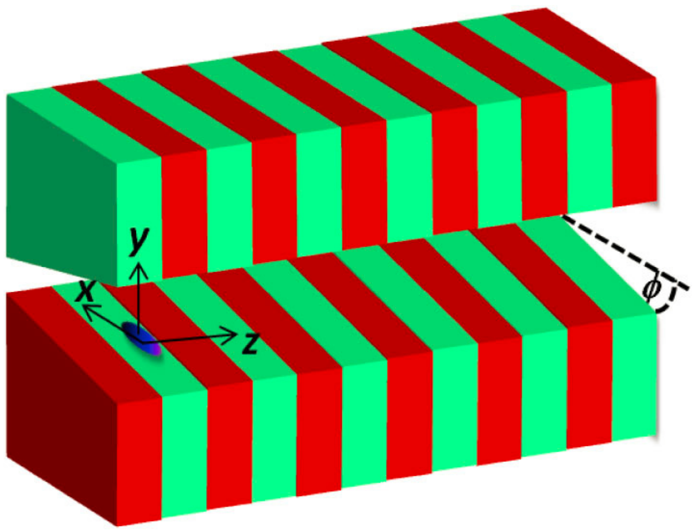
Bunching



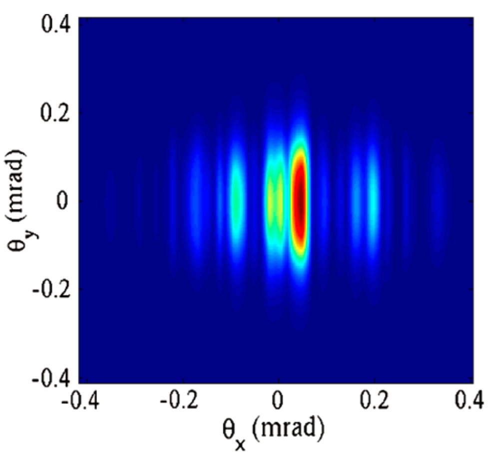
sensitivity

D. Xiang and G. Stupakov, New Journal of Physics, 2011

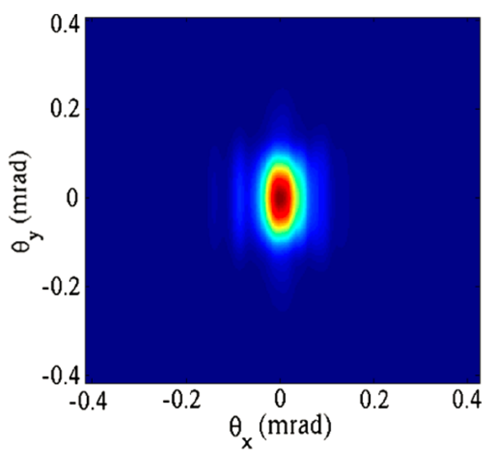
Direct seeding with laser plasma accelerator and TGU



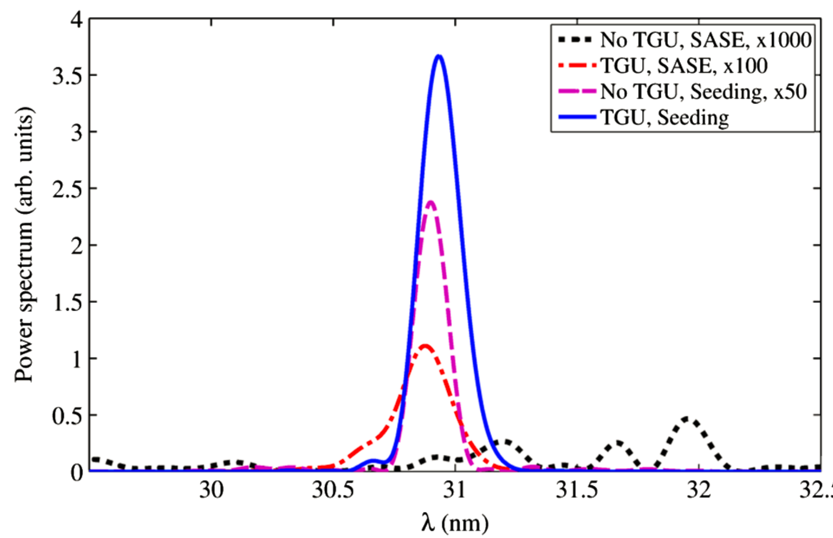
- By canting the undulator poles, generate a linear field gradient $\frac{\Delta K}{K_0} = \alpha x$
- Sort e-beam energy by dispersion η so that $x = \eta \frac{\Delta\gamma}{\gamma_0}$
- Resonance can be satisfied for all energies if $\eta = \frac{2 + K_0^2}{\alpha K_0^2}$



(a)SASE.

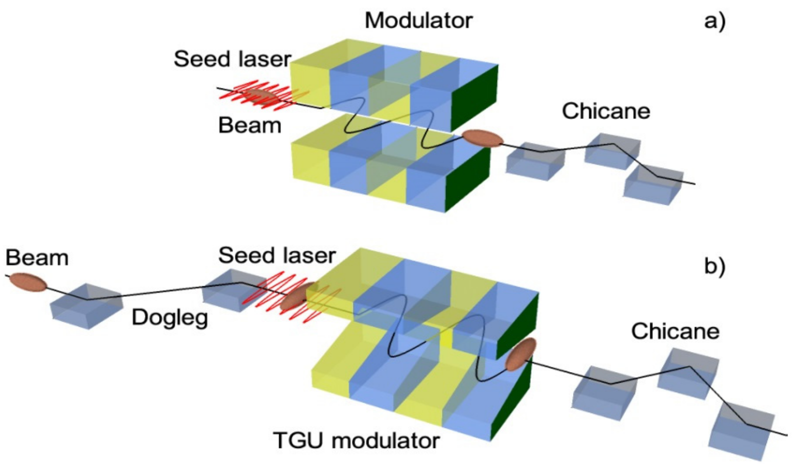


(b)Seeded.



Z. Huang, Y. Ding, C. B. Schroeder. Phys. Rev. Lett, 109 (2012) 204801

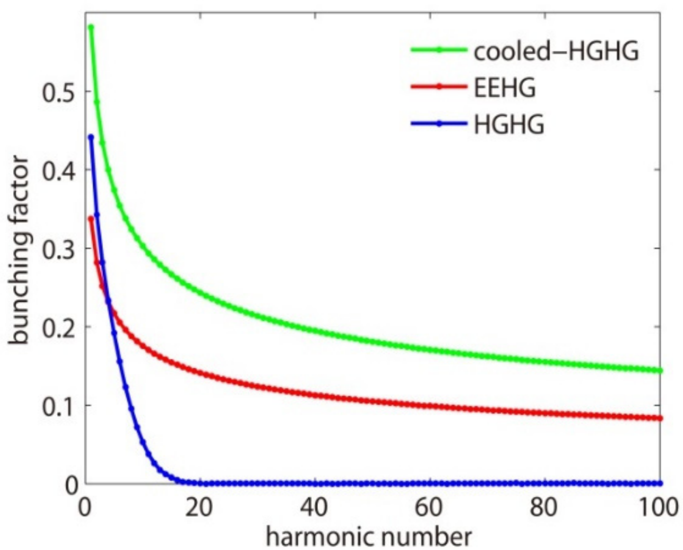
Improved HGHG: iHGHG (Cooled-HGHG)

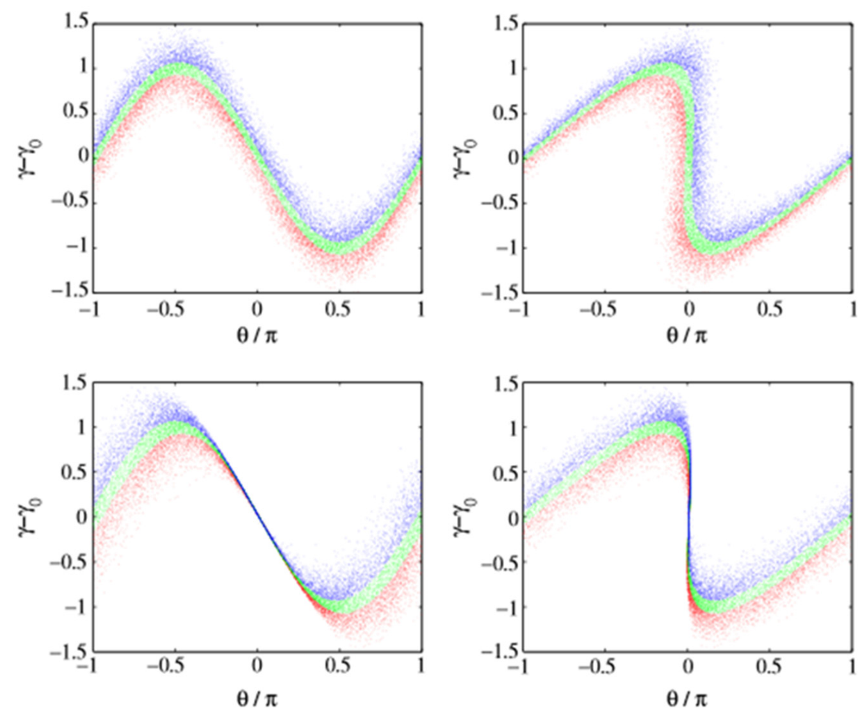


Bunching factor

standard $b_n = e^{-\frac{n^2 D^2 \sigma^2}{2}} J_n(nD\Delta\gamma)$

cooled $b_n = J_n(nD\Delta\gamma)$



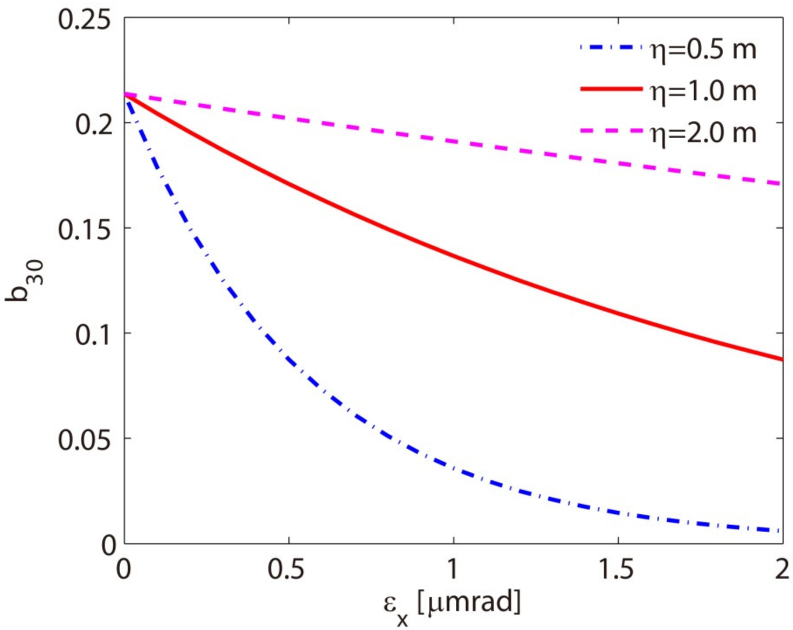


Haixiao Deng*, Chao Feng, Phys. Rev. Lett, 111 (2013) 084801

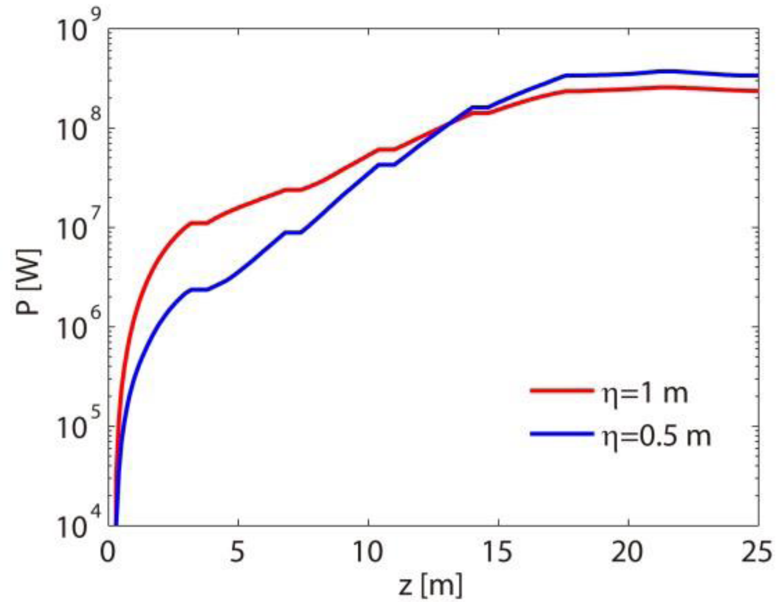
iHGHG (Cooled-HGHG)

$$b_n = e^{-\frac{n^2 D^2}{2}\frac{\gamma^2 \sigma_x^2}{\eta^2}} J_n(nD\Delta\gamma)$$

- The bunching factor of cooled-HGHG has no relation with the initial beam energy spread, but will be significantly degrade for large emittance.
- For the nominal parameters of SXFEL, the bunching factor of cooled-HGHG is close to that of EEHG.
- The configuration of cooled-HGHG is much simpler than EEHG.



Bunching factor .vs. Emittance

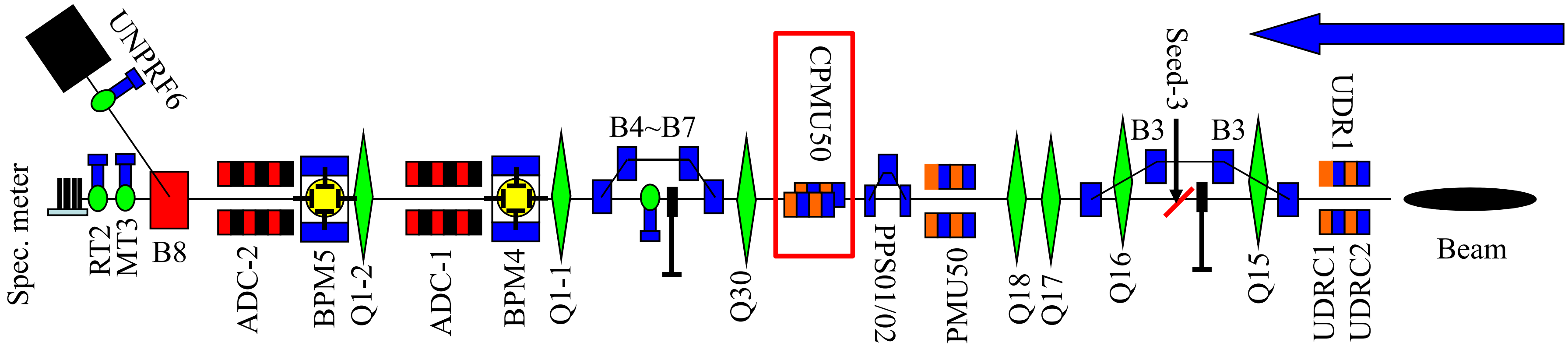


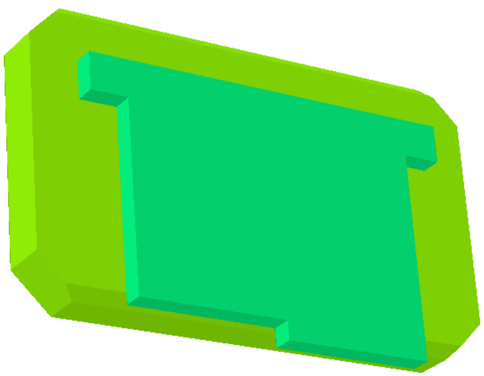
Gain curve for SXFEL

Haixiao Deng, Chao Feng, Phys. Rev. Lett, 111 (2013) 084801*

中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

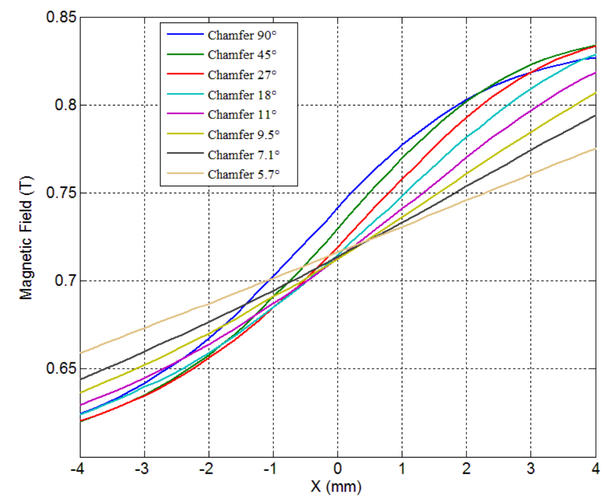
Experiment proposal at SDUV-FEL





Chamfer 90°

Chamfer 45°



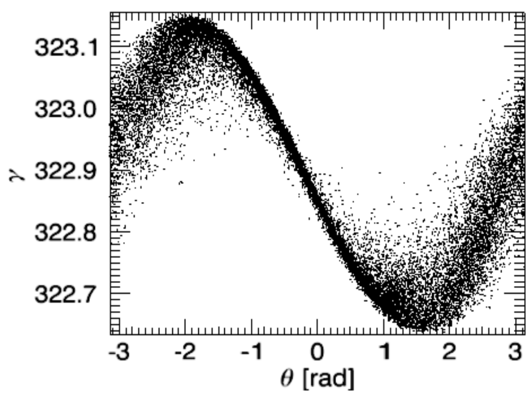
TGU configuration & field dependence

Alternatively, we may break a chicane and transversely shift all the followed elements in the accelerator tunnel, as proposed in the paper.

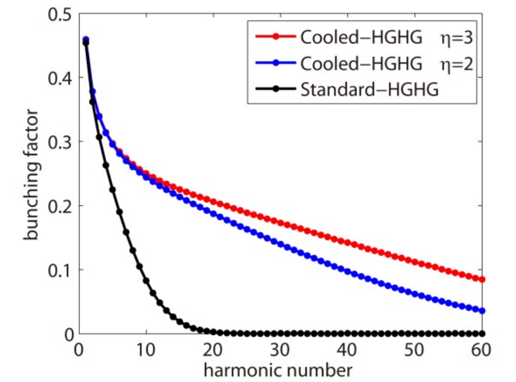
Experiment proposal at SDUV-FEL

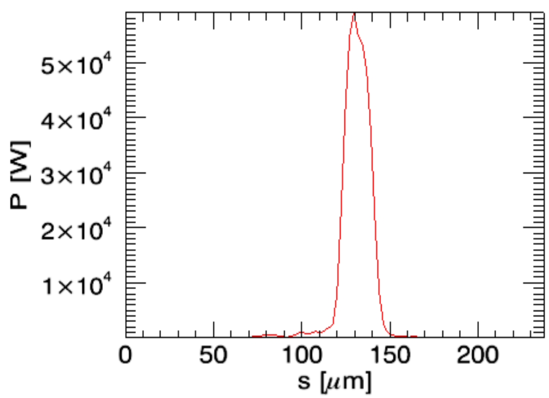
Parameter	Value
beam energy	165MeV
Slice energy spread	16keV
Slice emittance	2 mm-mrad
Peak current	100A
Seed wavelength	2400 nm
Seed pulse length	100 fs (FWHM)
Seed peak power	6 MW
Dispersion	2
Transverse gradient	$14 m^{-1}$
Radiation wavelength	120 nm

Phase space

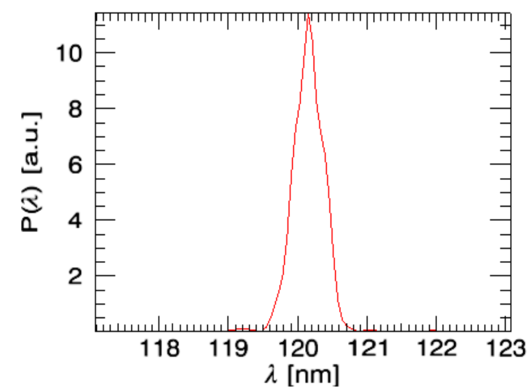


Bunching facor





20^{th} harmonic radiation pulse



spectrum

Future developments

- Self-seeding adopted by all SASE based facilities to improve the performance and temporal coherence.
- Direct-seeding with even shorter wavelength HHG seed.
- Three and even more stages cascaded HGHG or improved HGHG for higher harmonics.
- EEHG operation with higher harmonics up to hundred.

Summary

- Seeding is an indispensable method to significantly improve the performance of FEL facilities.
- Several seeded FEL schemes have been proposed and experimentally demonstrated and operated.
- The initial noise will be amplified during the harmonic up-conversion process. However, it is found that transform-limited radiation pulses can still be generated by properly setting the parameters.
- Seeding methods at very short wavelength are quite limited, novel ideas to improve performance of seeded FELs still need to explore.

ACKNOWLEDGEMENTS

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Shaukat Khan， Hiro Tomizawa, Dao Xiang

Thank you for your attention!