Experimental Studies of Echo-Enabled Harmonic Generation FEL

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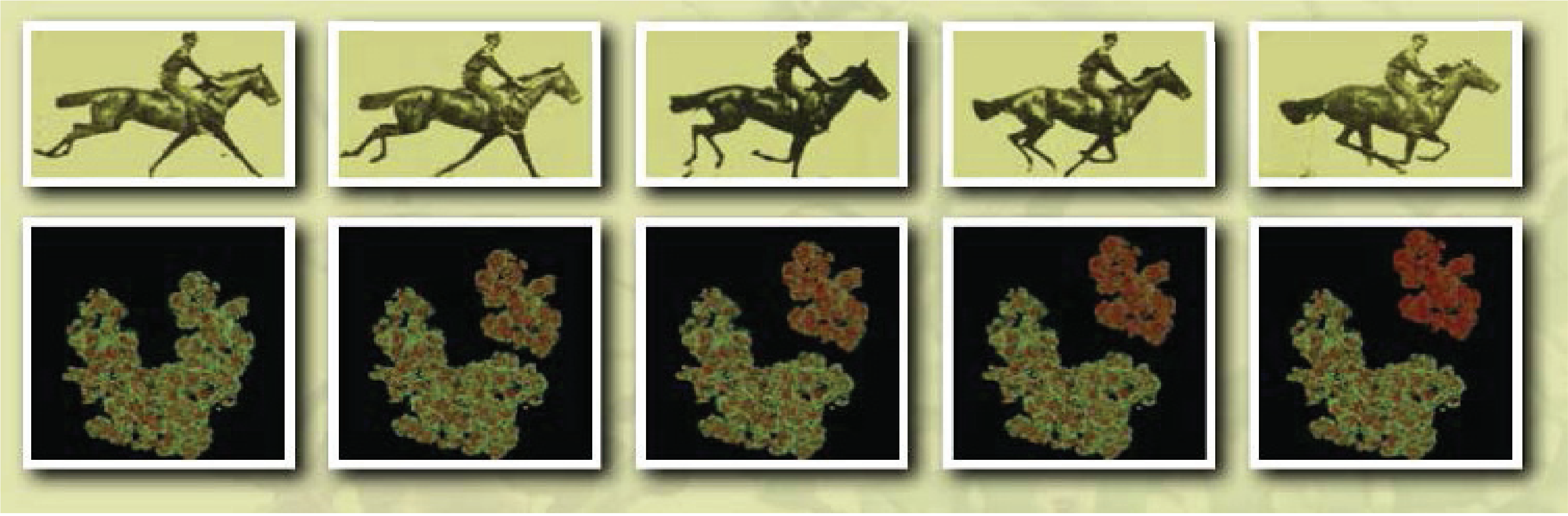
Outline

- Introduction
- Echo experiments at SLAC
- Echo experiments at SINAP
- Cool-HGHG experiment plan
- Summary

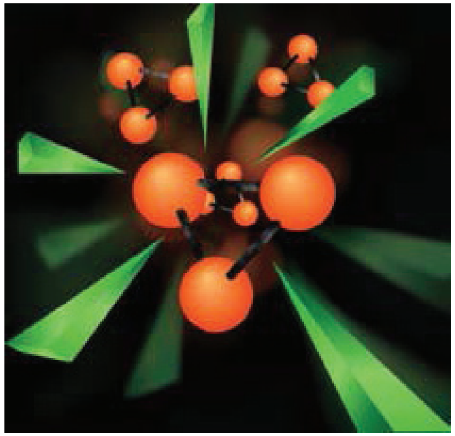
中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

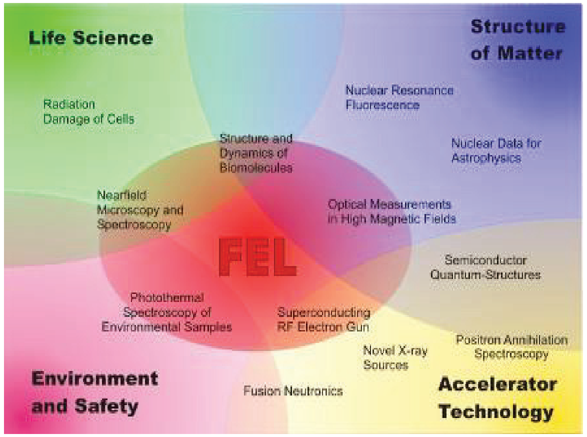
Ultra-small and Ultra-fast

Ultra-Fast



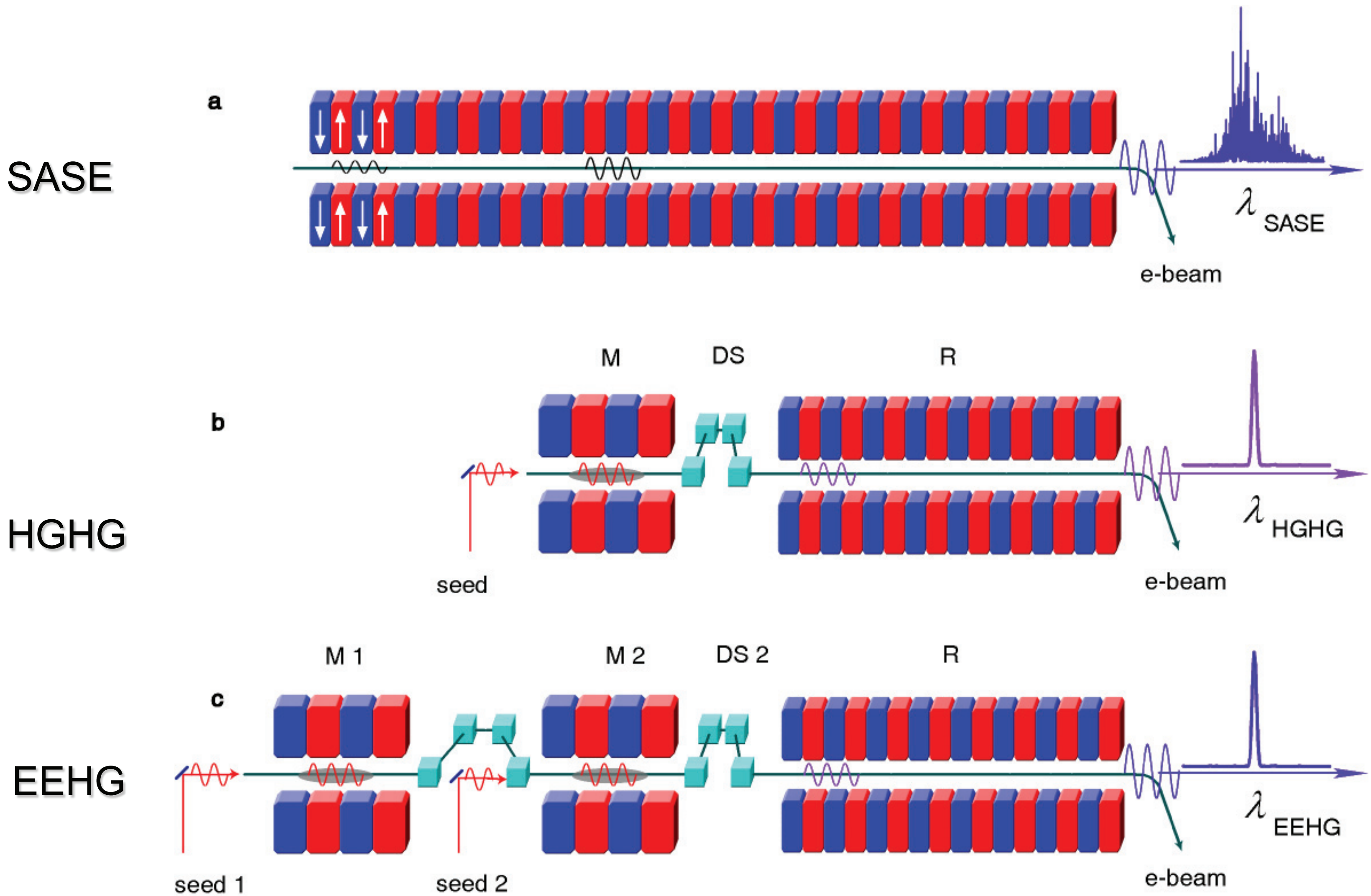
Ultra-Small





- Short wavelength
- Ultra fast
- Fully coherent

High-gain FELs

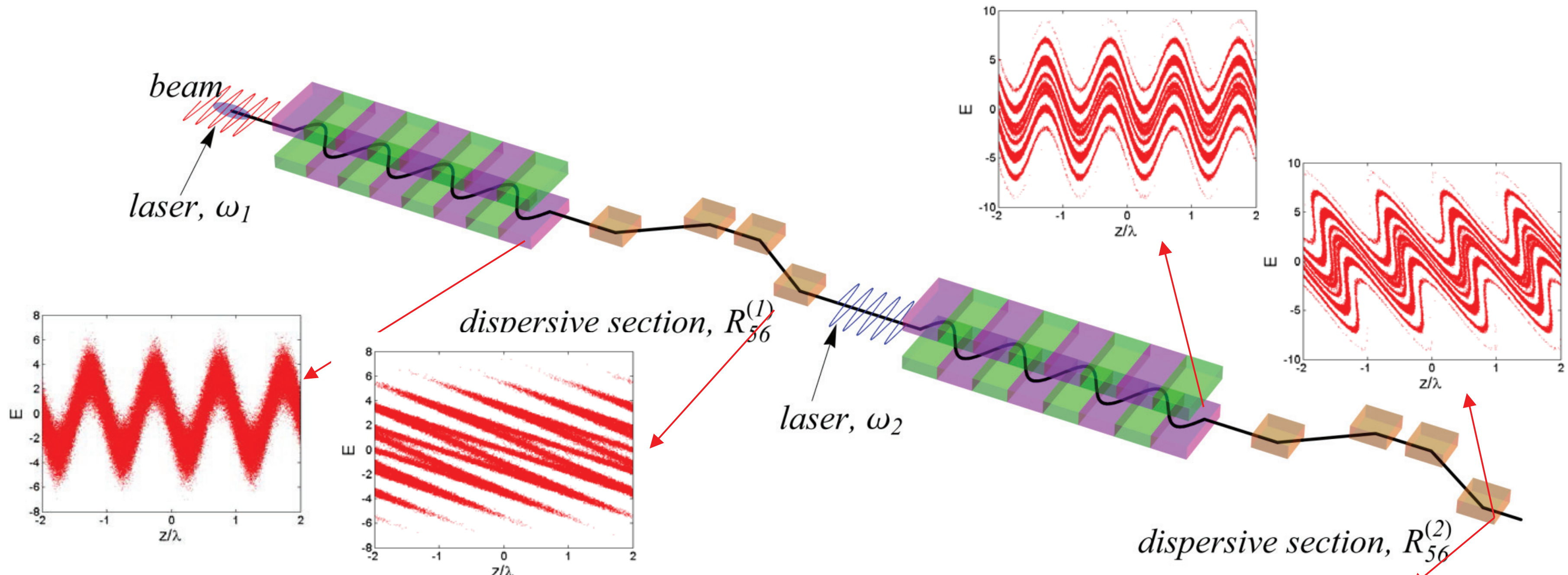


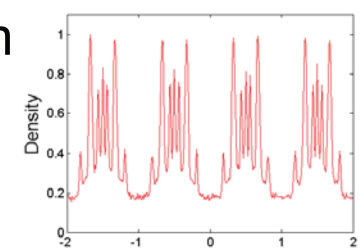
Echo-enabled Harmonic Generation (EEHG)

G. Stupakov, PRL, 2009;

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

Echo-Enabled Harmonic Generation (EEHG)

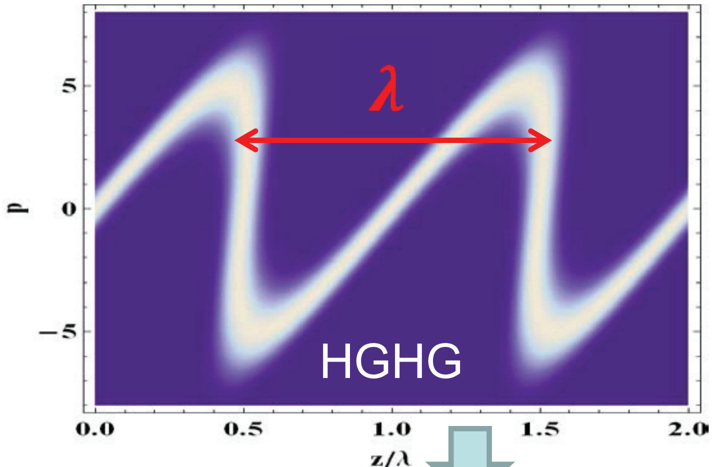


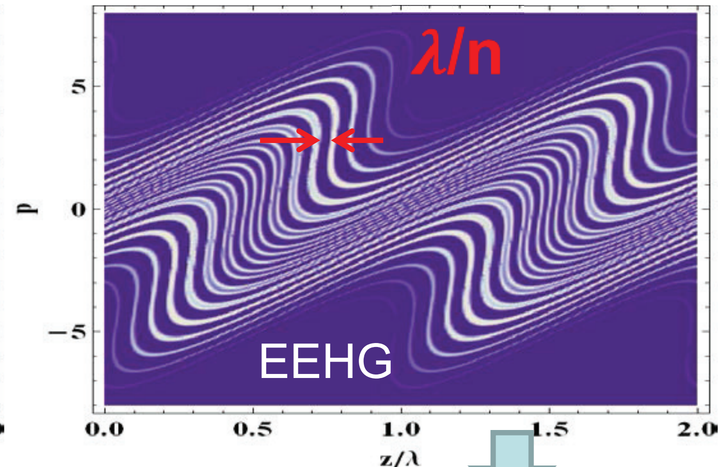


- First laser to generate energy modulation in electron beam
- First strong chicane to split the phase space
- Second laser to imprint energy modulation
- Second chicane to convert energy modulation into density modulation

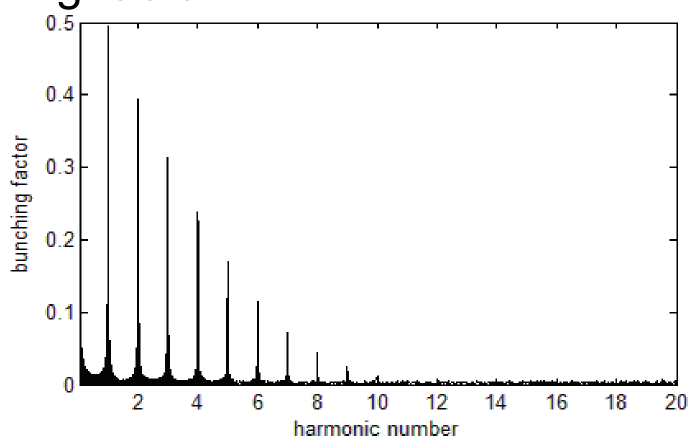
HGHG and EEHG

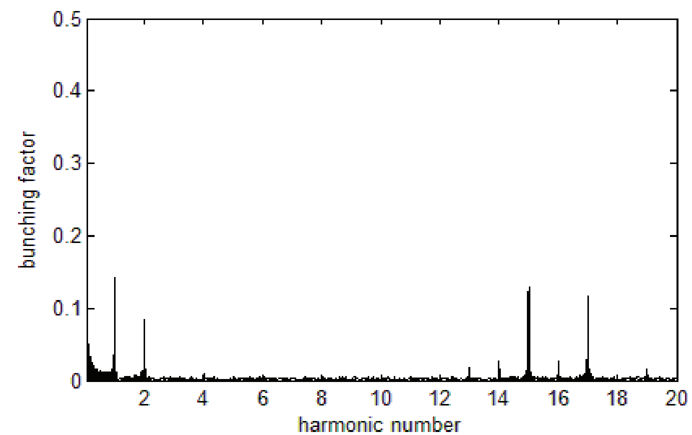
Phase space at the entrance to the radiator





Bunching factor:

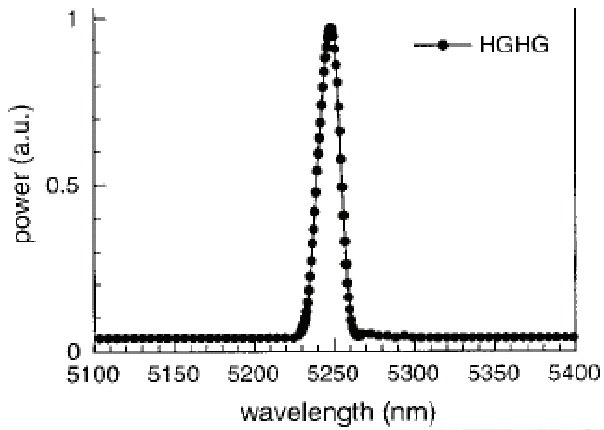




Remarkable up-frequency conversion efficiency: $b_n \sim n^{-1/3}$ ⇒ Fully coherent soft X-ray

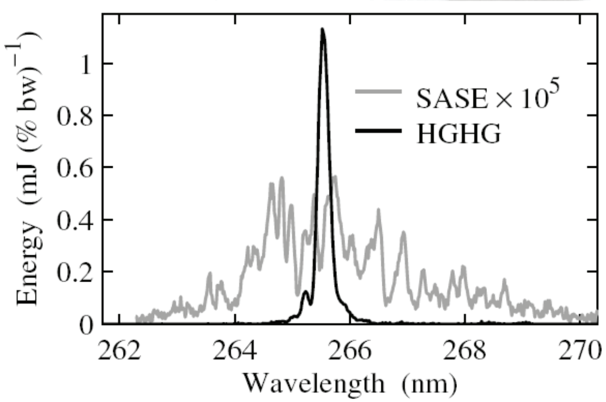
HGHG experiments

- BNL, 2000, 10.6 um -> 5.3 um



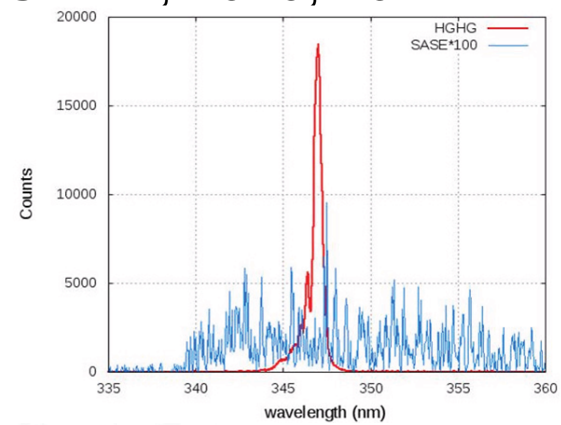
L.-H. Yu *et al.*, Science, 2000

- BNL, 2003, 800 nm -> 266 nm

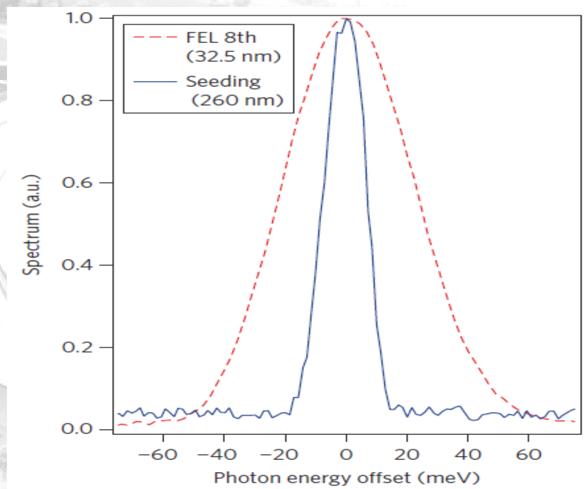


L.-H. Yu *et al.*, PRL, 2003

- SINAP, 2010, 1047 nm -> 347 nm

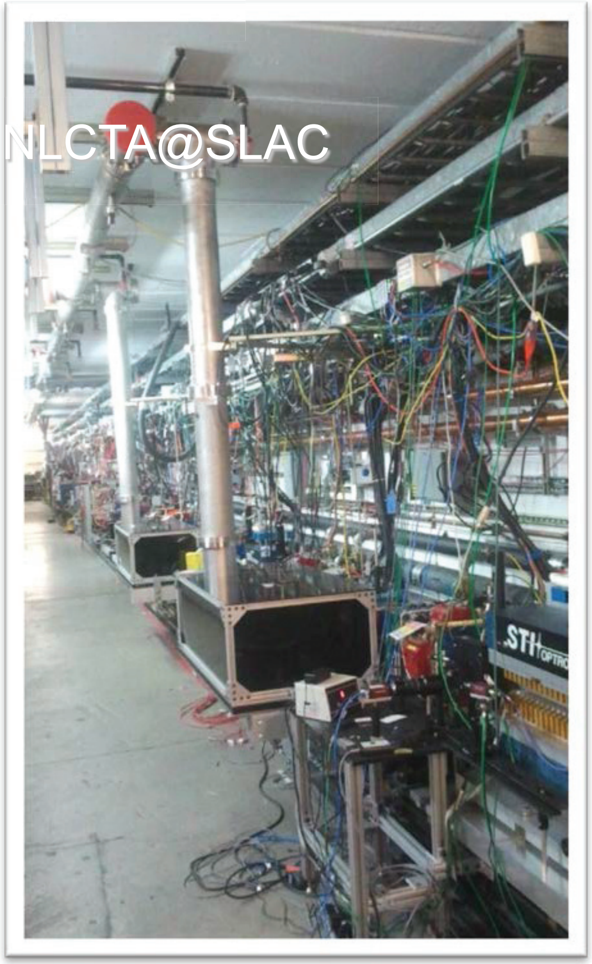


- Elettra, 2012, 260 nm -> 32.5 nm



E. Allaria, et *al.*, Nat. Photonics, 2012

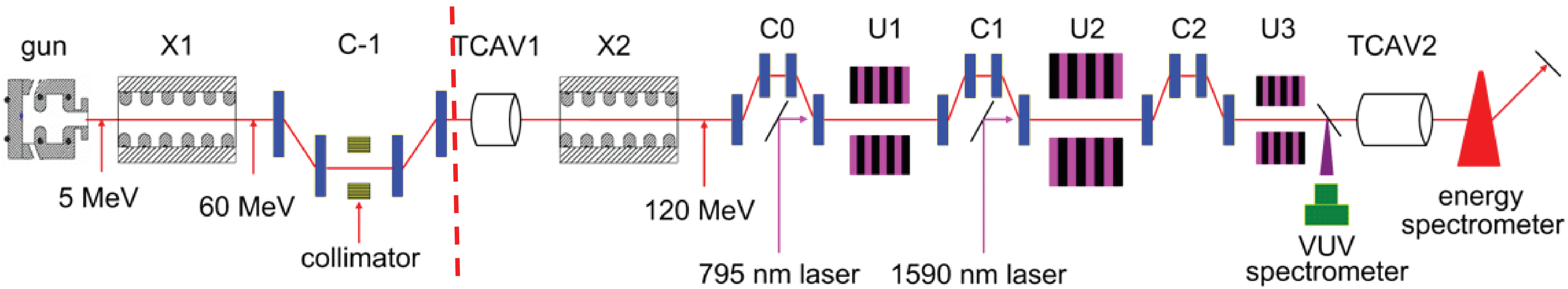
EEHG Experiments



Zhao, Z. T. & Wang, D. FEL2010
Xiang. D. *et al, PRL (2010)*
Xiang. D. *et al, PRL (2012)*
Zhao, Z. T. *et al, Nphoton (2012)*

Planed Experiments： **FLASH@DESY， FERMI@Elettra， NGLS@LBNL, SXFEL@SINAP**

ECHO-3,4 at NLCTA

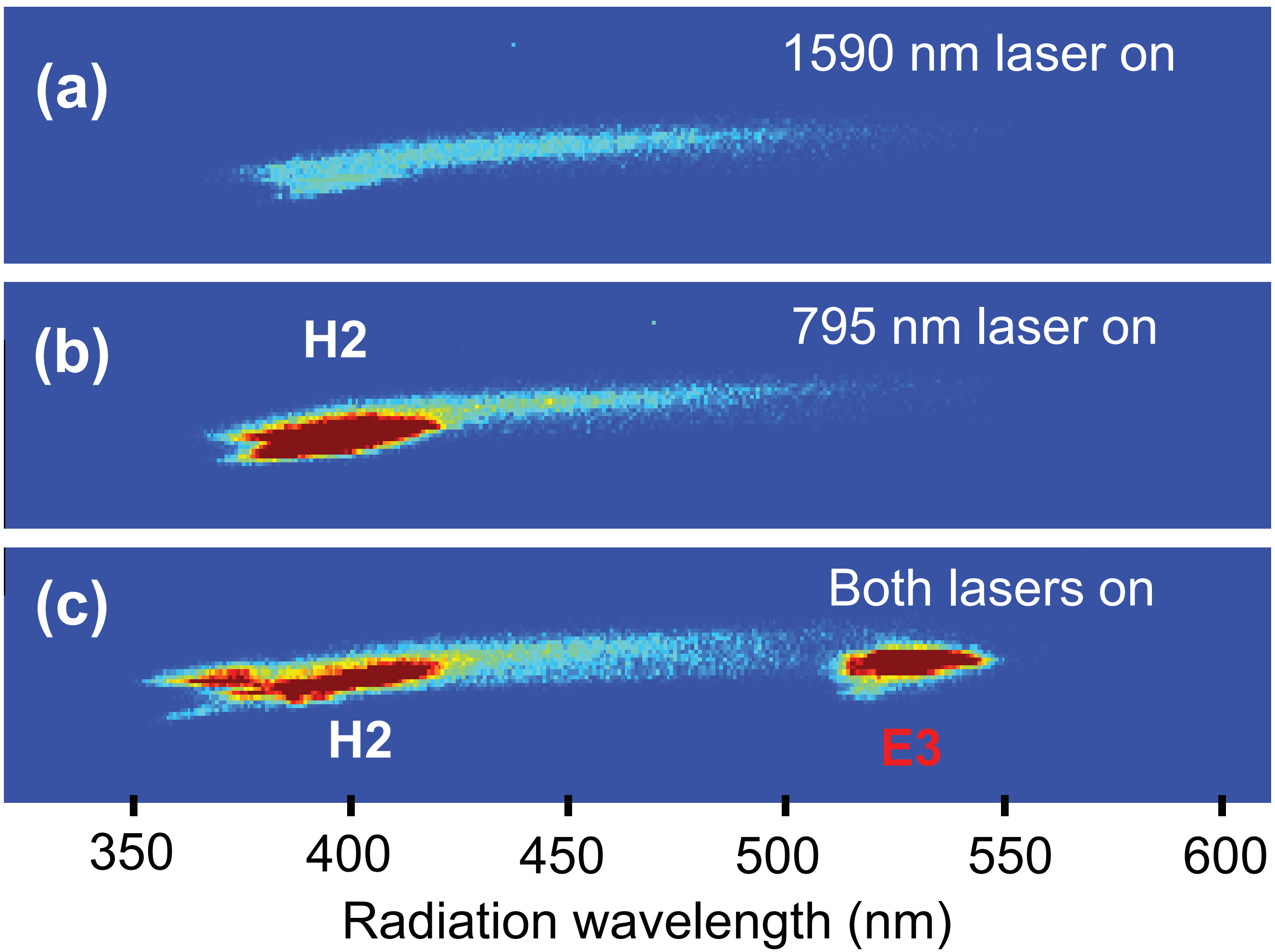


Existing ← → **Main Echo beam line constructed after 10/2009**

→ **TCAV1, TCAV2, VUV spectrometer after 1/2011**

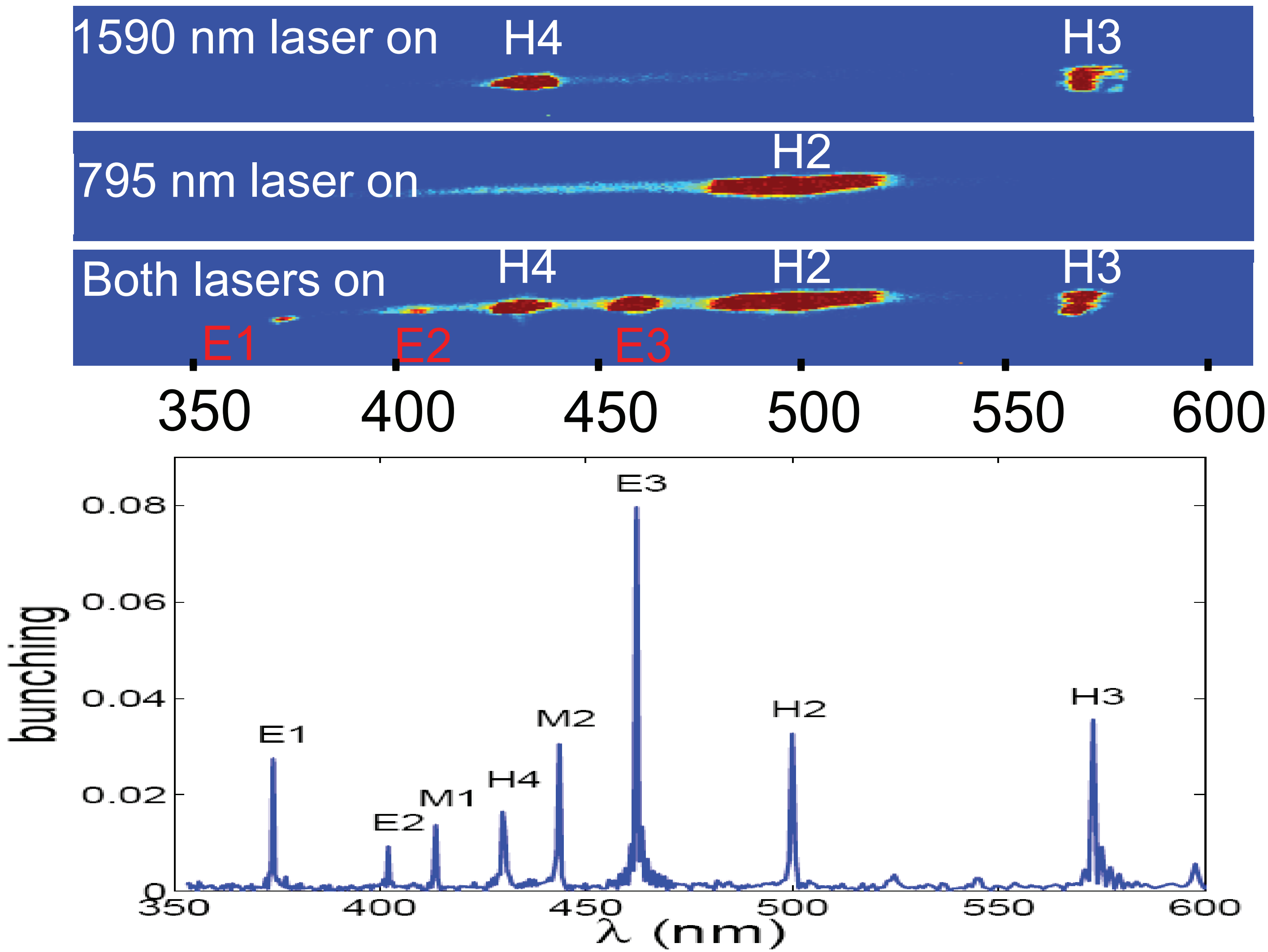
- **Additional lianc to boost beam energy from 60 MeV to 120 MeV**
- **3 chicanes + 3 undulators**
- **Quadrupoles, correctors, power supplies**
- **Laser systems and laser transport**
- **OTR, YAG, UV spectrometer, DAQ ……**

First unambiguous ECHO signal @NLCTA

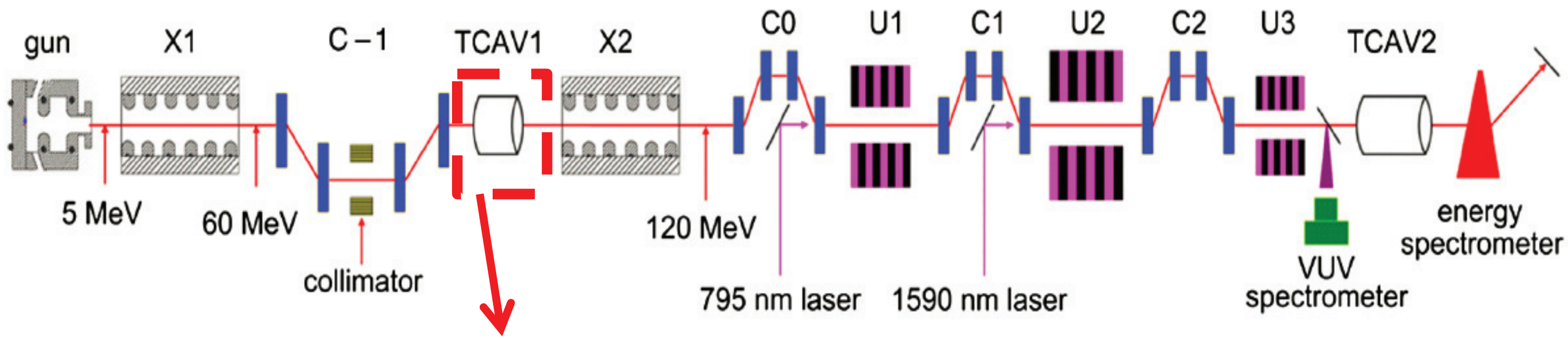


D. Xiang *et al.*, PRL, 2010; featured in Nature Photonics "News & Views"

In good agreement with theory

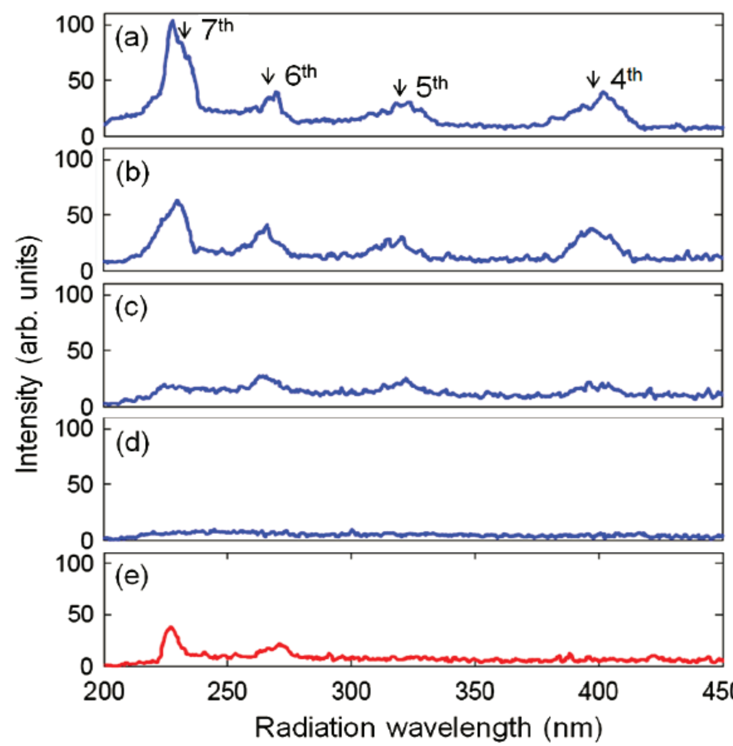


ECHO-7 at NLCTA



➢ In order to confirm the main advantage of EEHG over HGHG, a radio-frequency (RF) transverse cavity (TCAV1) is installed in the NLCTA beamline to increase the slice energy spread by 1 order of magnitude (works as a laser heater).

➢TCAV2 at the end of the beamline is used for measurements of the beam longitudinal phase space and laser energy modulations.



D. Xiang *et al.,* PRL, 2012

Echo Experiments at SINAP

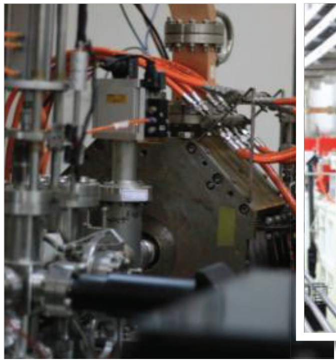
- SDUV-FEL is a test facility for seeded FELs
  - → Originally designed for HGHG
  - → With minor modification, it is now for a variety of seeded FEL schemes

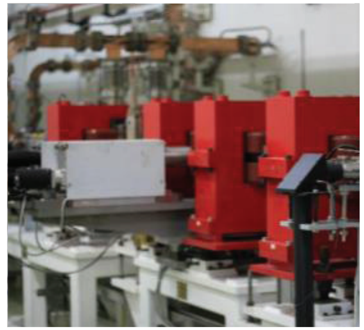
It has successfully carried out the HGHG, cascaded HGHG, and EEHG experiments

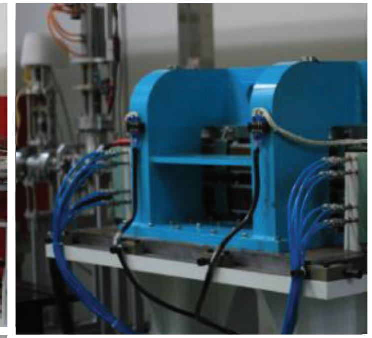
SDUV-FEL building

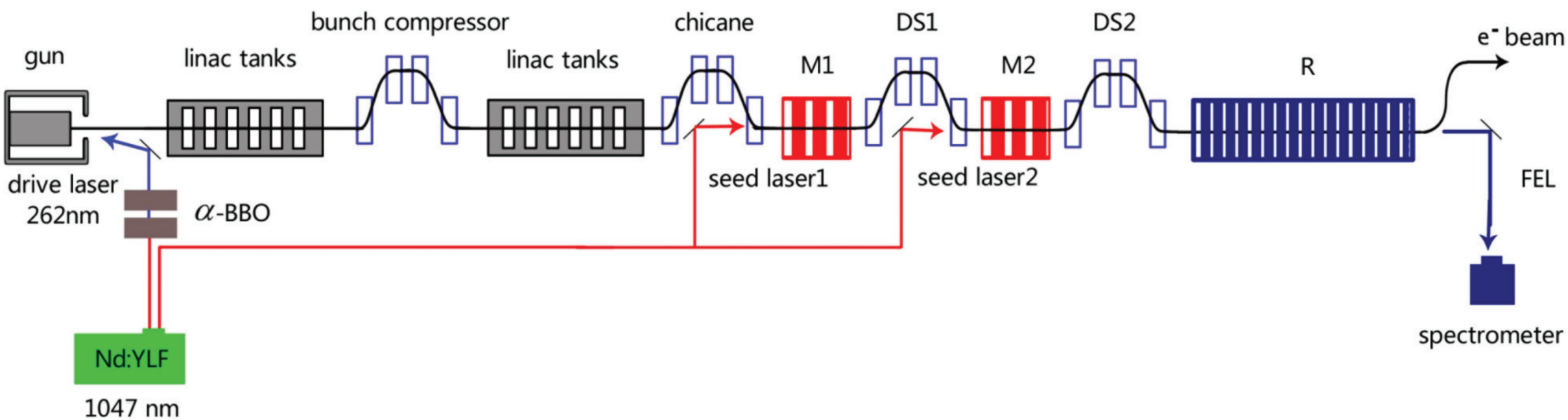
Tunnel

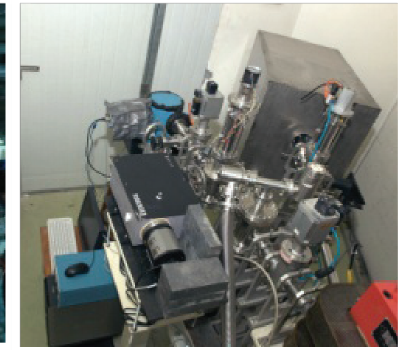
Layout of EEHG at SDUV-FEL





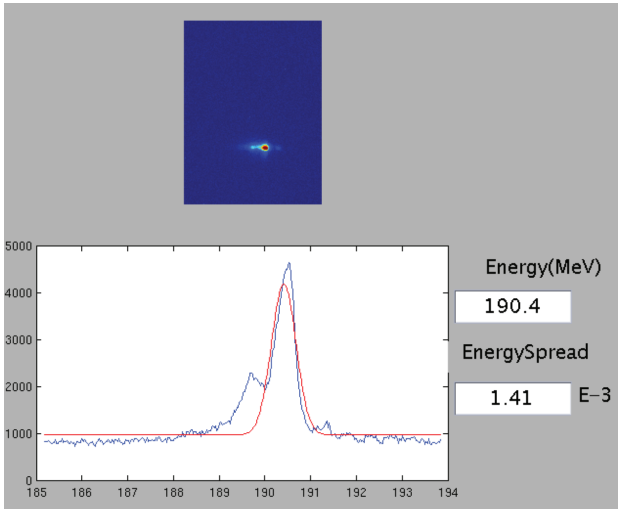




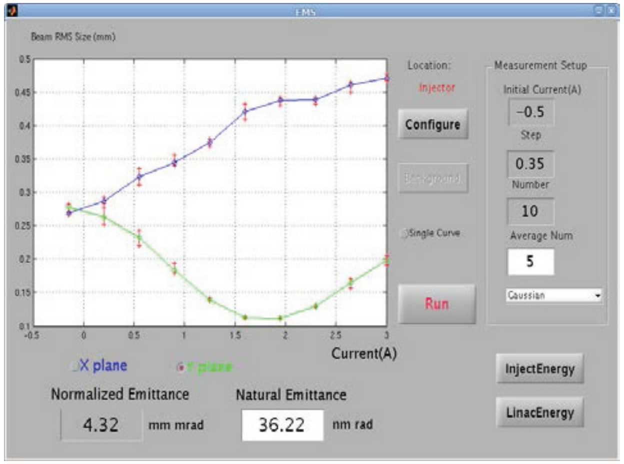


Main parameters (EEHG@SDUV)

Parameters	Measurement
Beam energy	135MeV
Beam energy spread (projected)	0.1-0.2%
Normalized emittance	4~5mm-mrad
Bunch charge	100pC
Seed laser wavelength	1047nm
Seed laser pulse length	8ps
Seed laser power (1, 2)	0~15MW
Modulator1 (EMU65)	10*6.5cm
	B=0~0.3T
Modulator2 (PMU50)	10*5cm
	Gap=12~80mm
R56 of dispersion section 1	1~70mm (16A)
R56 of dispersion section 2	1~10mm (4.2A)
Radiator: PMU25	6*60*2.5cm

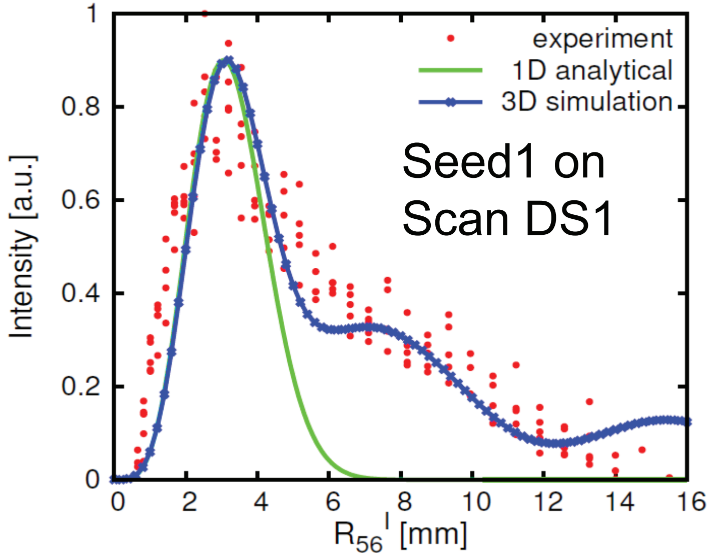


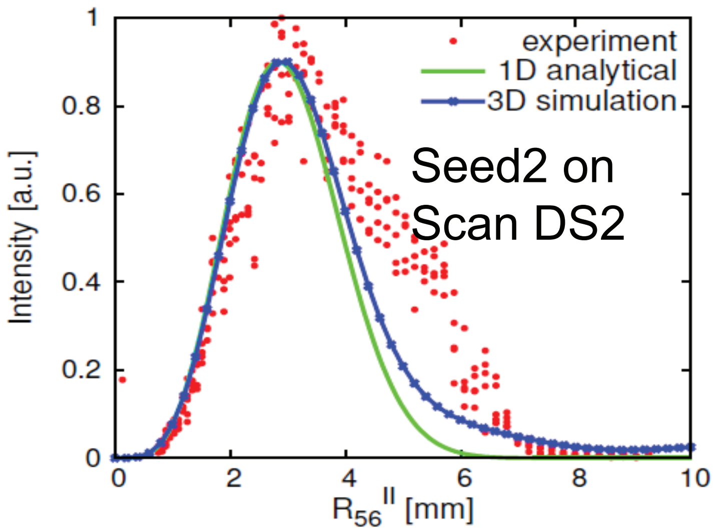
Beam energy and energy spread

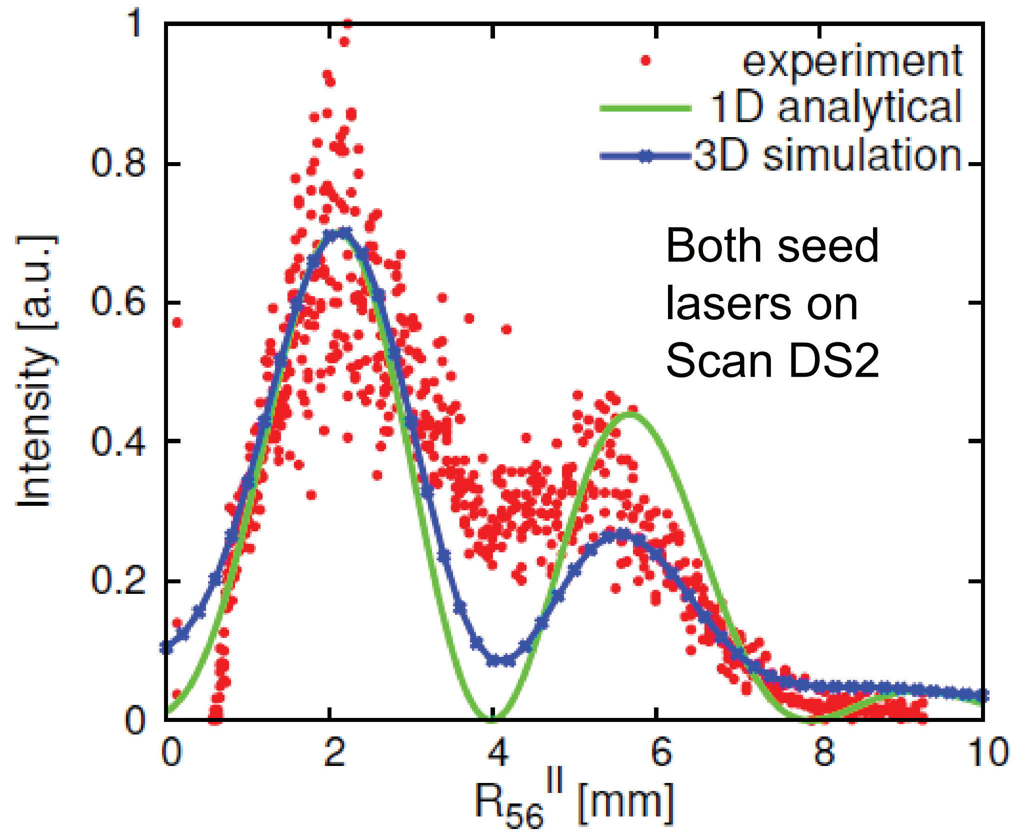


Parameters measurement

First demonstration of EEHG modulation @SDUV-FEL

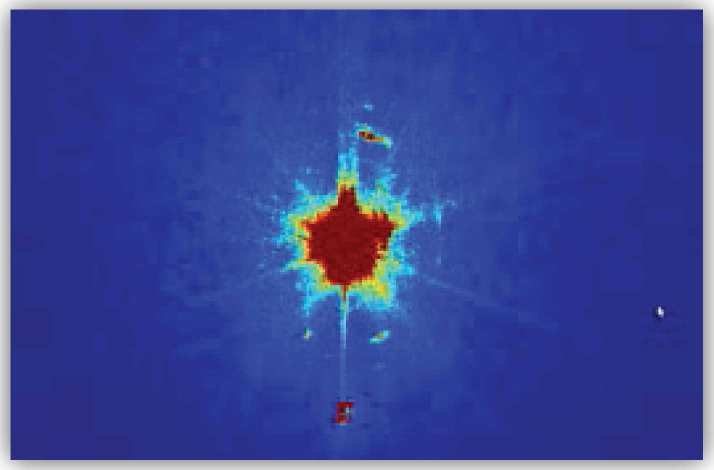


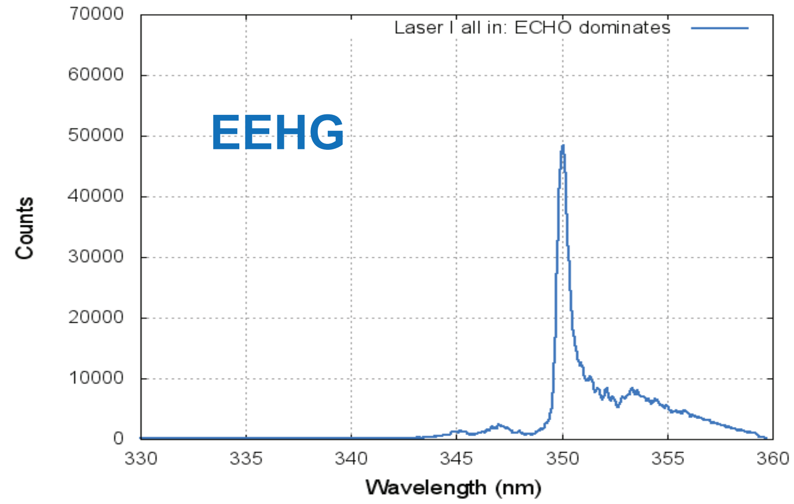


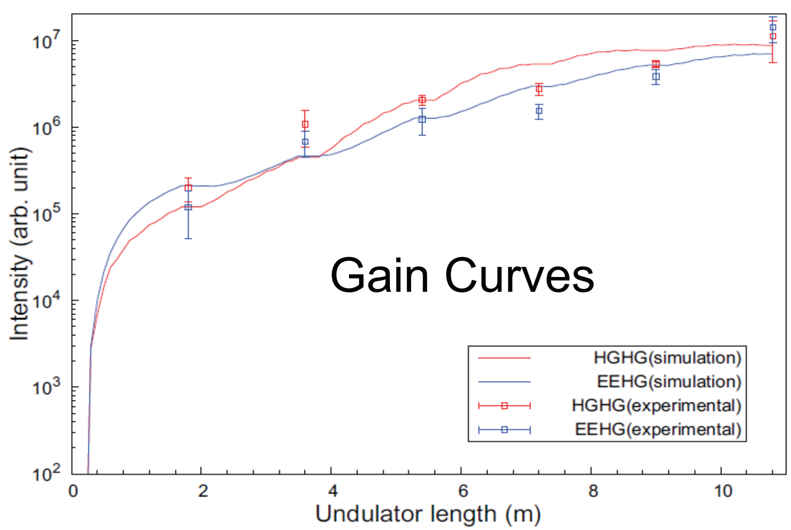


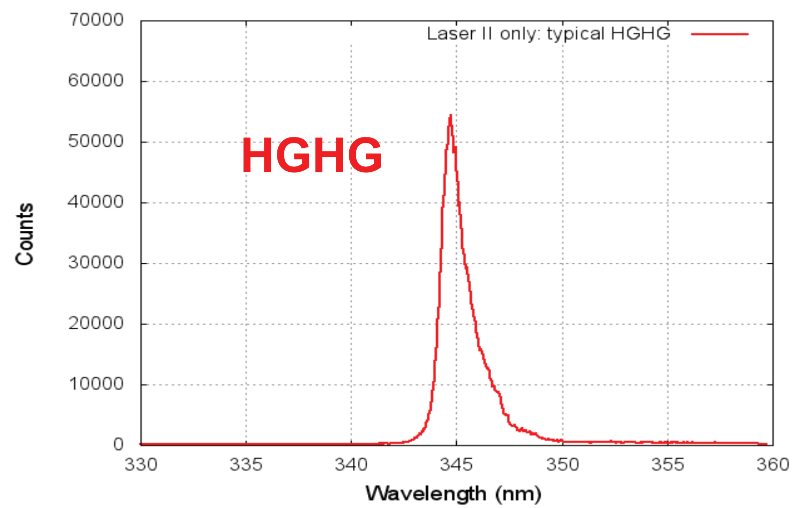
Echo's "double peak" structure

First lasing of an EEHG-FEL







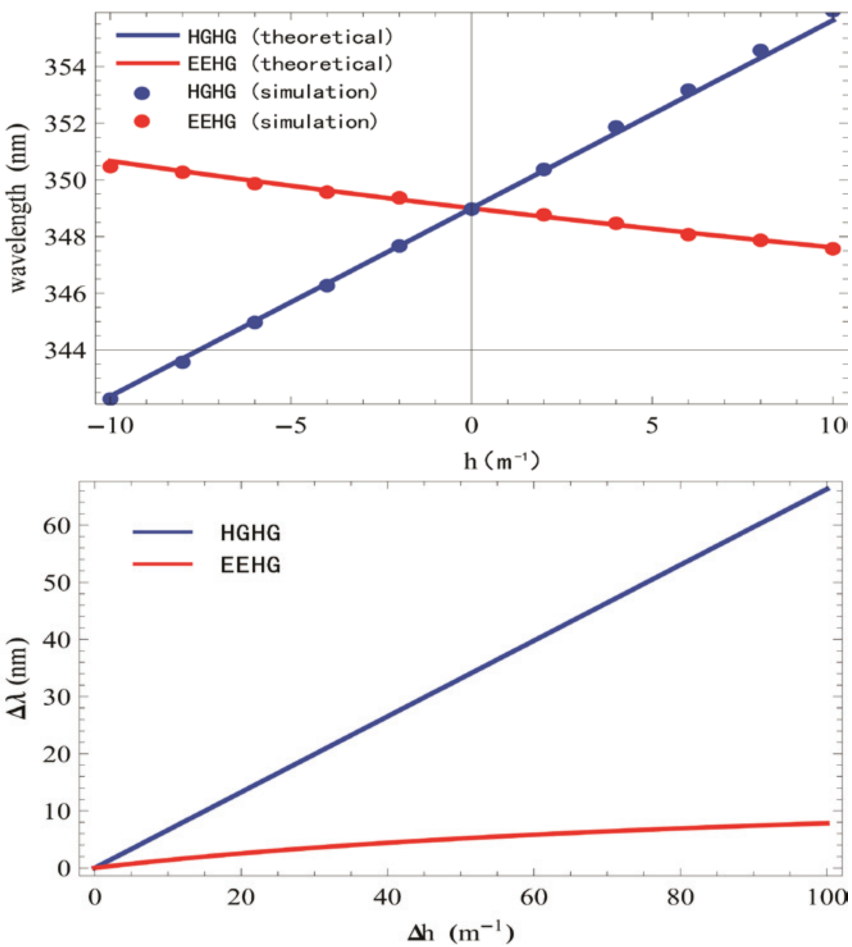


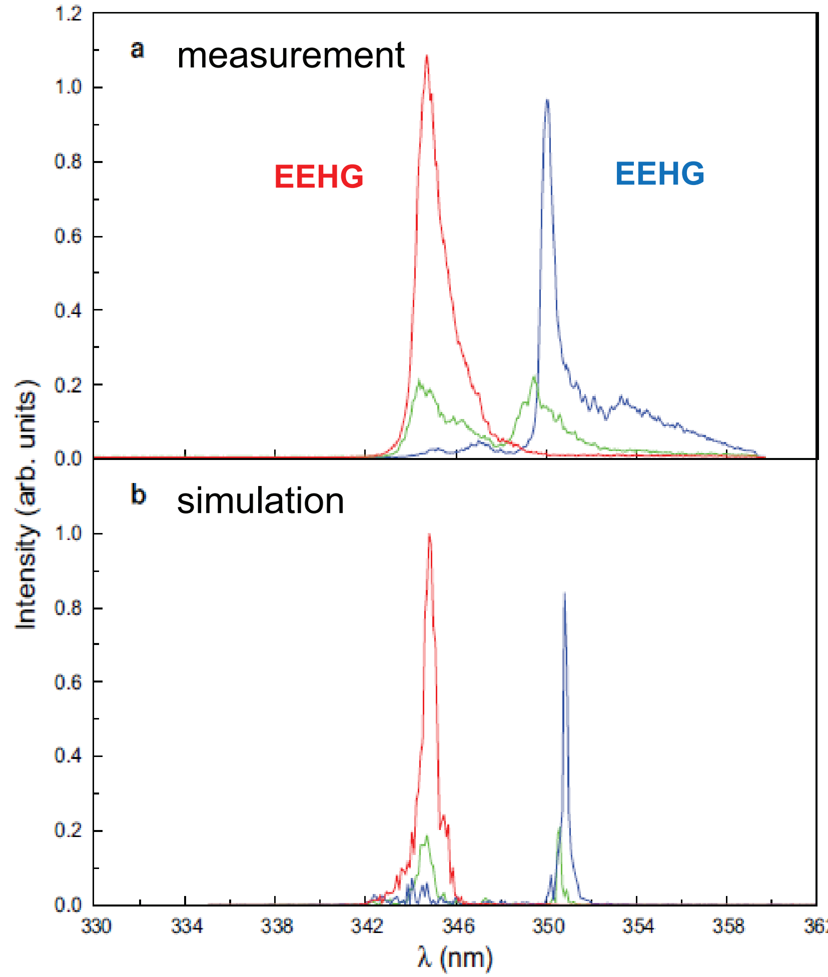
Z.T. Zhao et al., Nature photonics 6, 360 (2012)

HGHG vs. EEHG: Spectrum

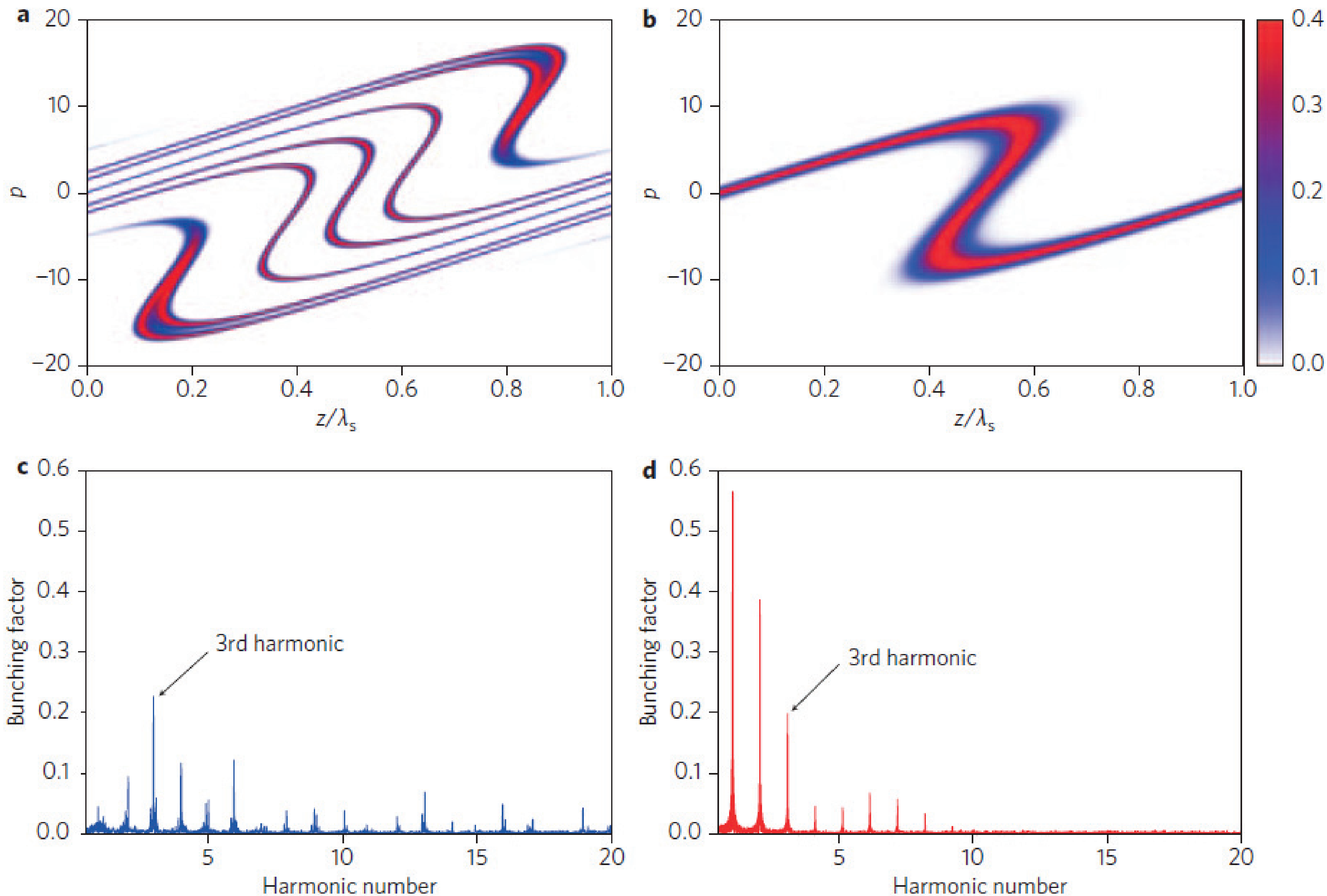
$$\lambda_{\mathrm{HGHG}} = \lambda_s(1 + hR_{56})/k,$$

$$\lambda_{\mathrm{EEHG}} = [1 + h(R_{56}^{(1)} + R_{56}^{(2)})]/[\frac{n}{\lambda_{s1}} + (1 + hR_{56}^{(1)})\frac{m}{\lambda_{s2}}],$$

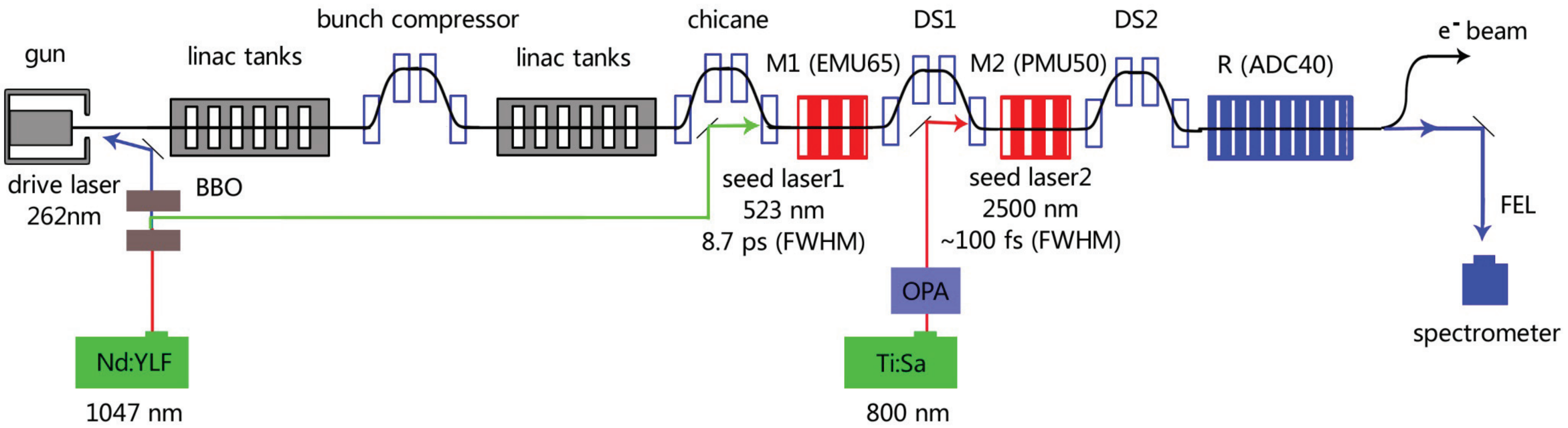




HGHG vs. EEHG: Bunching factor

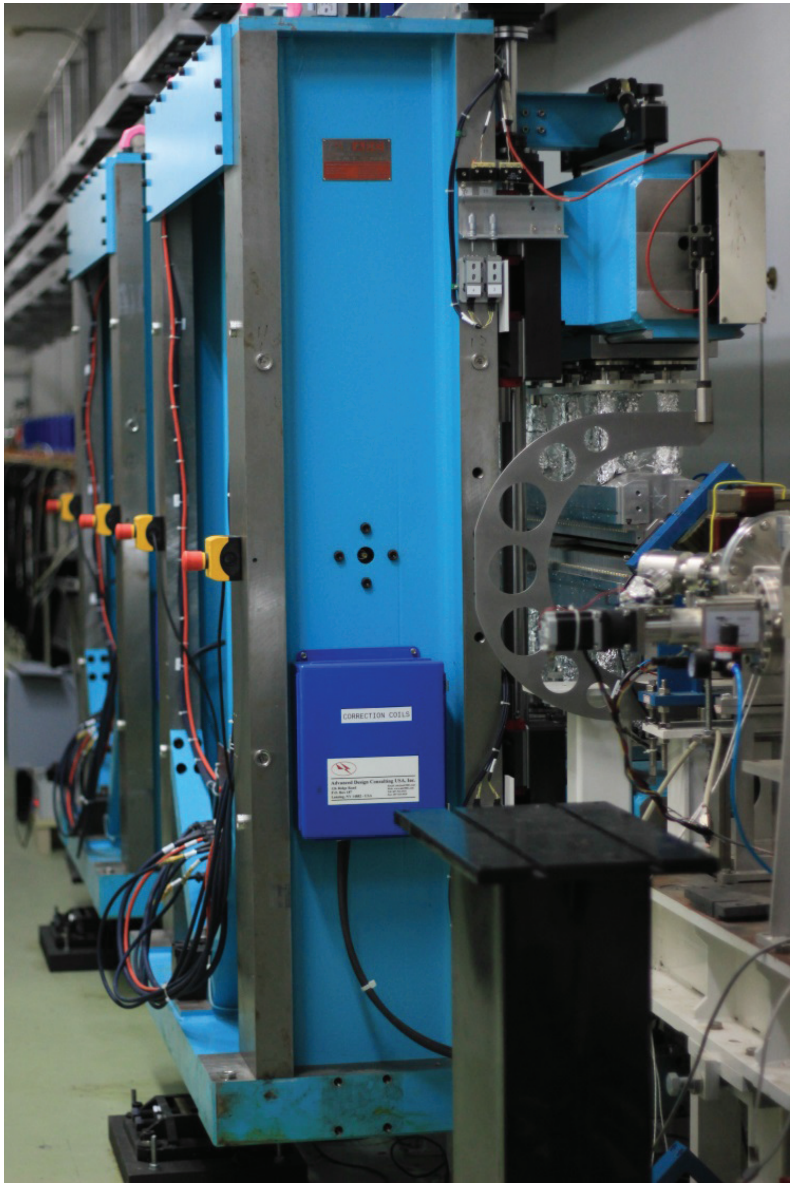


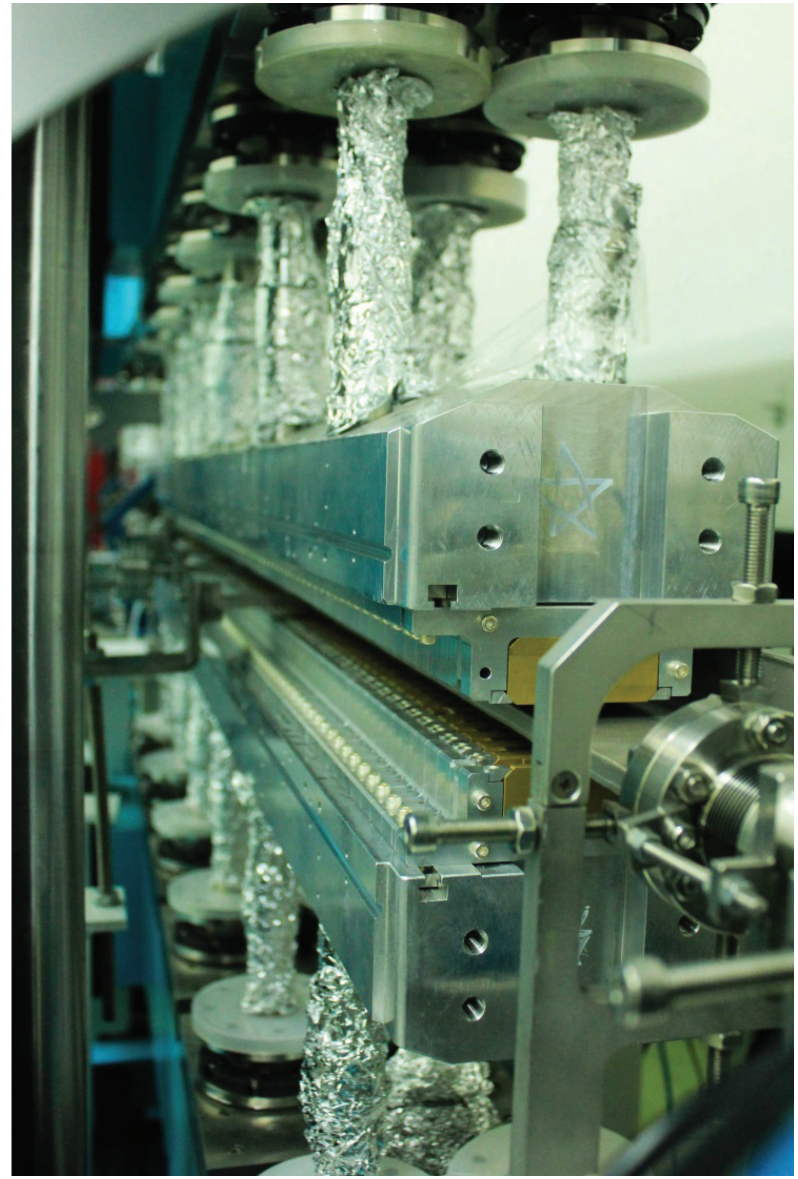
Upgrade SDUV-FEL for Echo-10, 20



- Beam: 165-175MeV, ~200 pC, 3~8ps
- Seed laser 1: 523 nm, 8.7 ps (FWHM), 60 μJ
- Seed laser 2: 2500 nm, ~100 fs (FWHM), 40 μJ
- Radiator: 40mm*80 periods, with variable gap.
- Output wavelength: 800 nm-200nm.
- The echo signal occurs at the wave number:
- $k_{EEHG}=nk_1+mk_2$, n and m are integers.

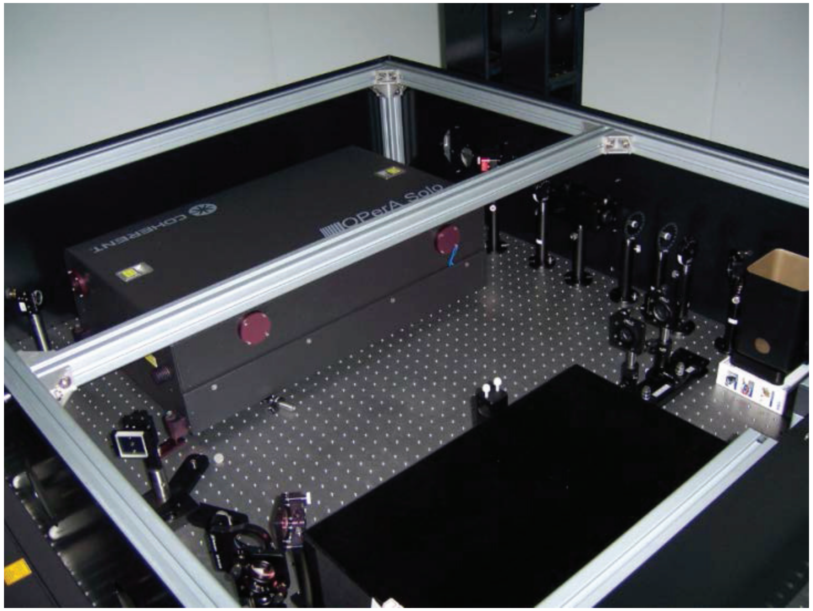
ADC40 (new radiator for EEHG)





40mm*80 periods, with variable gap

Ti sapphire laser as the 2nd seed laser of EEHG

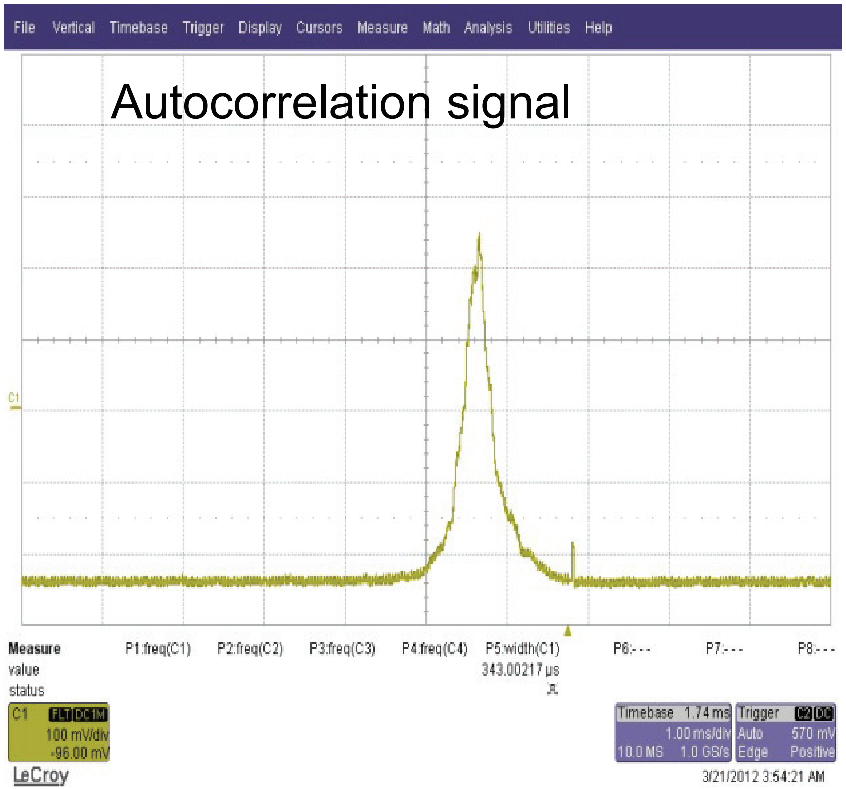


- Coherent, Legend
- Wavelength:750~860nm
- Repetition: 1kHz
- Power: 3.5W
- Pulse Width: 35fs,130fs,1ps

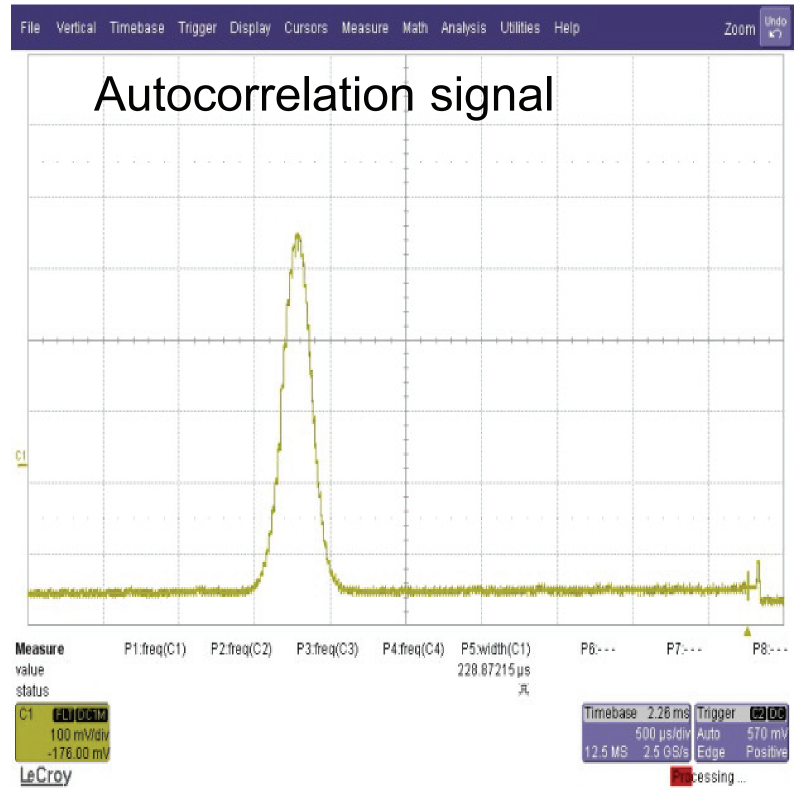
- OPA: 1160nm~2600nm,
  70mW~80mW

Ti sapphire laser as the 2nd seed laser of EEHG

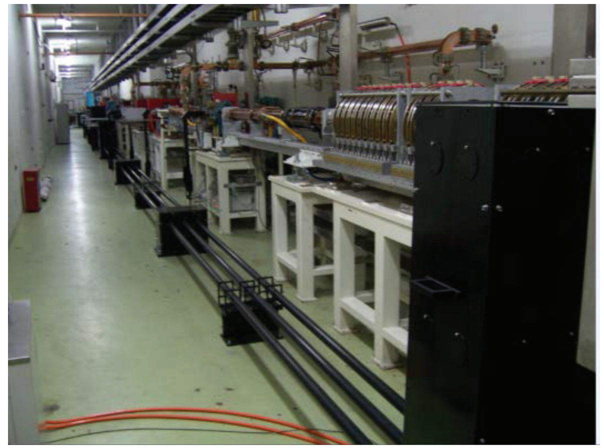
pump laser@800nm

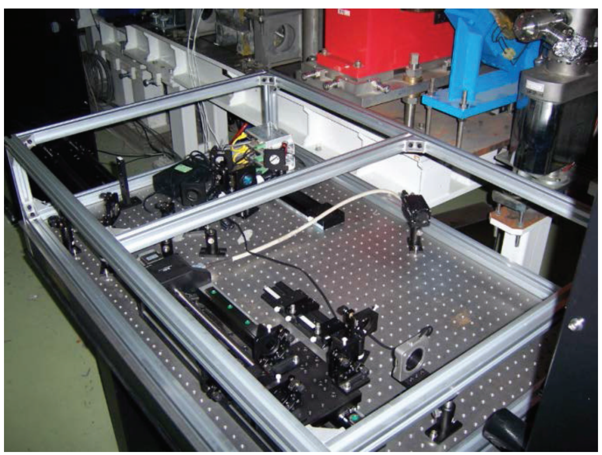


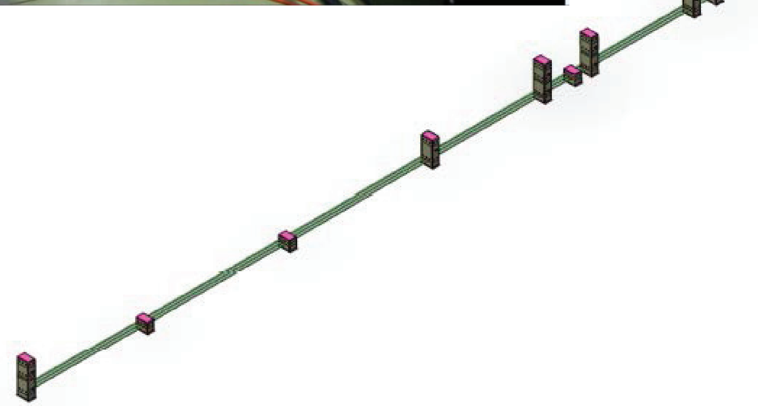
OPA output@1200nm

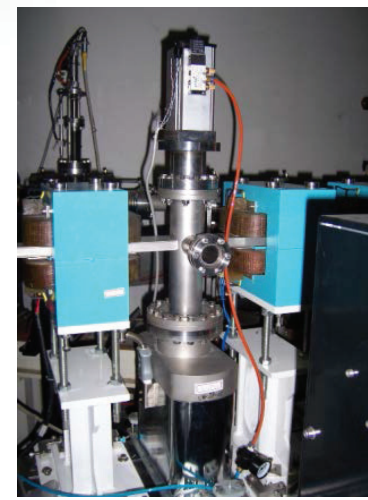


Seed laser transfer line





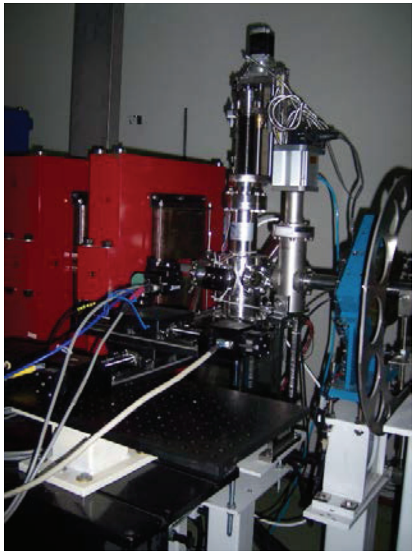
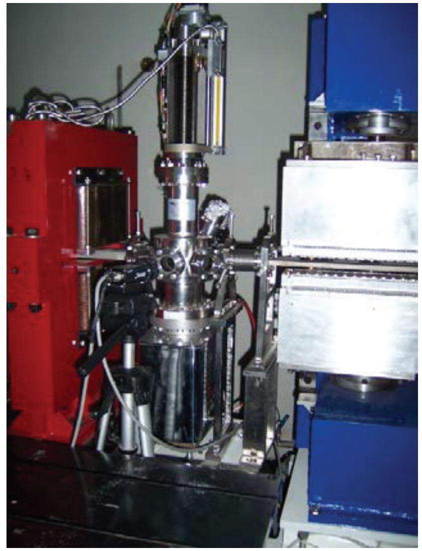
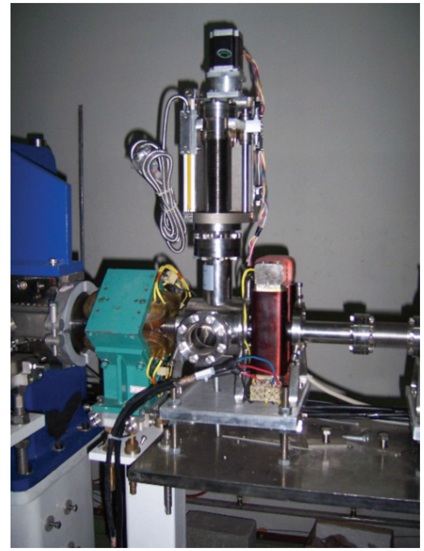
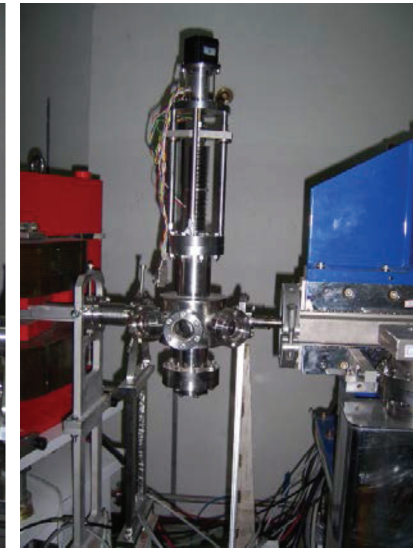
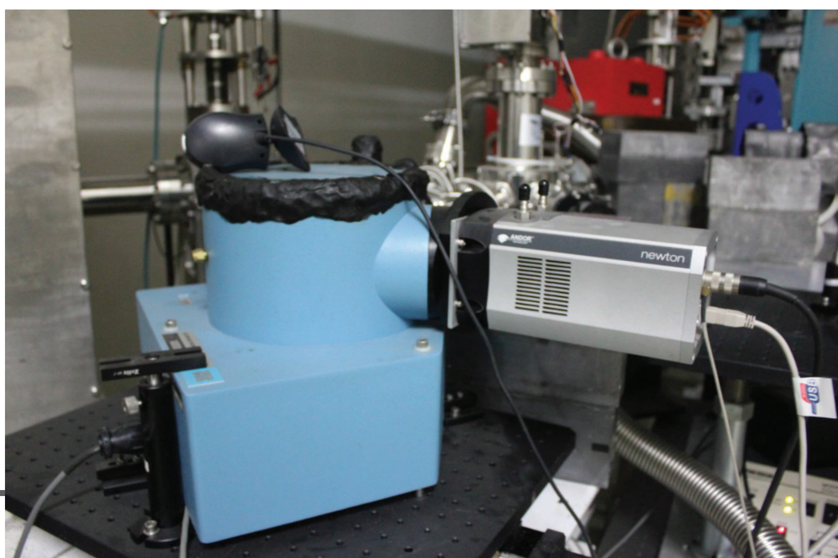




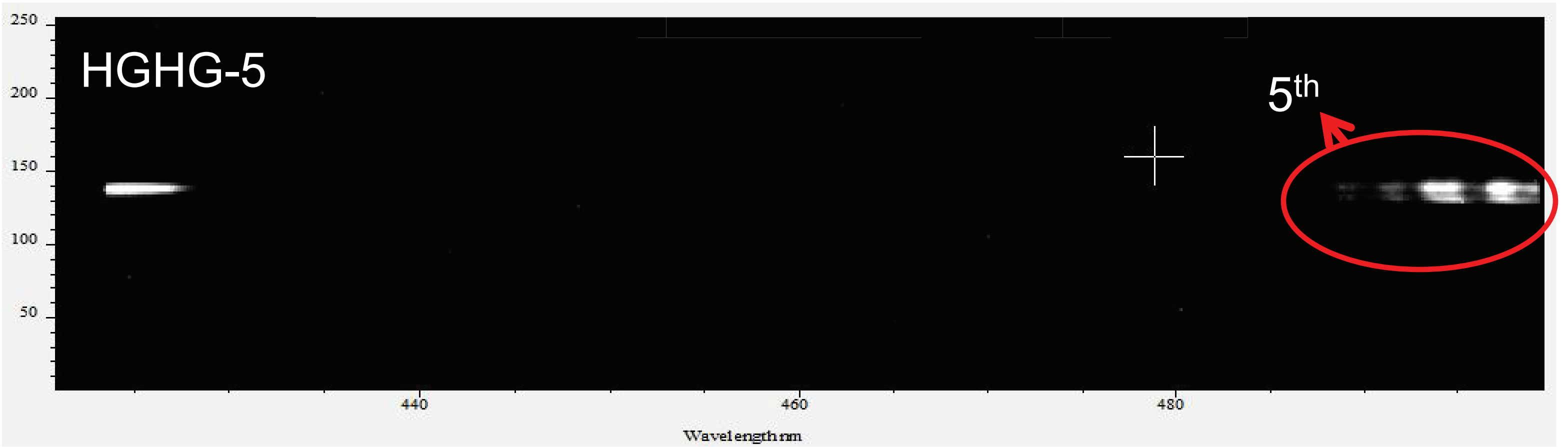
injection port

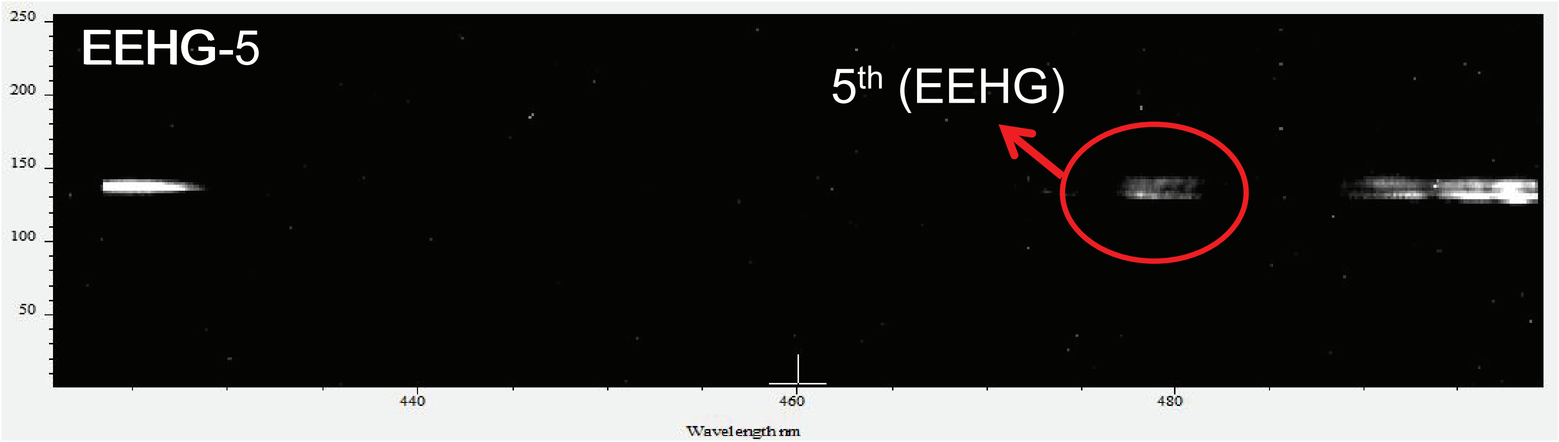
- Femtosecond level accuracy;
- Combine system for both 800nm and OPA laser (1160nm～2600nm);
- Three injection ports for different experiments;

Optical diagnostics and Spectrometers

Echo-5@SDUV-FEL

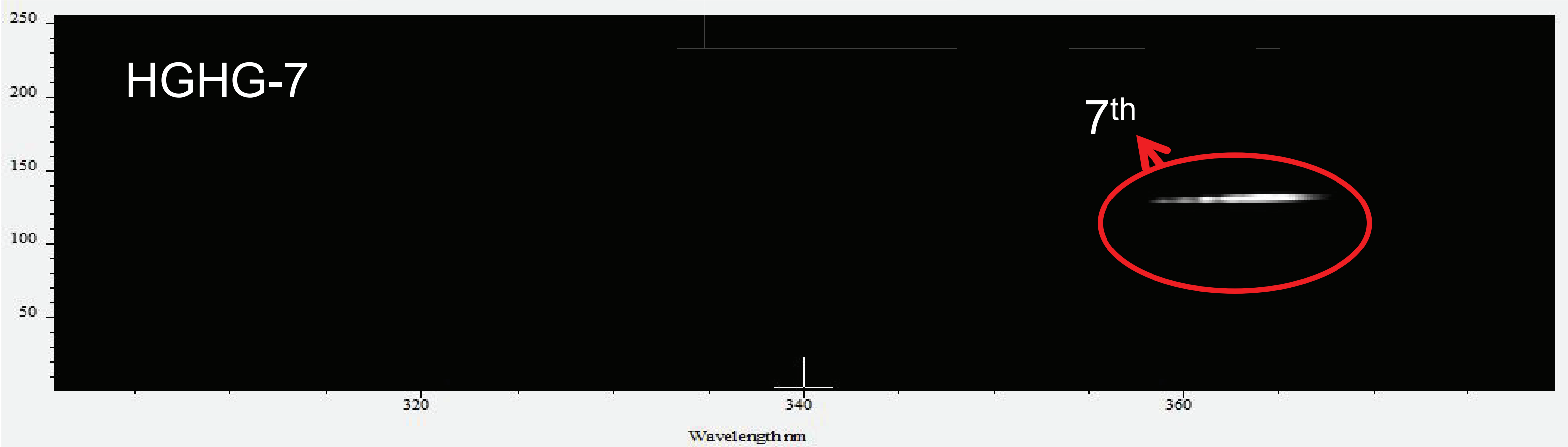


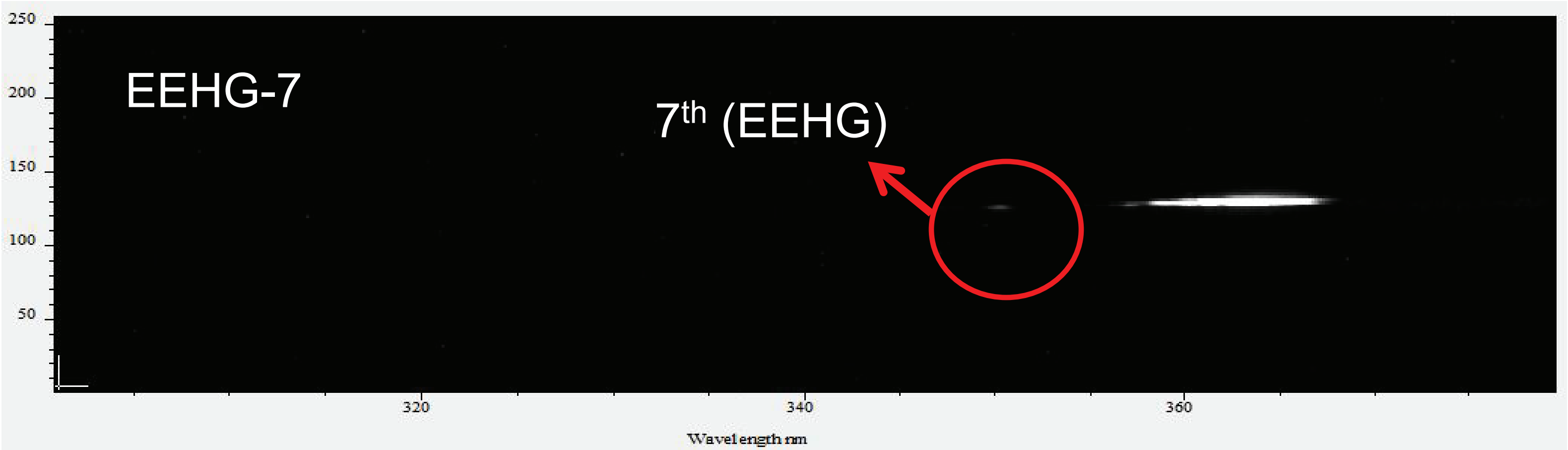


The central wavelength of HGHG and EEHG will be different because wavelengths of two seed lasers are different:

$$\lambda_{s1} = 523nm, \lambda_{s2} = 2500nm, \; for \; \text{m=10, n=-1,} \; a = 10 - \frac{\lambda_{s2}}{\lambda_{s1}} \approx 5.2$$

Echo-7@SDUV-FEL

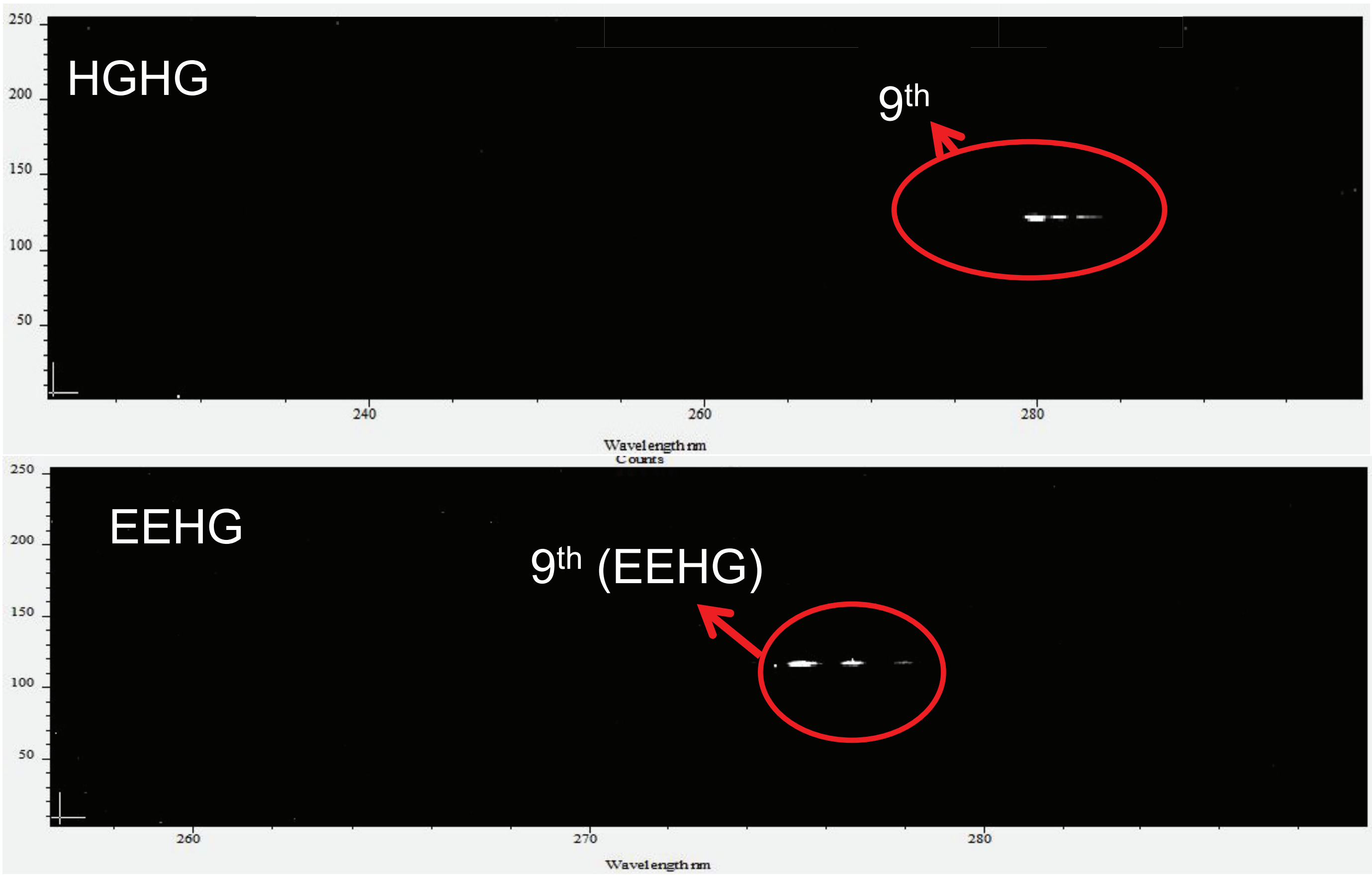




The central wavelength of HGHG and EEHG will be different because wavelengths of two seed lasers are different:

$$\lambda_{s1} = 523nm, \lambda_{s2} = 2500nm, \mathit{for}\ \text{m=12, n=-1, } a = 12 - \frac{\lambda_{s2}}{\lambda_{s1}} \approx 7.2$$

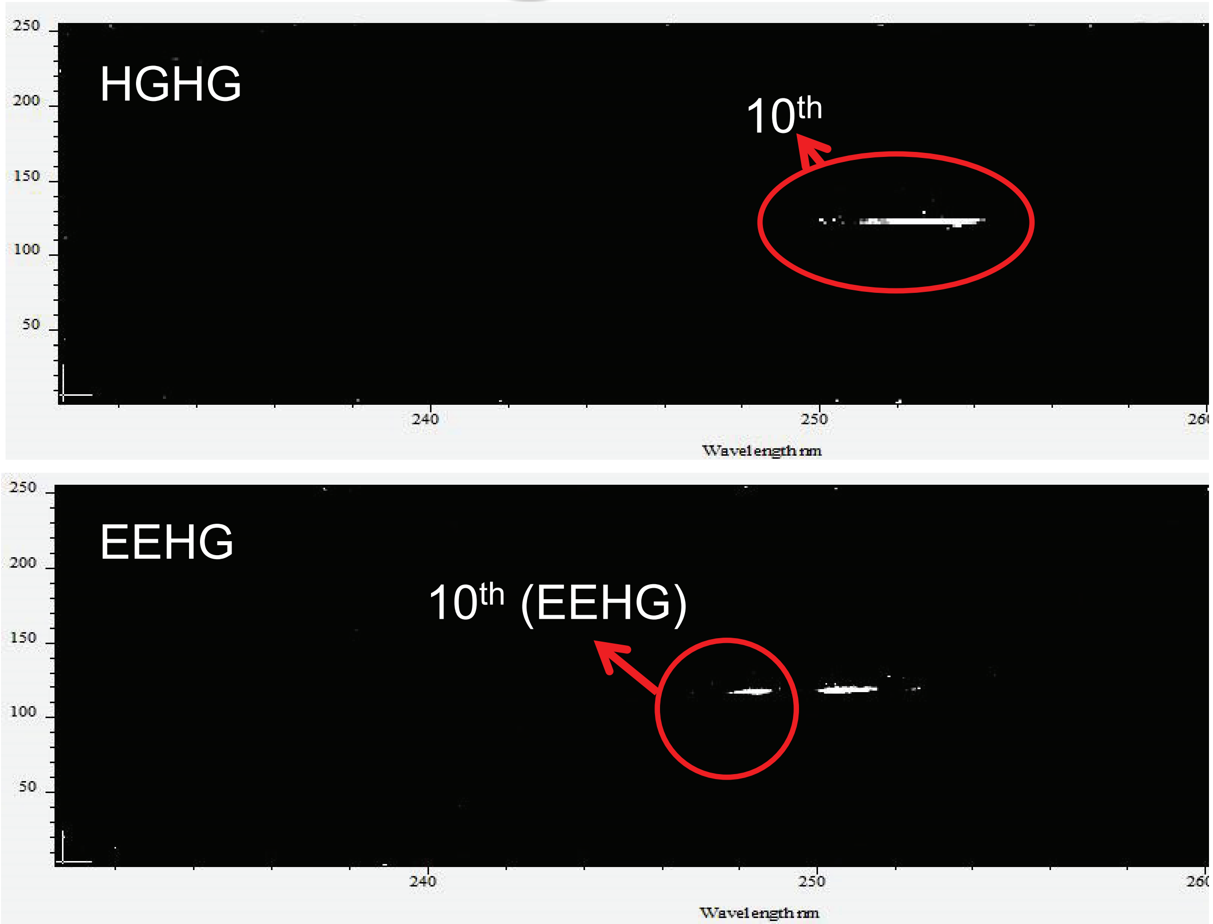
Echo-9@SDUV-FEL



The central wavelength of HGHG and EEHG will be different because wavelengths of two seed lasers are different:

$$\lambda_{s1} = 523nm, \lambda_{s2} = 2500nm, \textit{for}\ \text{m=14, n=-1}, a = 14 - \frac{\lambda_{s2}}{\lambda_{s1}} \approx 9.2$$

Echo-10@SDUV-FEL

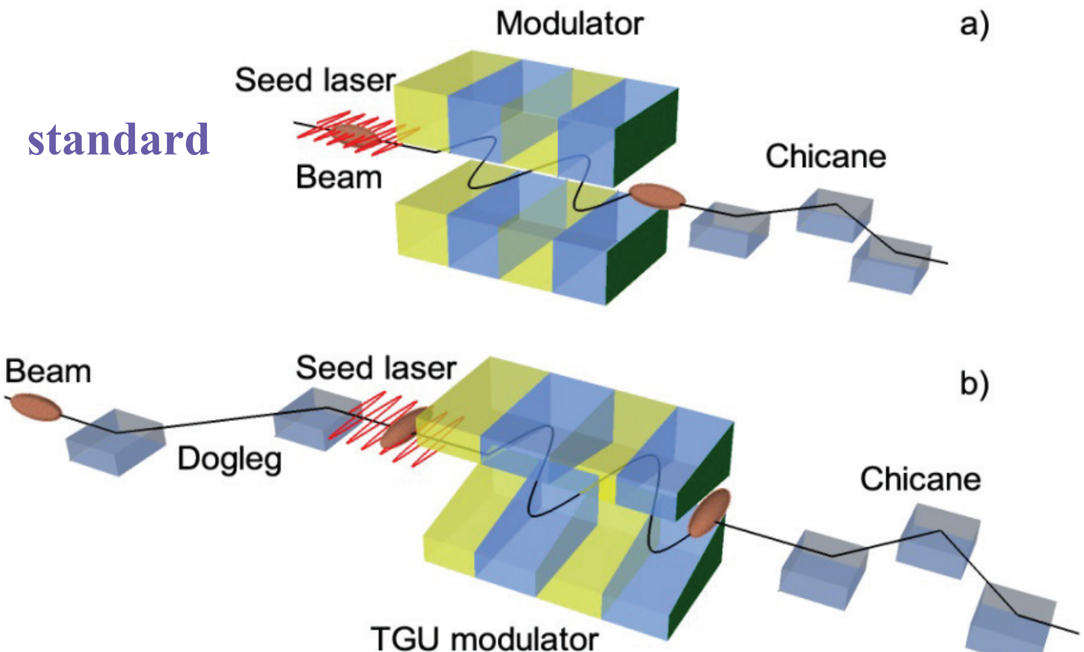


The central wavelength of HGHG and EEHG will be different because wavelengths of two seed lasers are different:

$$\lambda_{s1} = 523nm, \lambda_{s2} = 2500nm, \mathit{for}\ \mathrm{m{=}15,\ n{=}{-}1},\ a = 15 - \frac{\lambda_{s2}}{\lambda_{s1}} \approx 10.2$$

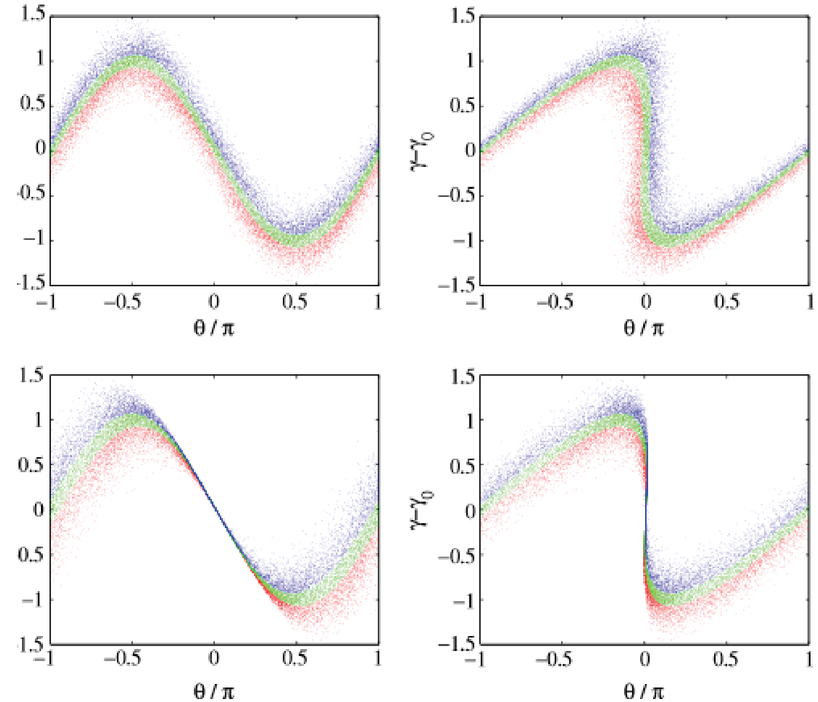
Cooled-HGHG

standard



cooled

1D theory



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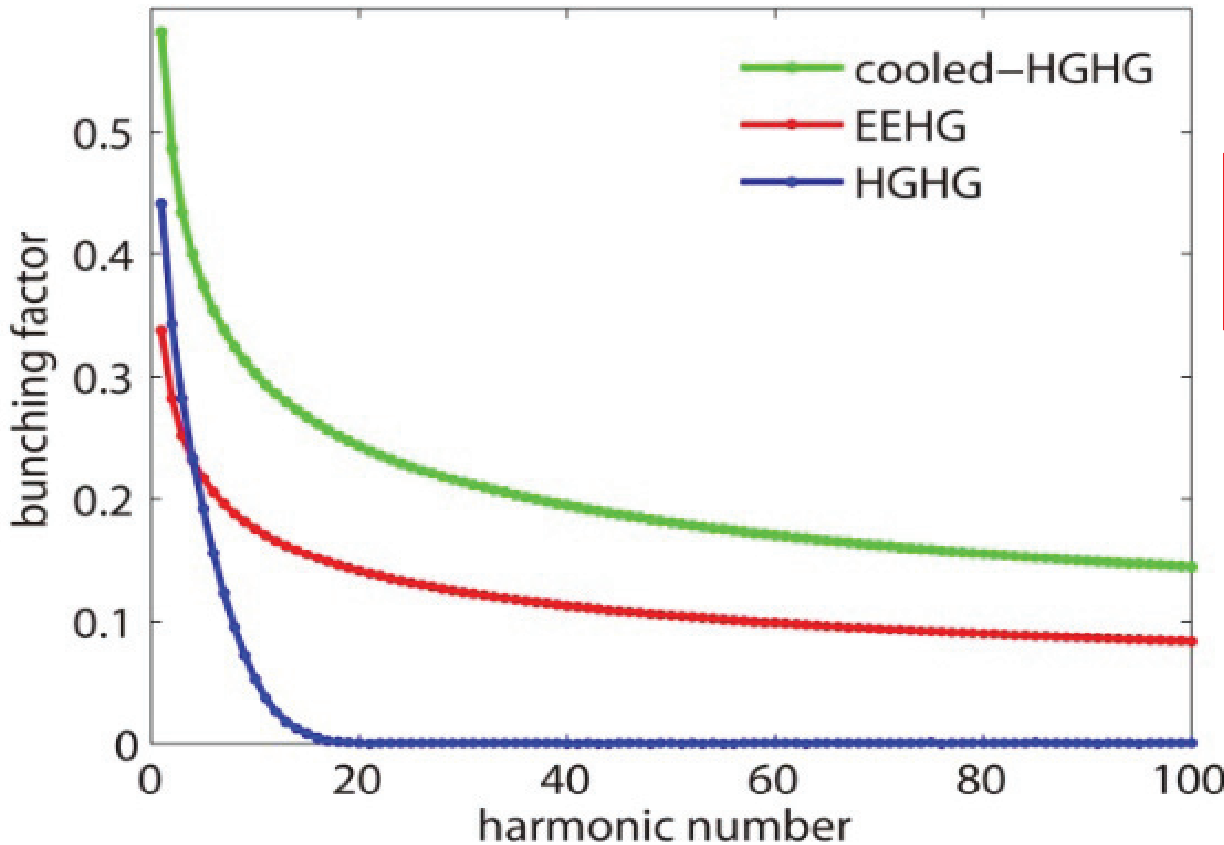
Cooled-HGHG



1D theory

Standard HGHG

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

Cooled HGHG

$$\boxed{b_n = J_n(nD\Delta\gamma)}$$

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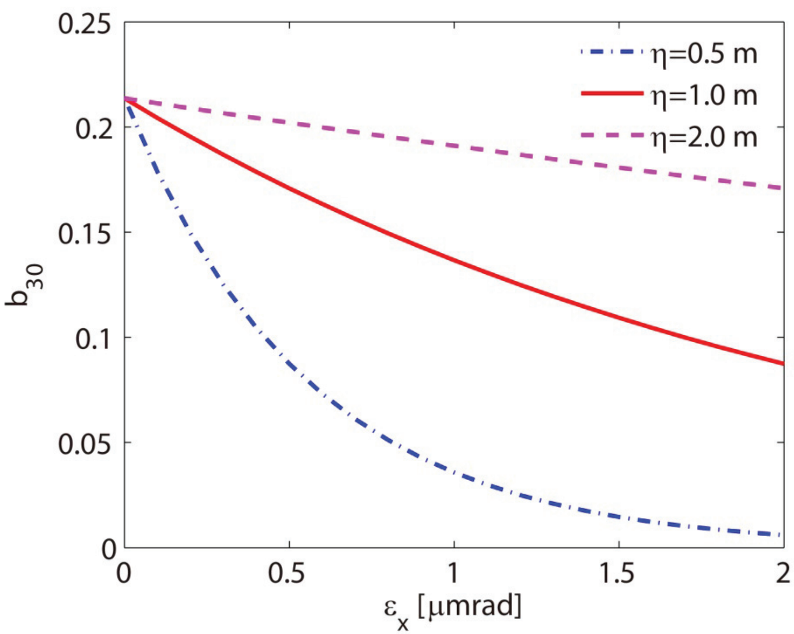
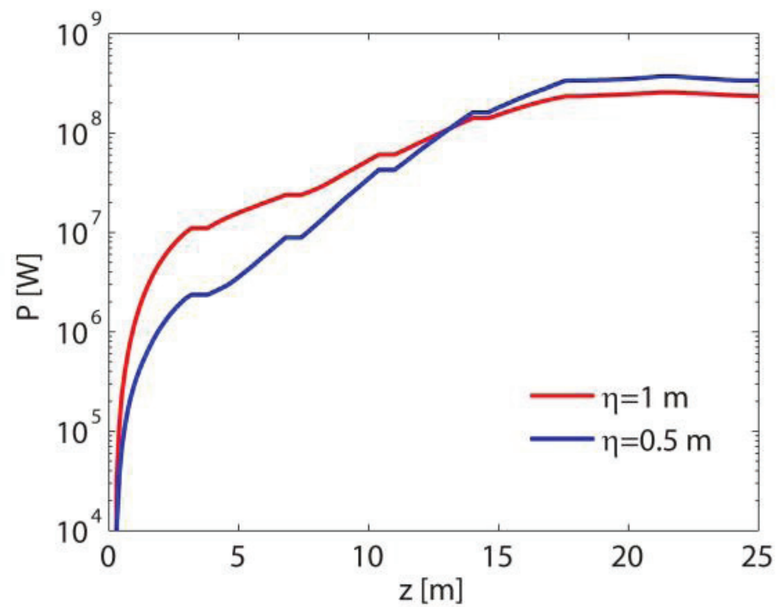
Cooled-HGHG

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

- 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

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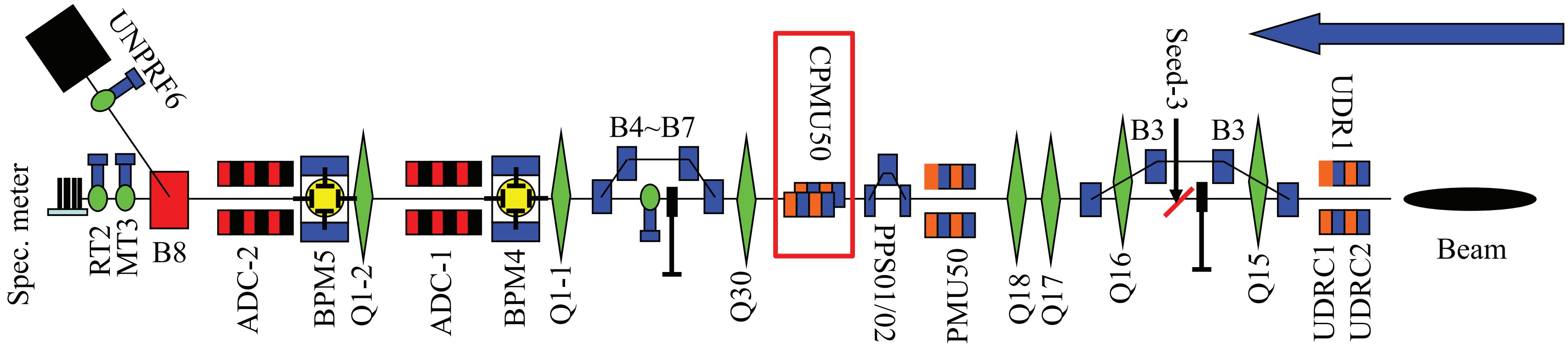
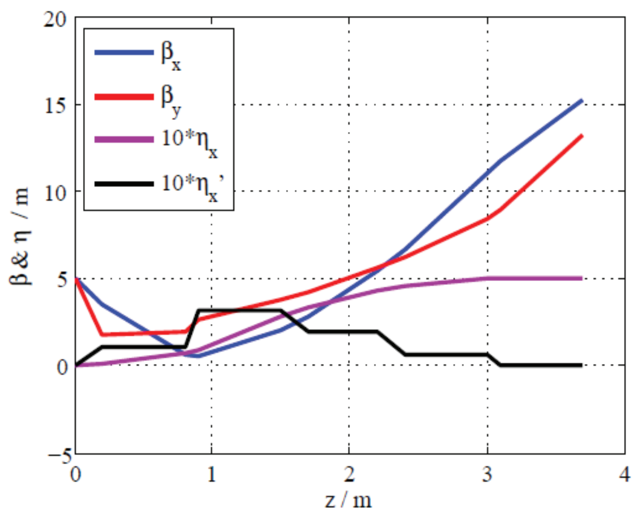
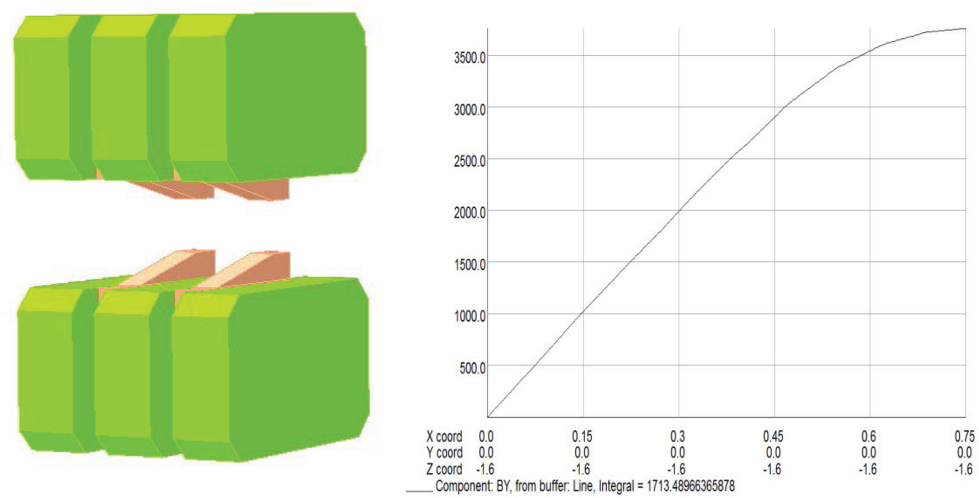
Experiment proposal at SDUV-FEL





Dispersion match



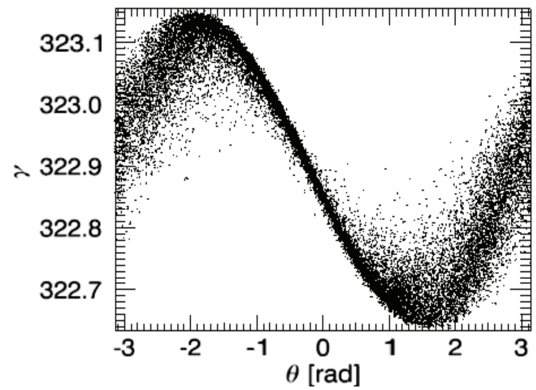
TGU configuration & field dependence

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

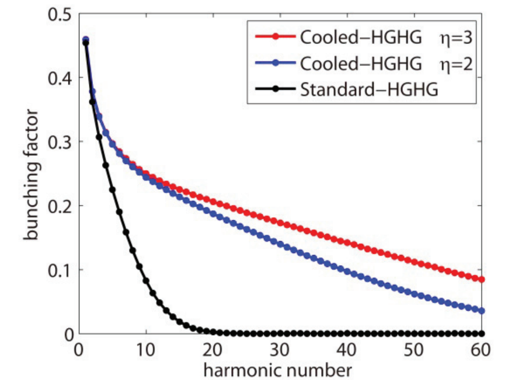
Experiment proposal at SDUV-FEL

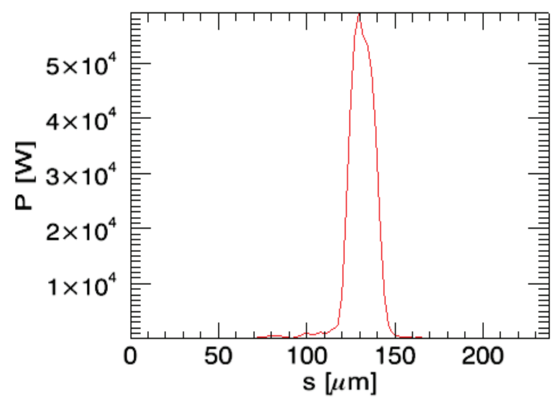
Parameter	Value
beam energy	165MeV
Slice energy spread	16keV
Slice emittance	2 mm-mrad
Peak current	100A
Seed wavelength	2400 nm
Seed pulse length	100 fs (FWHM)
Seed peak power	6 MW
Dispersion	2
Transverse gradient	$14m^{-1}$
Radiation wavelength	120 nm

Phase space

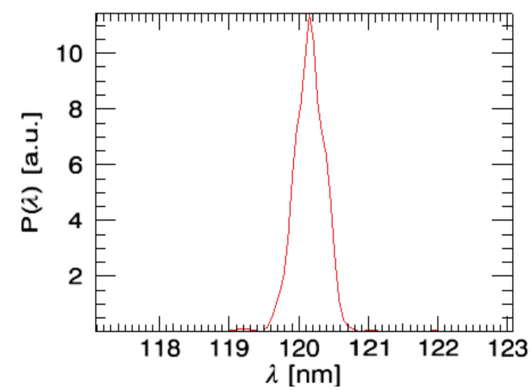


Bunching factor





20^{th} harmonic radiation pulse



spectrum

Summary

- EEHG has high up-conversion efficiency such that one may generate fully coherent soft x-rays directly from an ultraviolet seed laser.
- The principle of EEHG has been demonstrated at SLAC and SINAP at low harmonic numbers, the first lasing of EEHG is obtained at SDUV-FEL.
- Novel methods have been developed at SINAP and SLAC for the accurate measurement of slice energy spread and energy modulation amplitude induced by the seed laser, which are very important parameters for seeded FELs.
- Echo-20, Cooled-HGHG and even higher harmonics seeded FEL experiments in the near future.

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Thank you for your attention
谢谢！
AURORA