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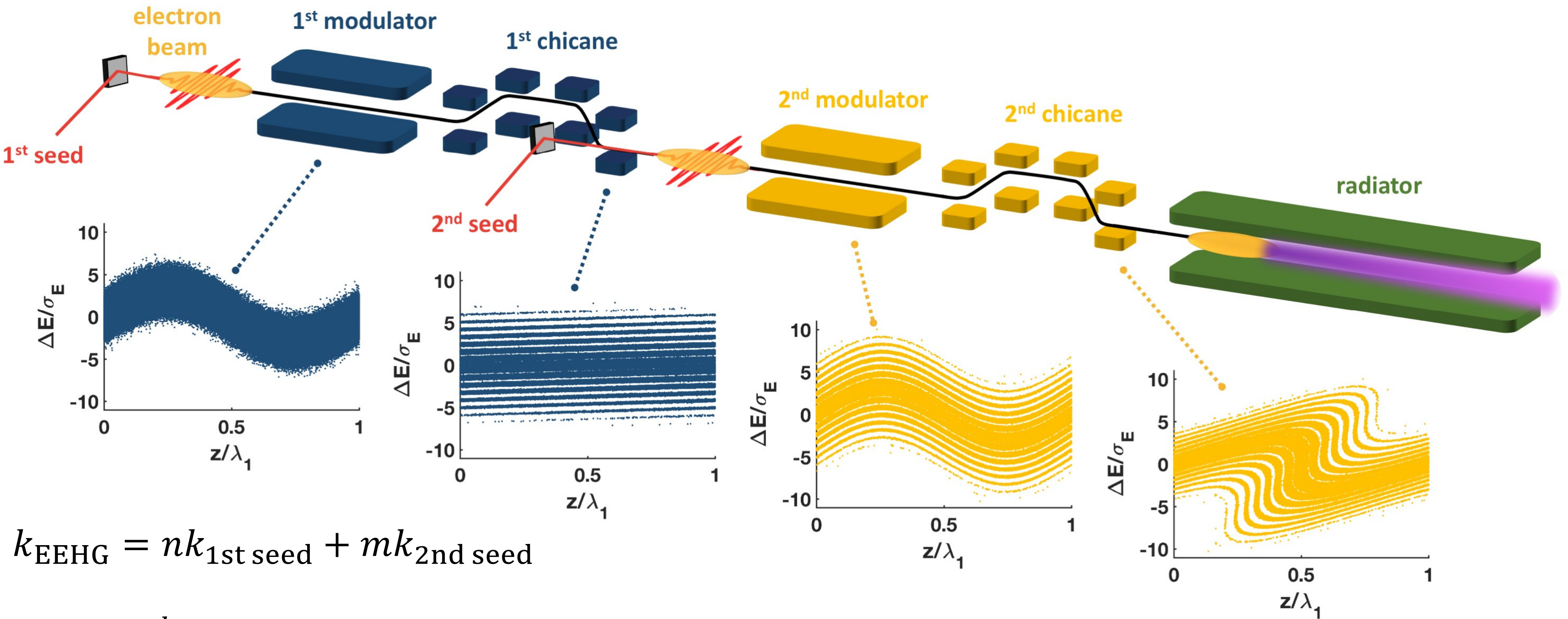
Trieste

Echo-enabled harmonic generation lasing of the FERMI FEL in the soft x-ray spectral region

Primož Rebernik Ribič (on behalf of the EEHG collaboration*)

FEL2019, Hamburg, August 2019

The EEHG scheme



$$k_{\mathrm{EEHG}} = n k_{\mathrm{1st\,seed}} + m k_{\mathrm{2nd\,seed}}$$

For $K = \frac{k_{\mathrm{2nd\,seed}}}{k_{\mathrm{1st\,seed}}} = 1$, $k_{\mathrm{EEHG}} = h k_{\mathrm{2nd\,seed}}$, harmonic number $h = n + m$.

Highest bunching for $n = -1$ $(m = h + 1)$, which requires high dispersions.

$$b_{n,m} = |e^{-(1/2)[nB_1 + (Km+n)B_2]^2} J_m[-(Km+n)A_2B_2] \times J_n\{-A_1[nB_1 + (Km+n)B_2]\}|.$$

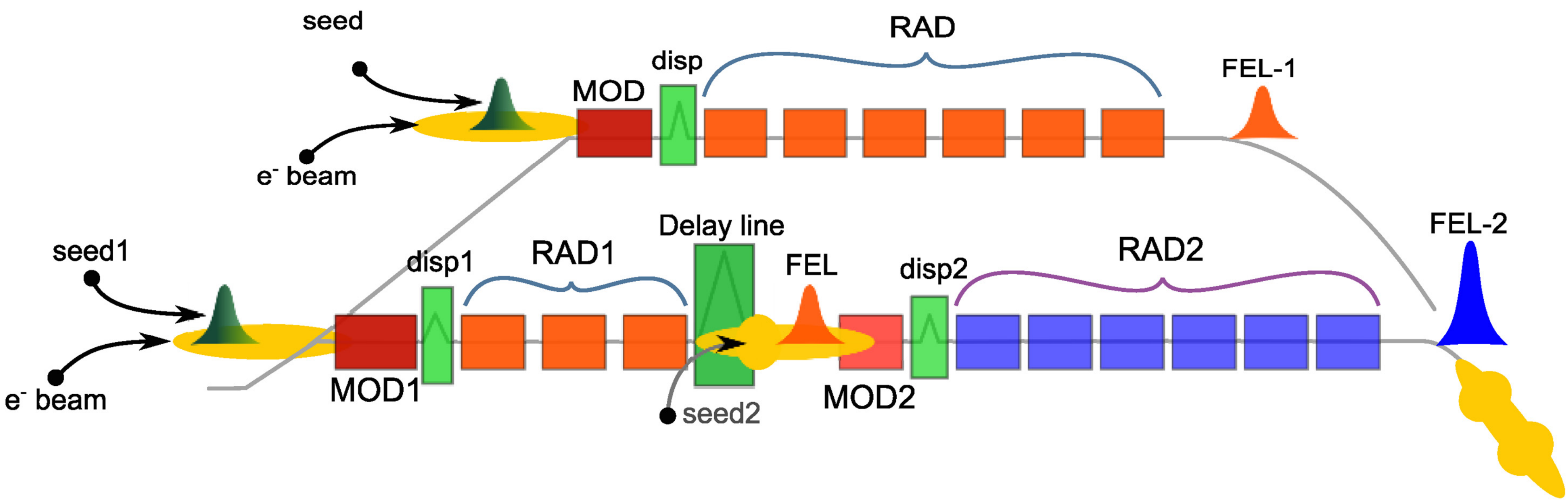
D. Xiang and G. Stupakov, PRSTAB 2009

FERMI layout

FERMI is a seeded FEL based on high-gain harmonic generation (HGHG):

FEL-1 line: single-stage harmonic up-conversion (100-20 nm)

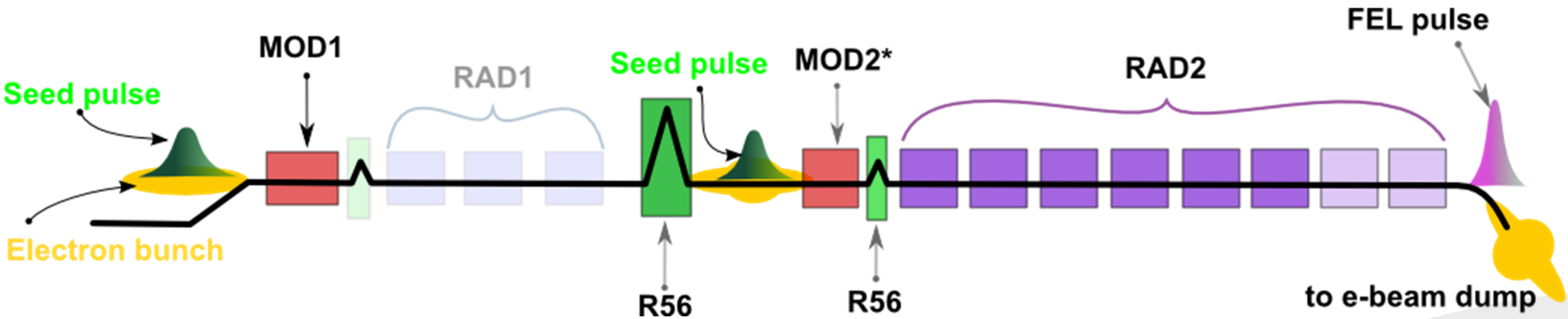
FEL-2 line: two-stage cascade based on the fresh bunch technique – HGHG-FB (20-4 nm)



FERMI layout

From HGHG-FB to EEHG:

- open first stage radiators
- upgrade delay-line to increase the available dispersion
- design new laser injection system for the second (visible) seed
- replace second modulator (to allow resonant interaction at 264 nm)



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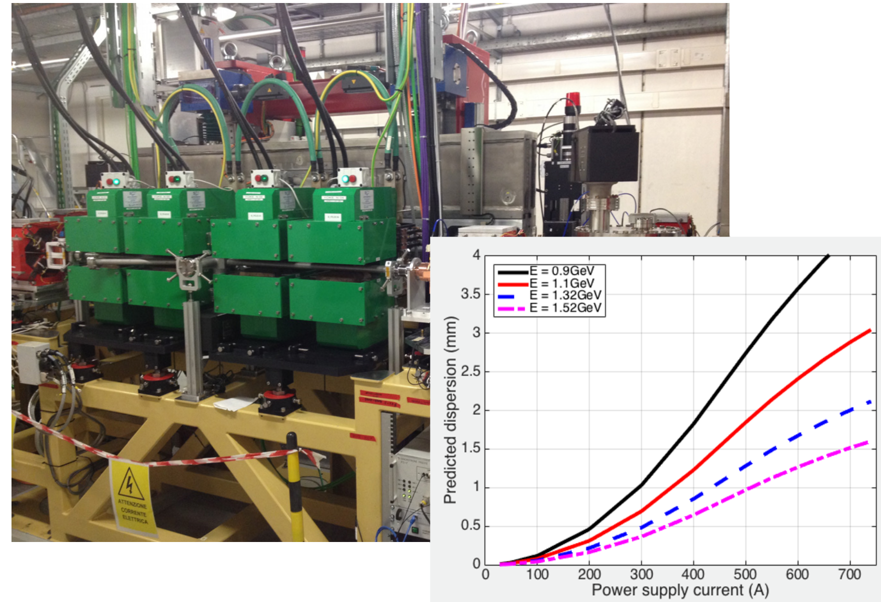
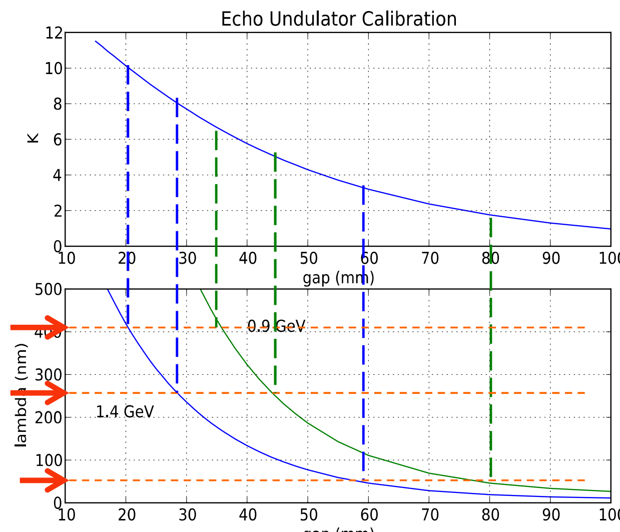
Hardware modifications

Delay line upgrade: new supports for magnets allowing to increase their separation and two power supplies installed in parallel to generate currents up to 750 A. The upgrade resulted in dispersions of **>2 mm** for e-beam energies around 1.3 GeV.



Replacement of the second modulator (with a refurbished one):
Length: ~1.5 m
Period: 11.3 cm
Minimum gap: 10 mm
Tuning to the seed laser wavelength of 264 nm was possible in the whole energy range (0.9 - 1.5 GeV).
The “new” modulator still allowed operation in the HGHG-FB mode down to 8 nm.

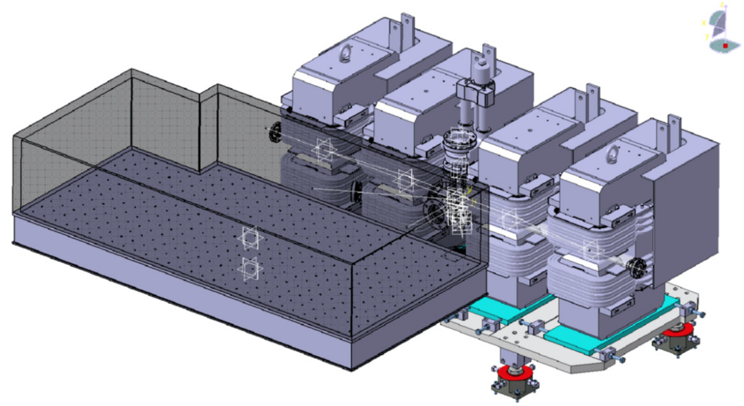


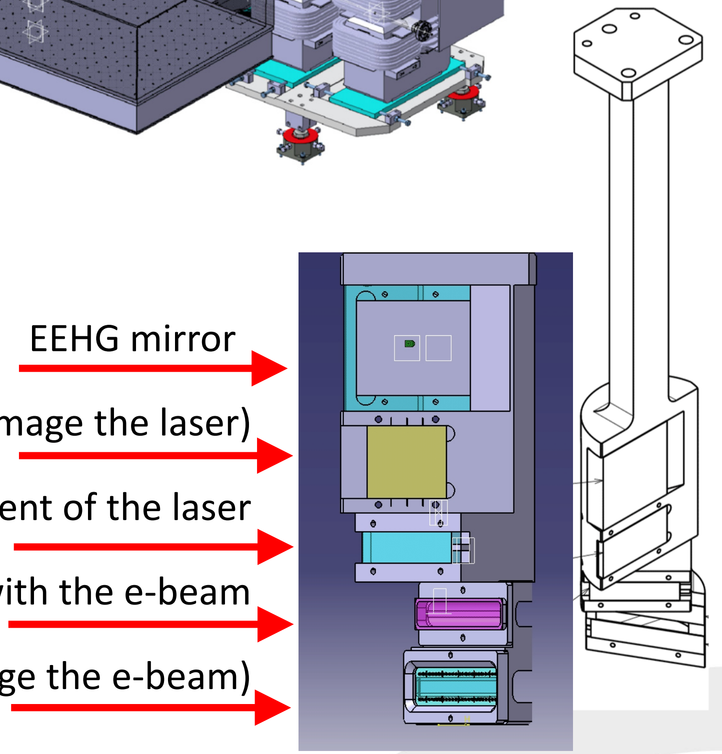
Hardware modifications

Second seed laser: IR pulse generated using the same oscillator as for the first seed and amplified by a separate stage (timing jitter between seeds below 5 fs).

Third harmonic generation was done on an optical table close to the undulator in the tunnel.

Given the limited dispersion of the delay line, EEHG required a relatively high energy per pulse (>20 μJ) at high harmonics.





Injection and diagnostics: manipulator with an in-vacuum mirror and several laser and e-beam diagnostic screens installed in the delay-line chicane.

Signature of EEHG: FEL intensity and spectra as a function of the (second) dispersive strength

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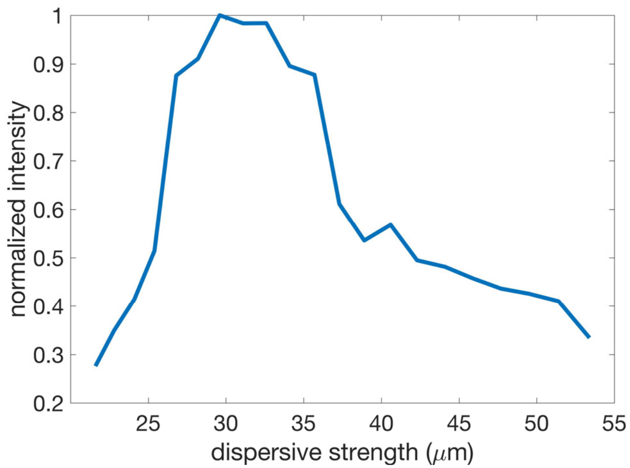
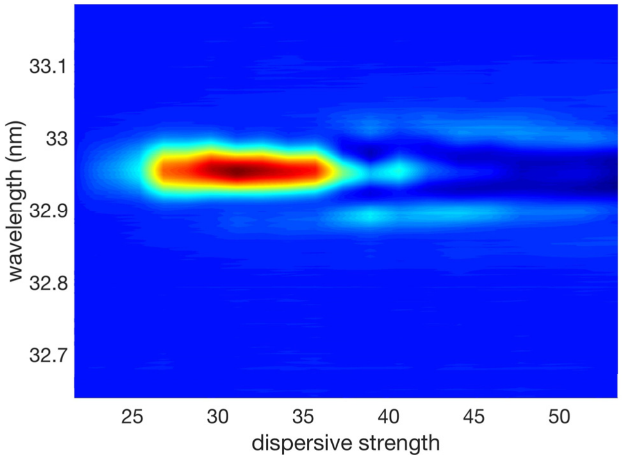
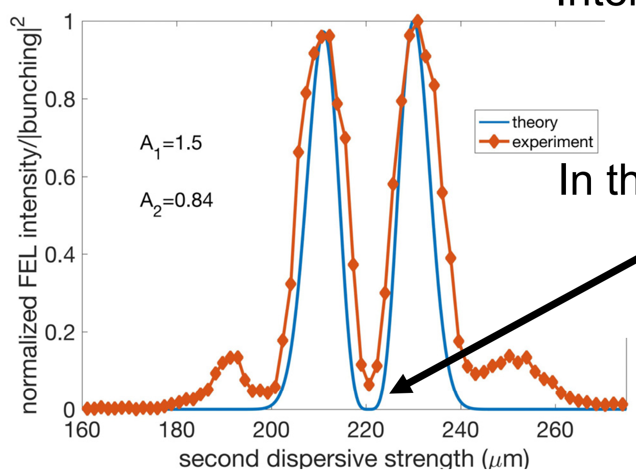
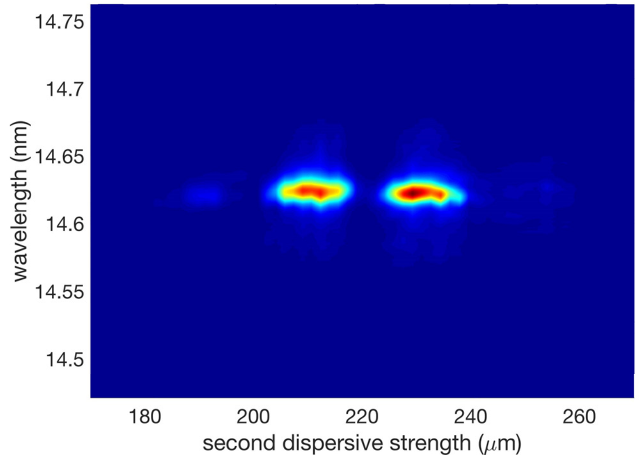
HGHG





EEHG



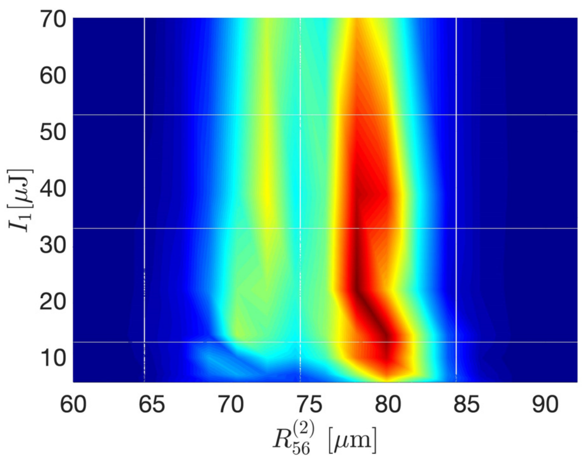


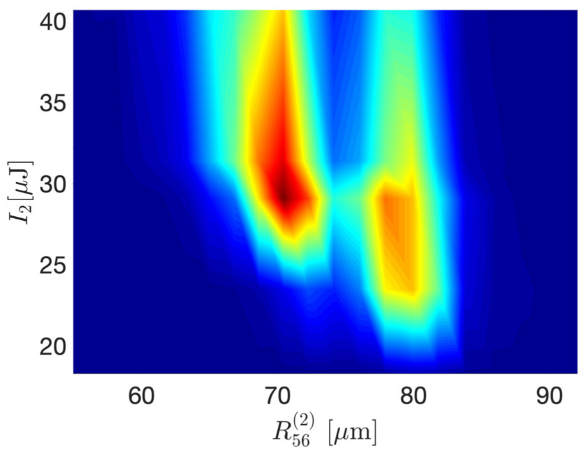
Intensity minimum occurs at $|n|\frac{R56_1}{h}$

In this case: $2 \times \frac{2000\ \mu\text{m}}{18} = 222\ \mu\text{m}$

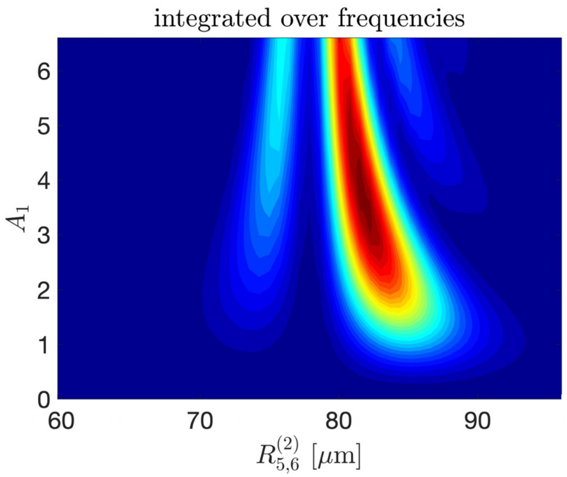
Comparison with theory: n=-1

Intensity vs. A1/A2 and 2nd R56: experiment



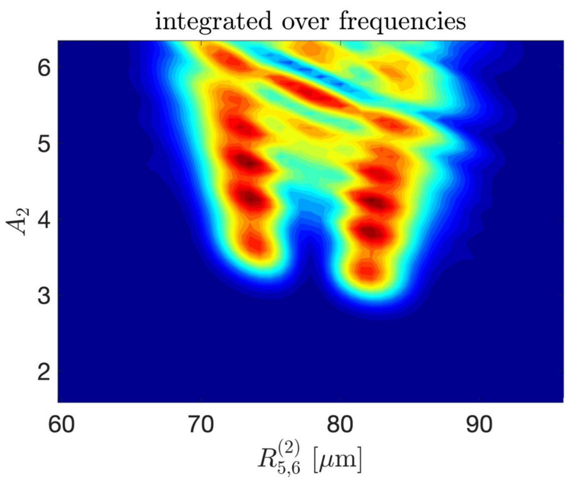


Intensity vs. A1/A2 and 2nd R56: theory (bunching)



A2=3.3

$\sigma_E = 200$ keV

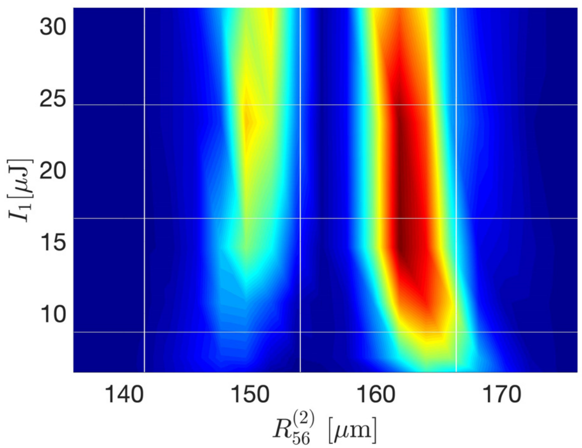


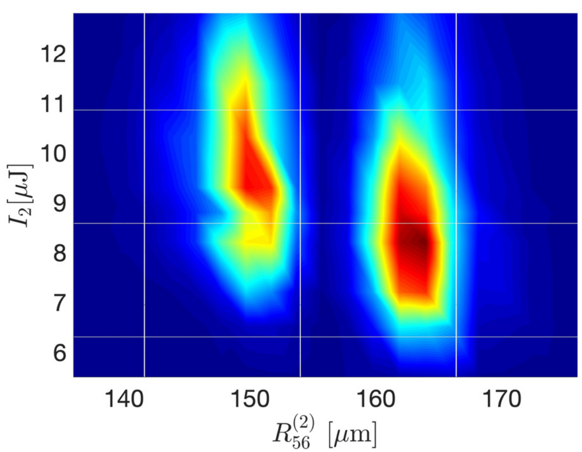
A1=3.0

$\sigma_E = 200$ keV

Comparison with theory: n=-2

Intensity vs. A1/A2 and 2nd R56: experiment





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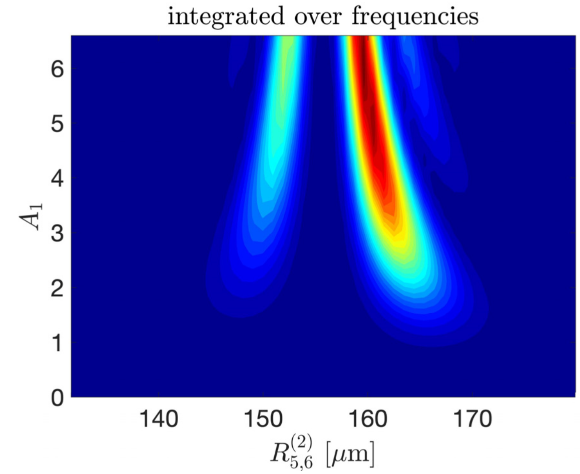
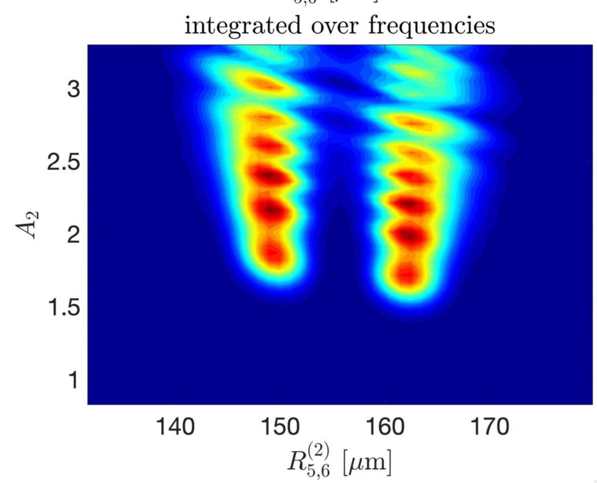


A2=1.6

$\sigma_E = 200$ keV



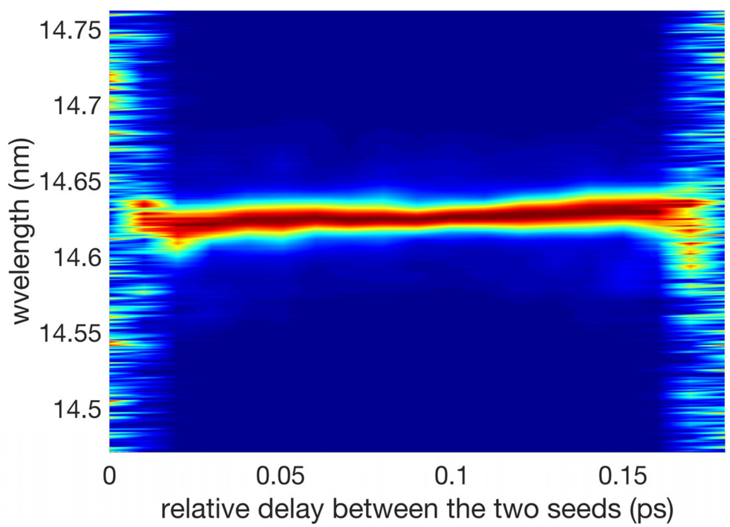
A1=3.3

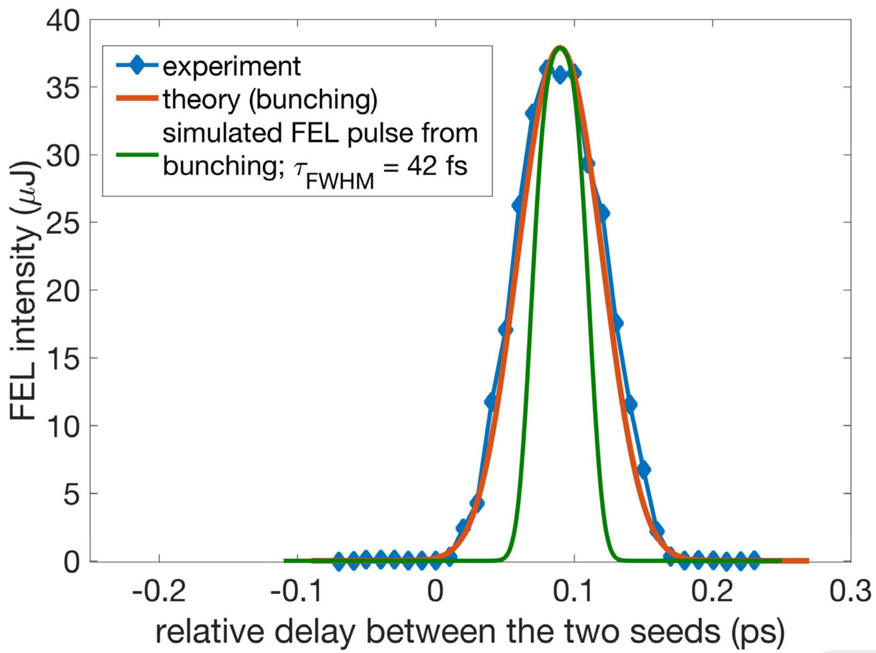
$\sigma_E = 200$ keV

Information on the pulse duration in EEHG

FEL spectra (h=18) and intensity as a function of relative delay between the two seeds:

$R56_1 = 2\text{ mm}$, n = -2

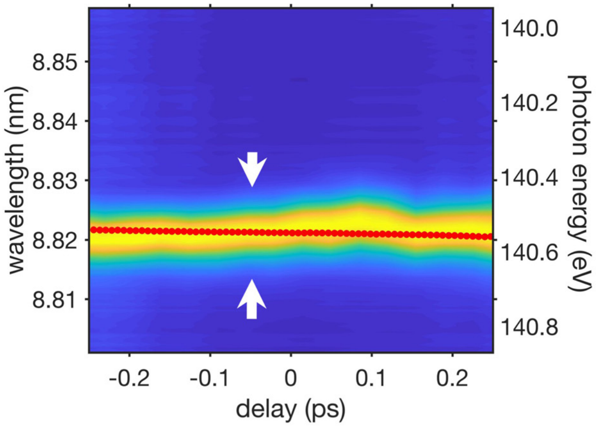


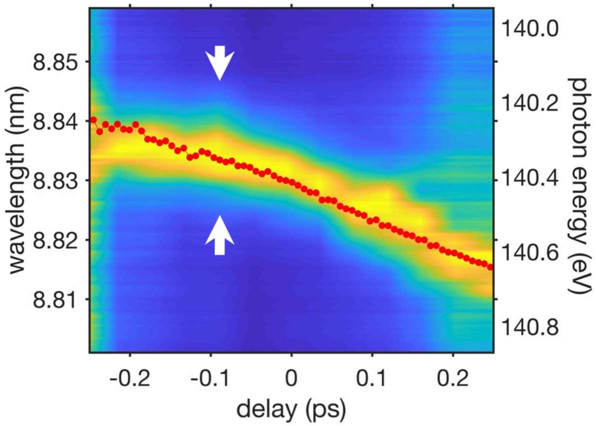


Sensitivity to e-beam properties, h=30

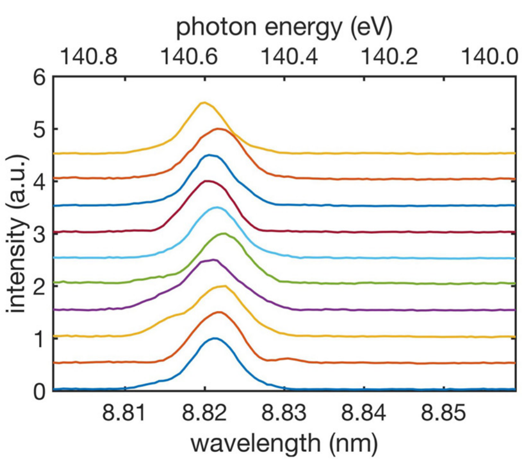
EEHG vs. HGHG: spectrum as a function of delay between the seed(s) and e-beam:

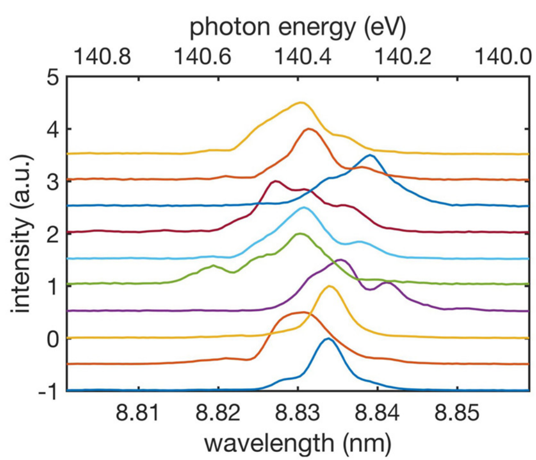
Phase near k_{EEHG} : $\Delta\psi = -k_{EEHG}\left(R_{56}^{(2)} + \frac{n}{h}R_{56}^{(1)}\right)\frac{dE}{E} \;\Rightarrow\; \frac{d\lambda}{\lambda} \approx \frac{1}{E}\left(R_{56}^{(2)} + \frac{n}{h}R_{56}^{(1)}\right)\frac{dE}{dz}$



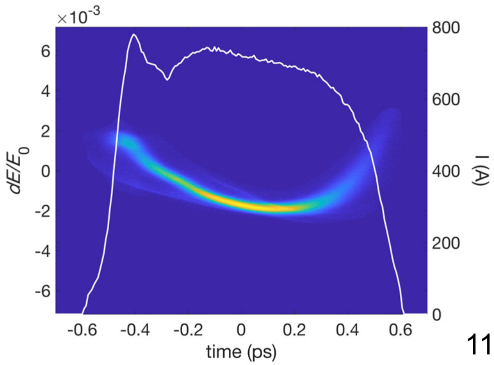


EEHG works close to the condition $R_{56}^{(2)} = \frac{|n|}{h}R_{56}^{(1)}$, with $n < 0$, leading to a near cancellation of the terms in the brackets!





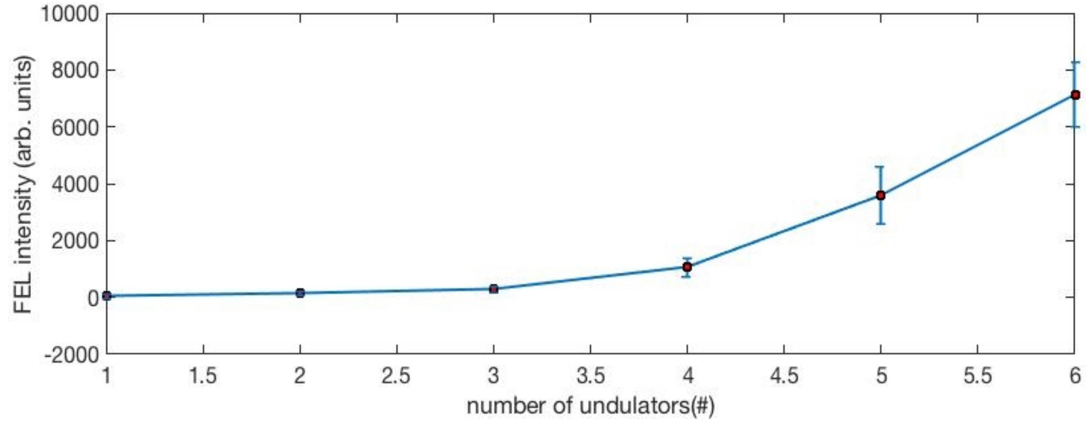
E-beam phase space:



Amplification of EEHG

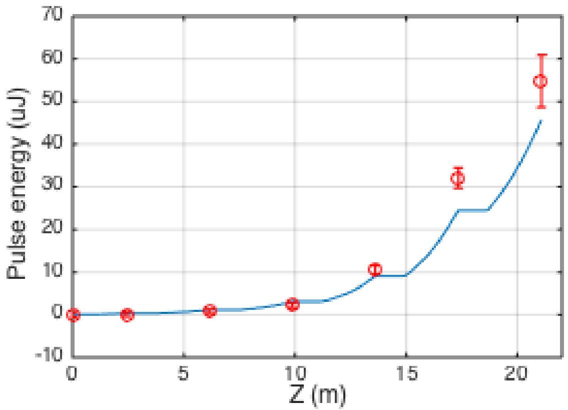
EEHG bunching at high harmonics is limited to less than 10%.

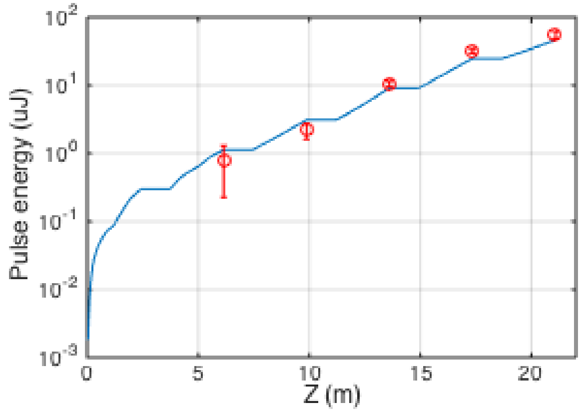
Generation of usable radiation in the soft-x-ray region critically depends on the exponential growth of FEL radiation in the long radiator.



For the first time amplification of EEHG was measured and characterized down to ~5nm.

Experimental exponential growth rate matches results of numerical simulations.





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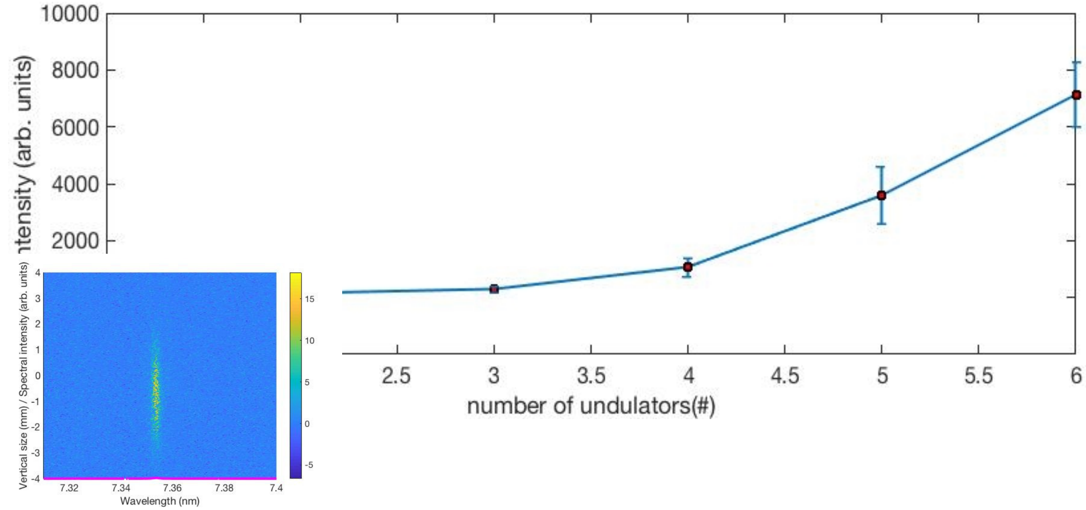

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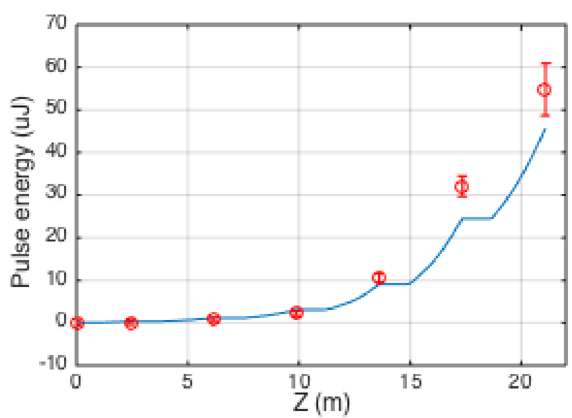

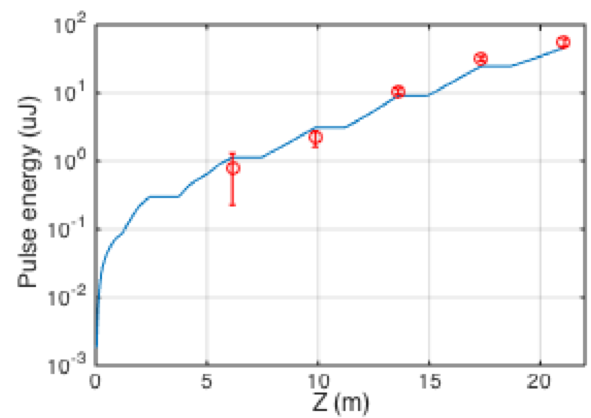

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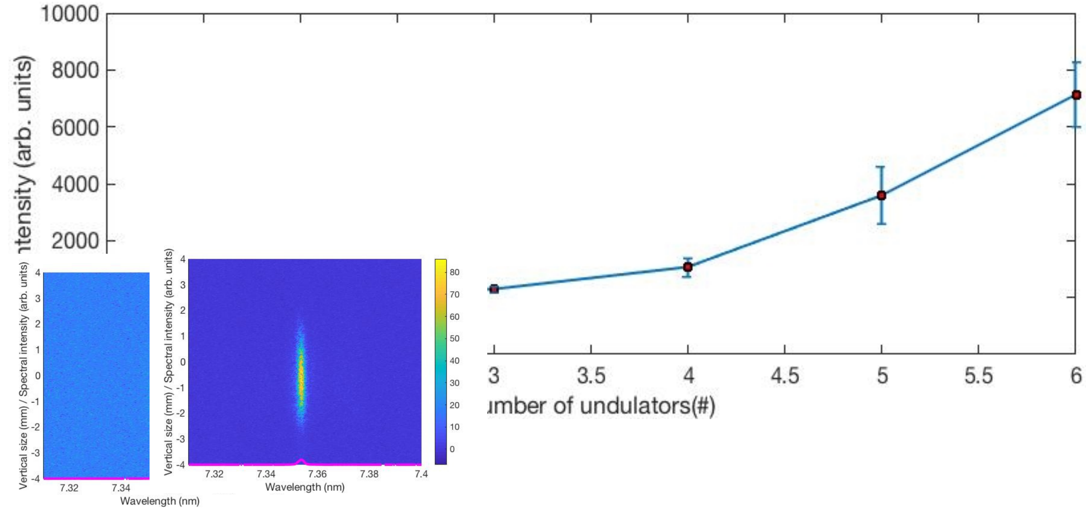

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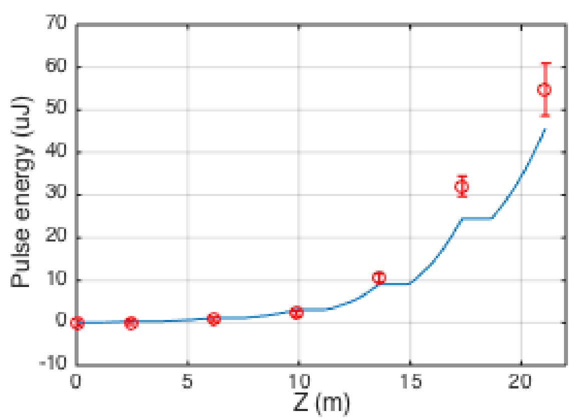

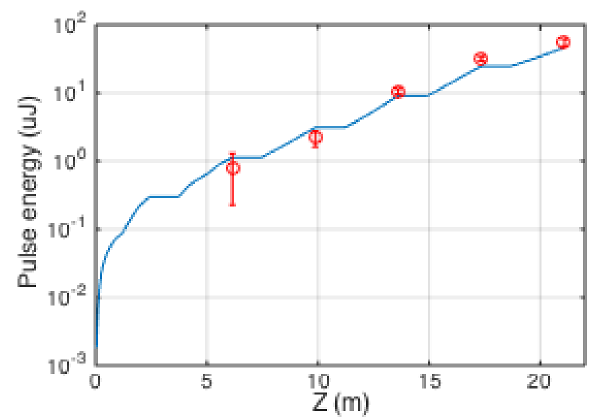

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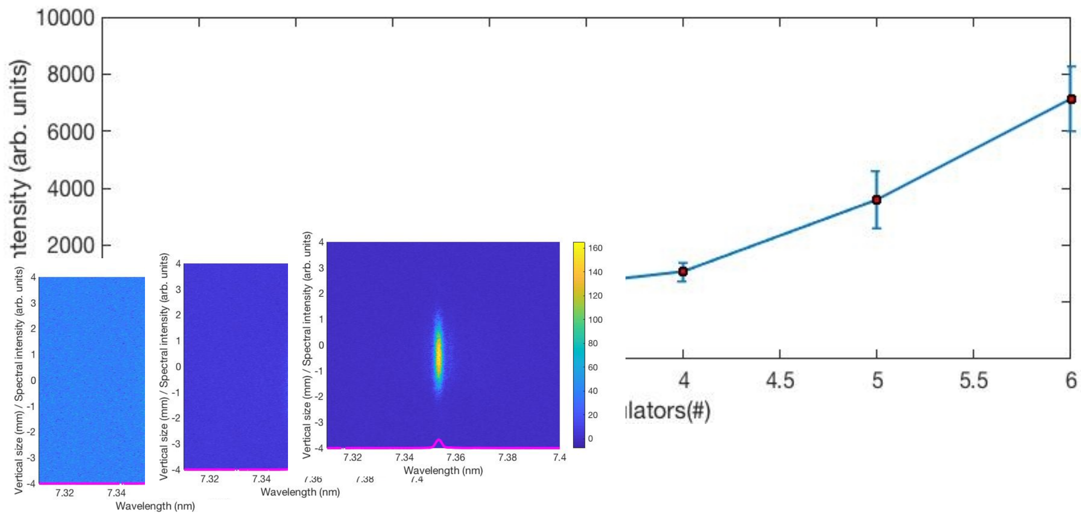

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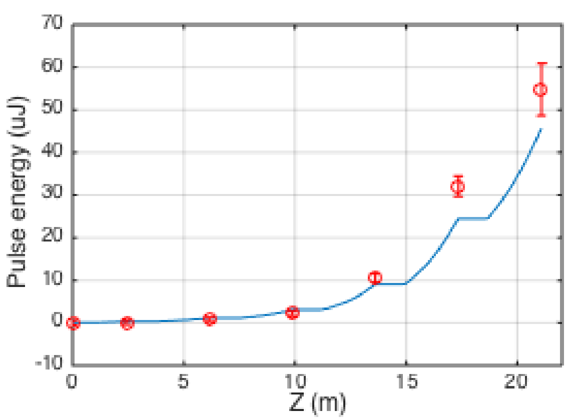

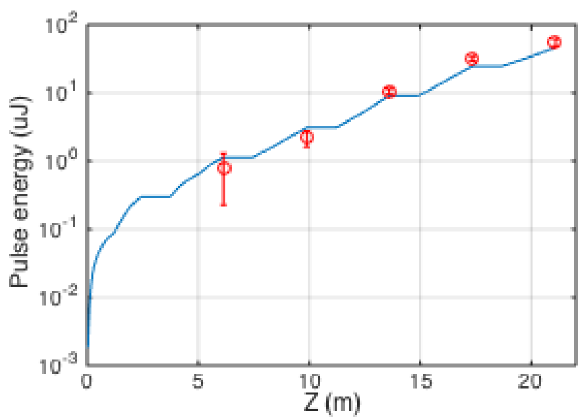

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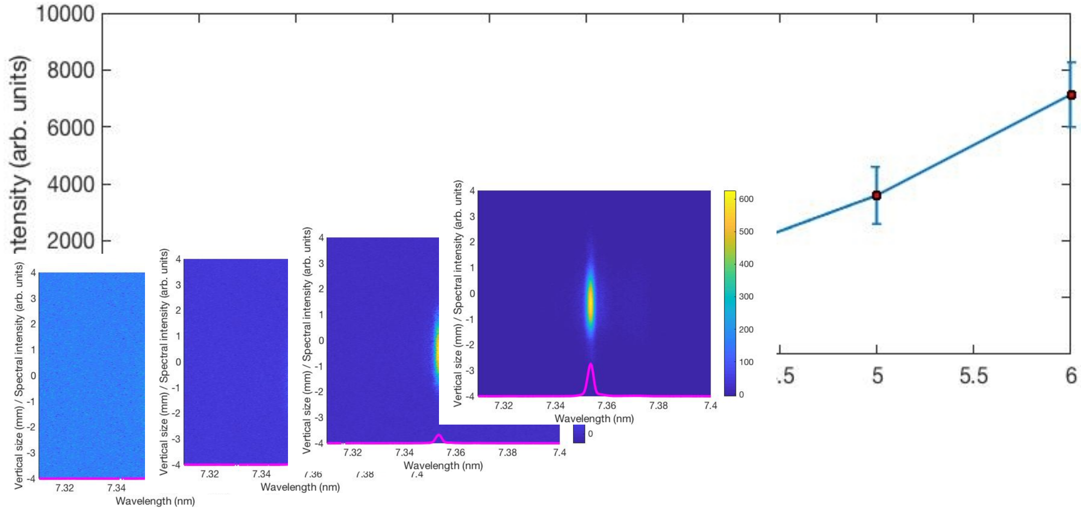

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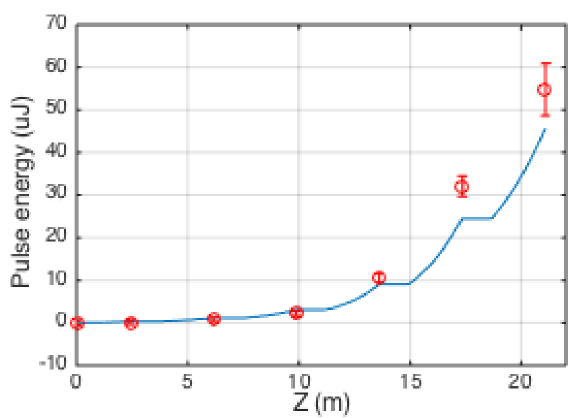

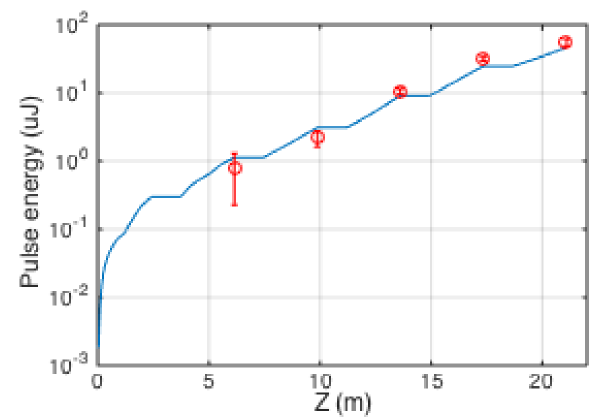

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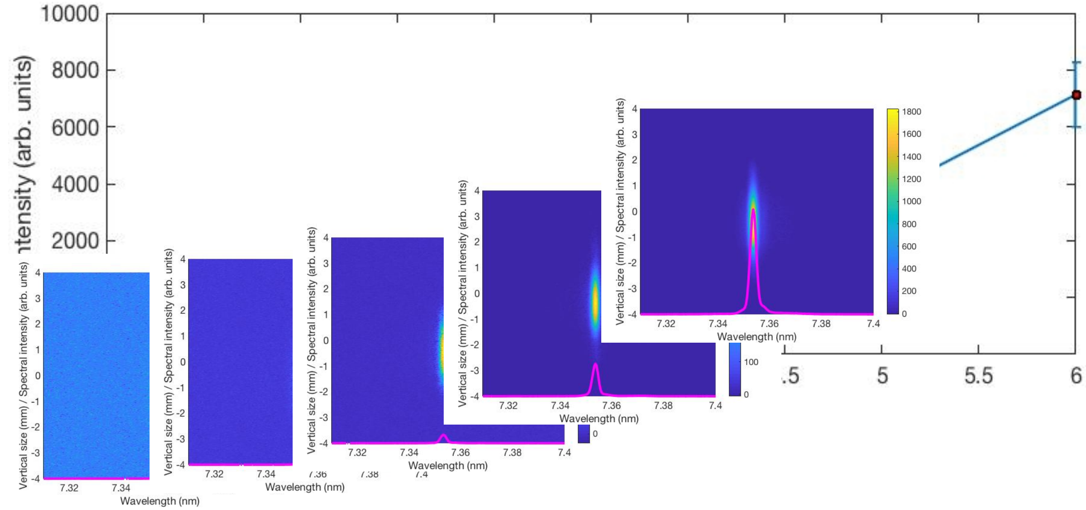

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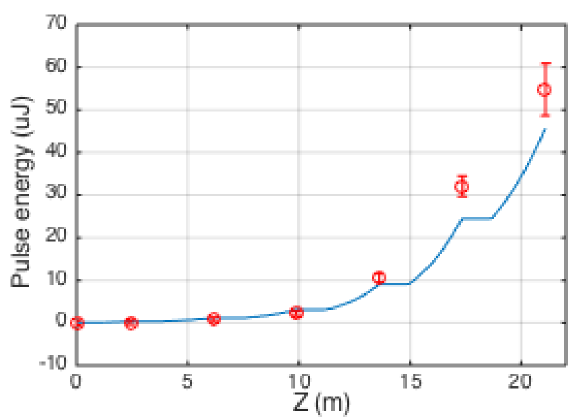

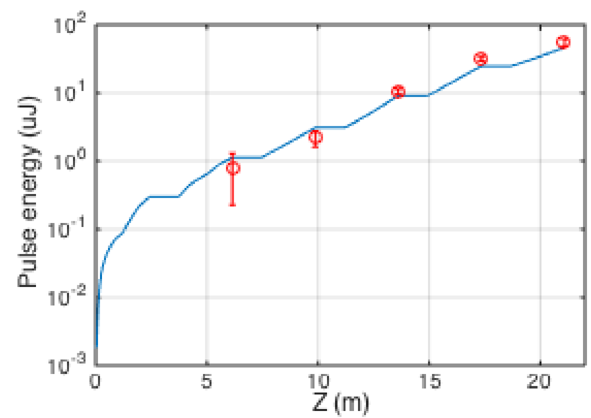

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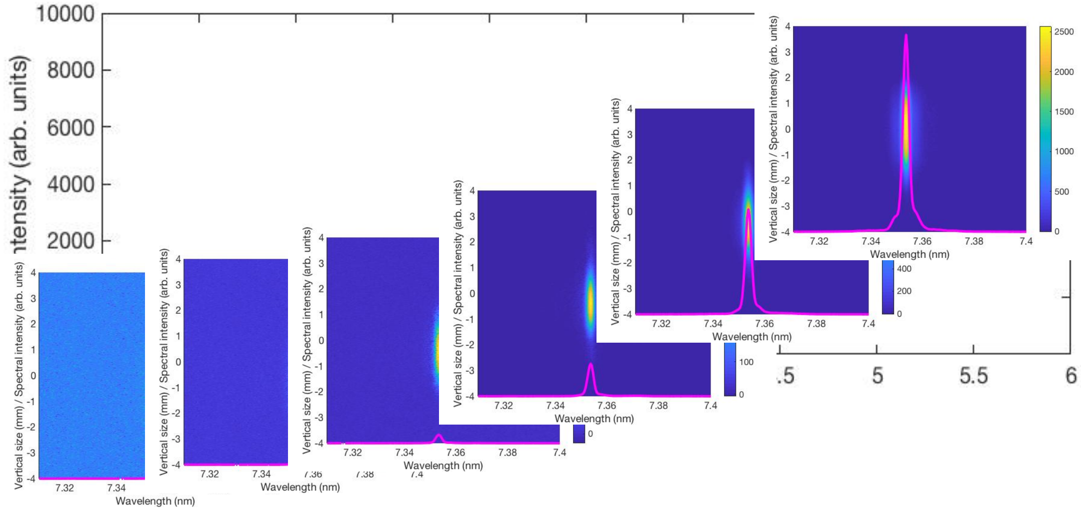

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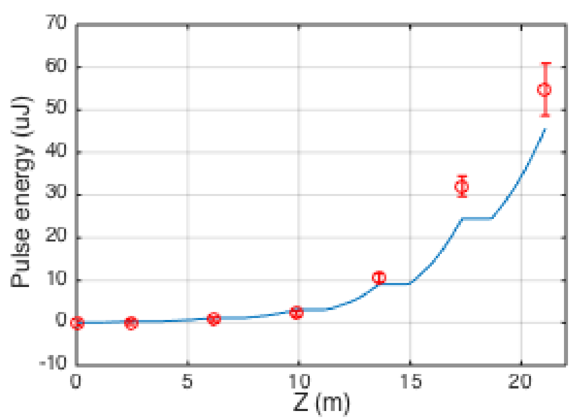
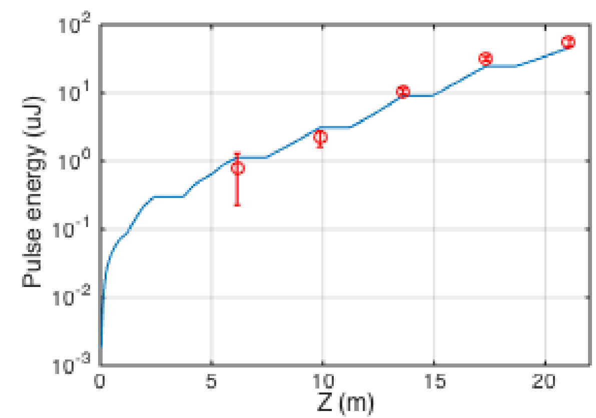
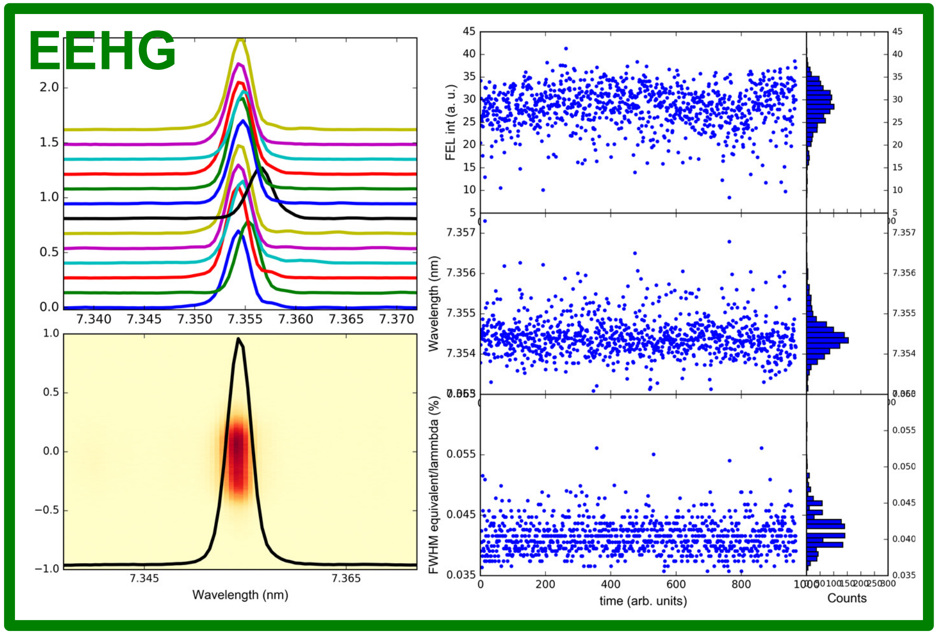
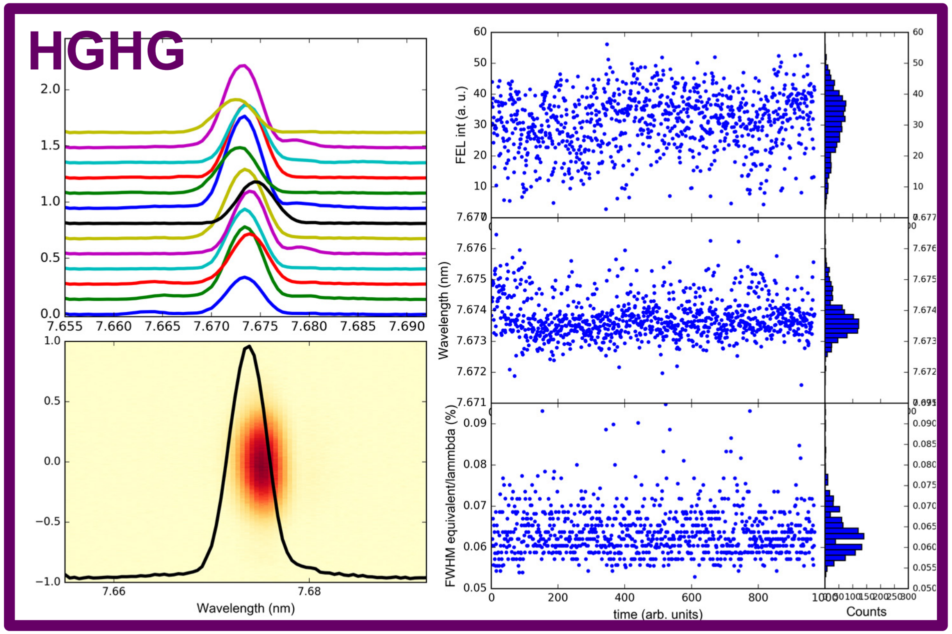




EEHG at h = 36 (7.3 nm)

Best EEHG vs. ”some of the best” HGHG-FB (not the same e-beam nor seed laser):





In both cases FEL optimized for clean spectra.

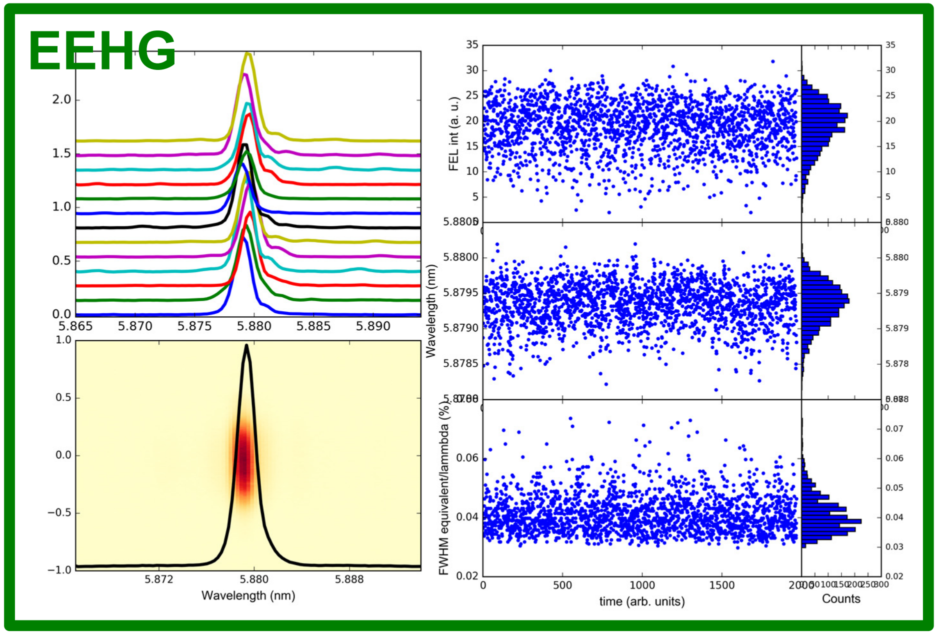
Standard FWHM spectral width might be related to slightly different seed laser pulses.

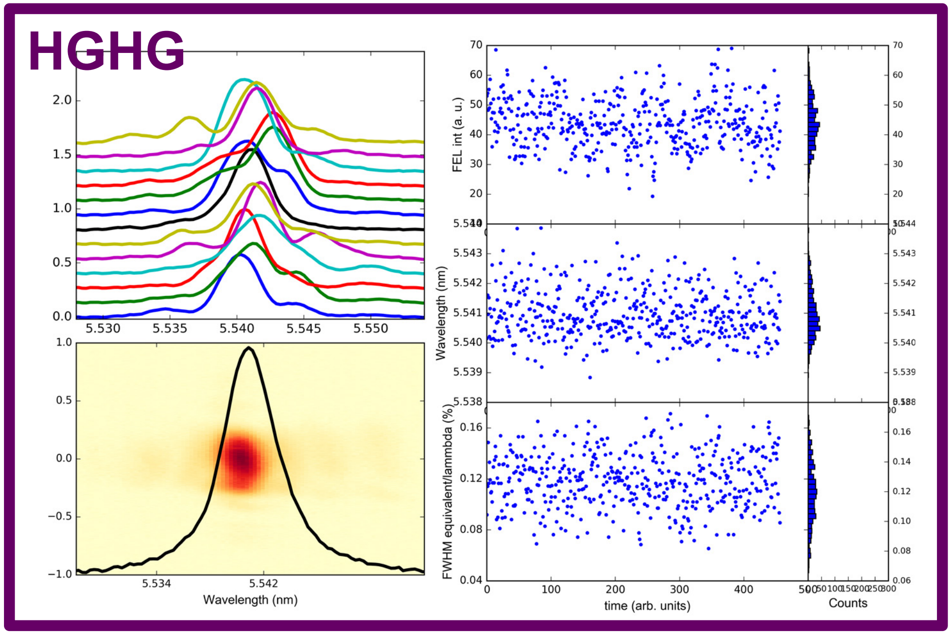
FWHM equivalent (width containing 76% of the energy) is affected by sidebands that are more evident in HGHG.

Spectral reproducibility is higher in EEHG.

EEHG at h = 45 (5.9 nm)

Best EEHG vs. ”some of the best” HGHG-FB (not the same e-beam nor seed laser):





The difference is more pronounced at higher harmonics.

For HGHG cleaner spectra can generally be obtained by reducing the overall FEL intensity.

At harmonics ~45 also EEHG starts to show some structures in the spectrum.

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Qualitative comparison between EEHG and HGHG

Best EEHG vs. “some of the best” HGHG-FB:

	EEHG 36		HGHG 34		EEHG 45		HGHG 48	
	mean	sigma	mean	sigma	mean	sigma	mean	sigma
Photon energy (eV)	168,584	0,012	161,568	0,015	210,879	0,014	223,755	0,027
Spectral FWHM (meV)	60,5	2,2	90,9	5,1	59,4	3,4	172,3	55,3
Spectral FWHM equivalent (meV)	70,0	4,9	103,7	21,3	88,2	23,9	271,8	56,1

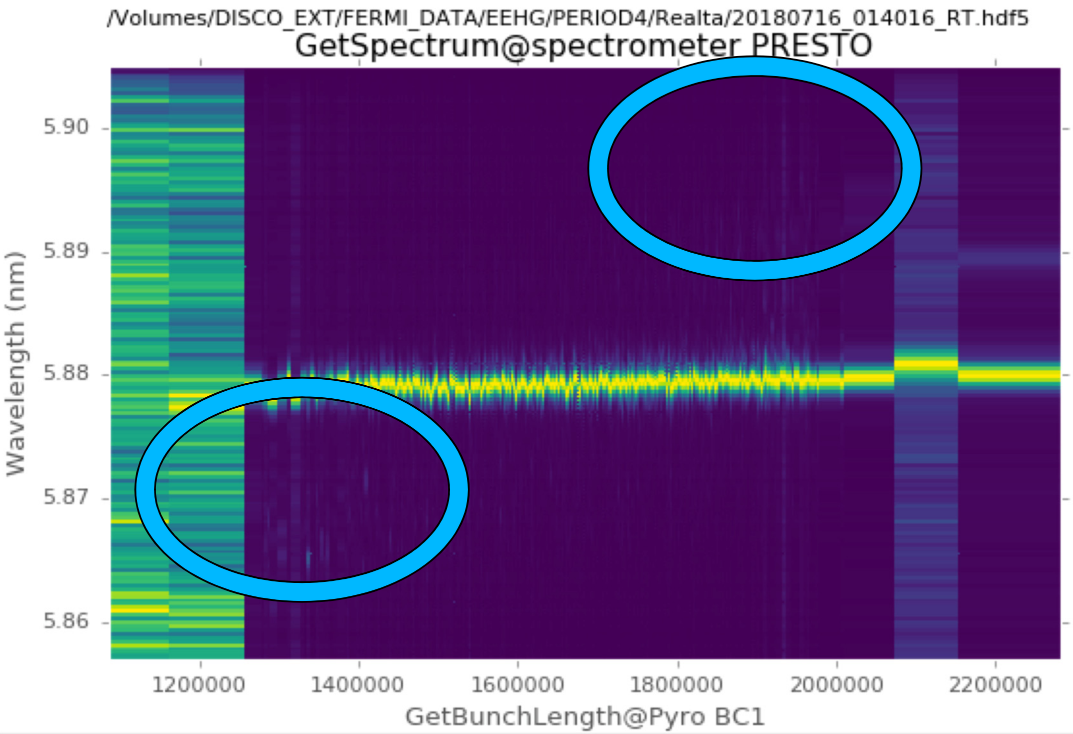
Standard FWHM.

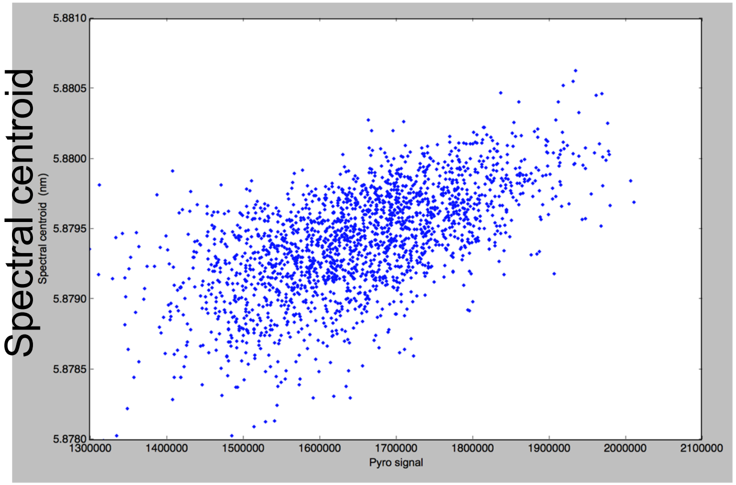
Affected by strong sidebands due to microbunching instability.

Defined as the FWHM containing 76% of energy. For a Gaussian beam, this is equivalent to the standard FWHM.

EEHG at high harmonics

It is important to identify the origin of sidebands: problems might come from the phase noise of the seed laser that is frequency multiplied and could deteriorate the FEL coherence; however…

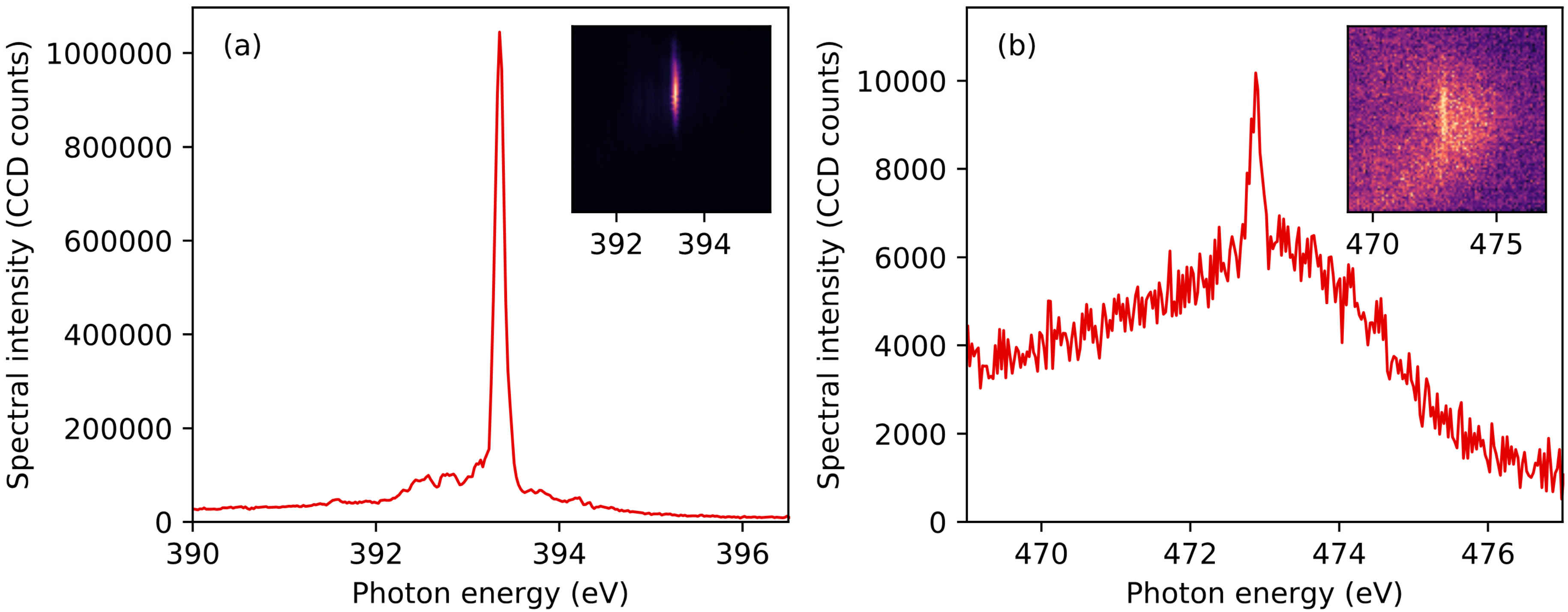




…our results show that EEHG sidebands are correlated with e-beam properties suggesting that up to h = 45 laser phase noise is not relevant.

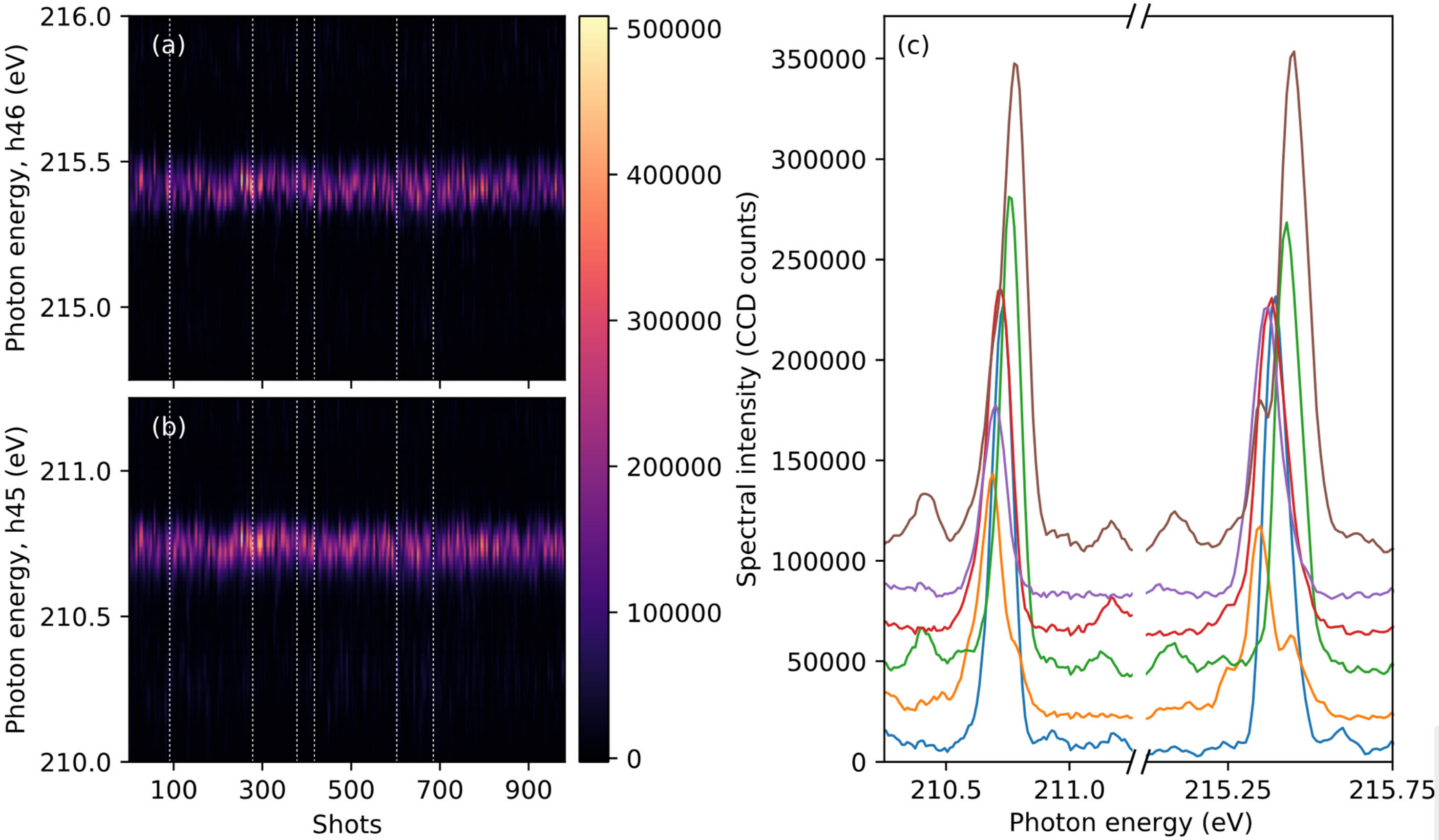
EEHG at very high harmonics

Coherent emission at h = 84 and h = 101:



Two-color emission

Split-undulator scheme, two-color emission at neighboring harmonics:



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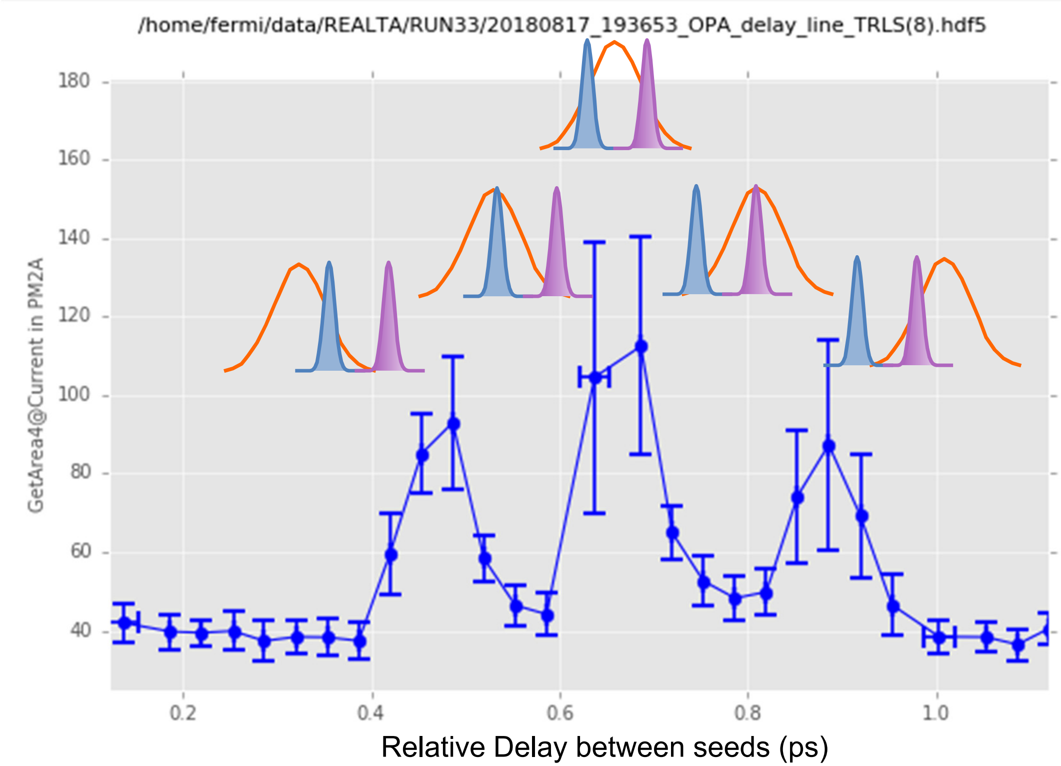
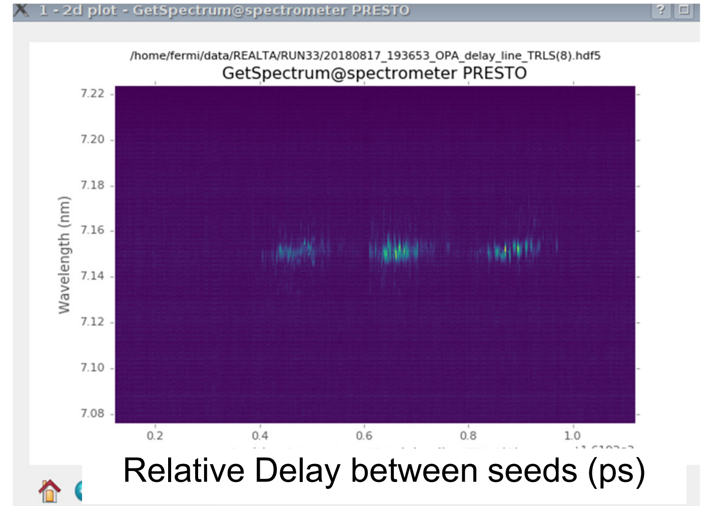
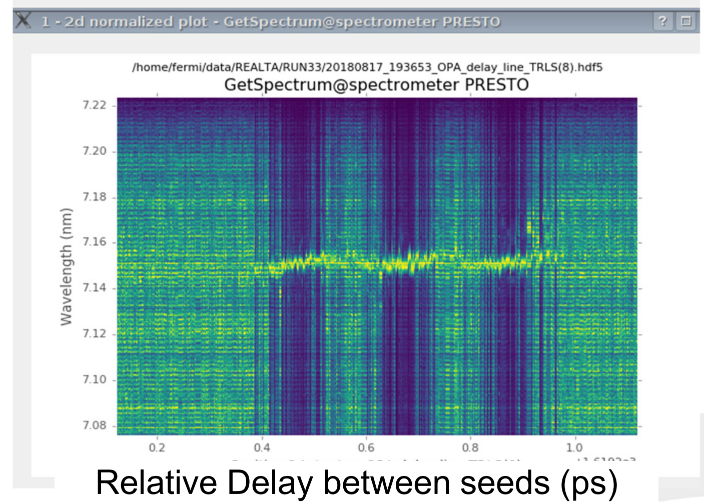
Two pulses

A twin laser pulse was used as the 2nd seed in combination with a long 1st seed laser pulse for double-pulse EEHG operation.







Increasing the first seed intensity suppresses single-pulse emission; this occurs when one of the twin pulses is perfectly overlapped with the first seed.

Two-pulse FEL emission is observed when one or both twin pulses are aligned on the tails of the first seed.

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Conclusions

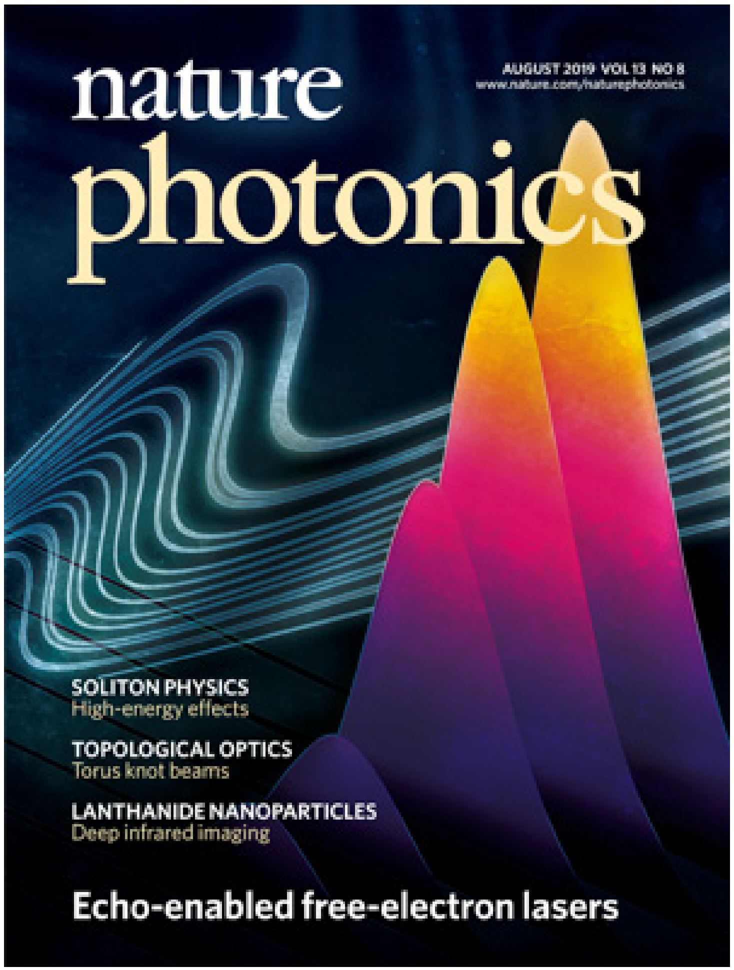
CURRENT CAPABILITIES:

1. EEHG bunching up to h = 101
2. amplification (gain) at harmonics as high as 45 (5.9 nm)
3. EEHG is less sensitive to ebeam properties and therefore shows better performance in terms of spectral quality and stability compared to HGHG-FB
4. demonstrated two-color and two-pulse operation

EXTENSION TO SHORTER WAVELENGTHS:

1. lower bunching in EEHG compared to HGHG-FB requires strong exponential amplification
2. signs that ebeam imperfections might deteriorate the spectrum at wavelengths < 5 nm
3. these problems might be overcome with a more flexible setup (stronger first chicane, more radiators), more studies needed

*The EEHG collaboration



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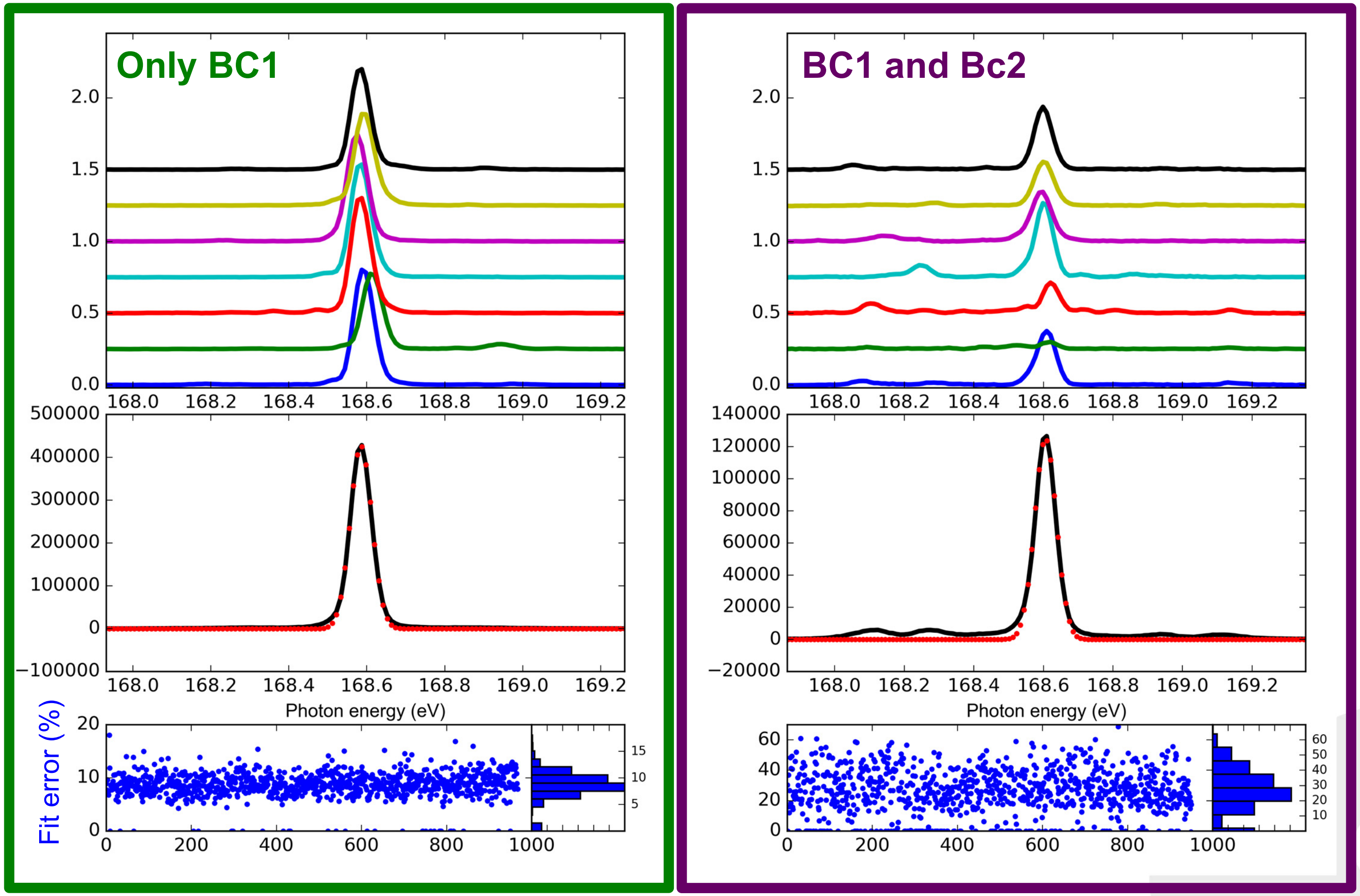
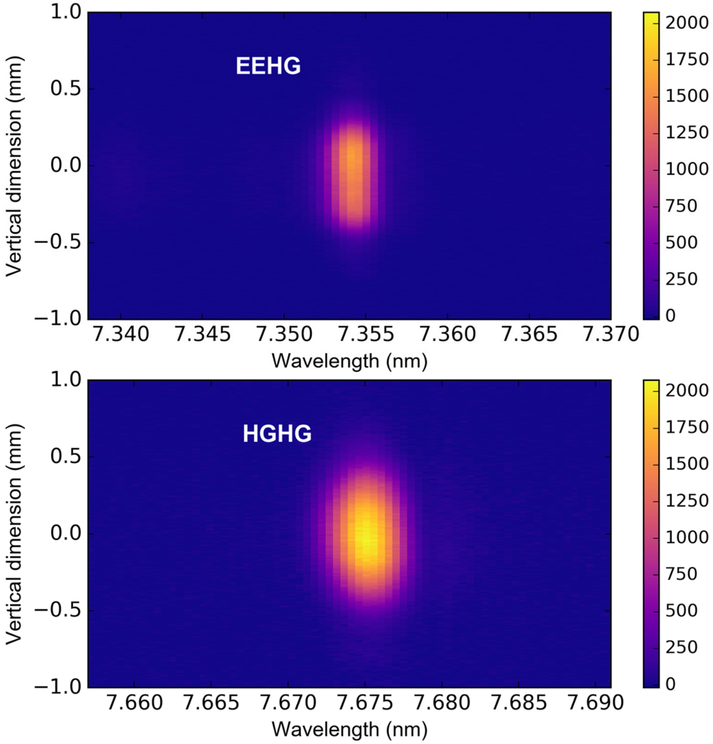
EEHG at high harmonics

Single vs. 2 bunch compressors (left column): structured spectrum at high harmonics a consequence of e-beam properties (and not seed laser phase errors).

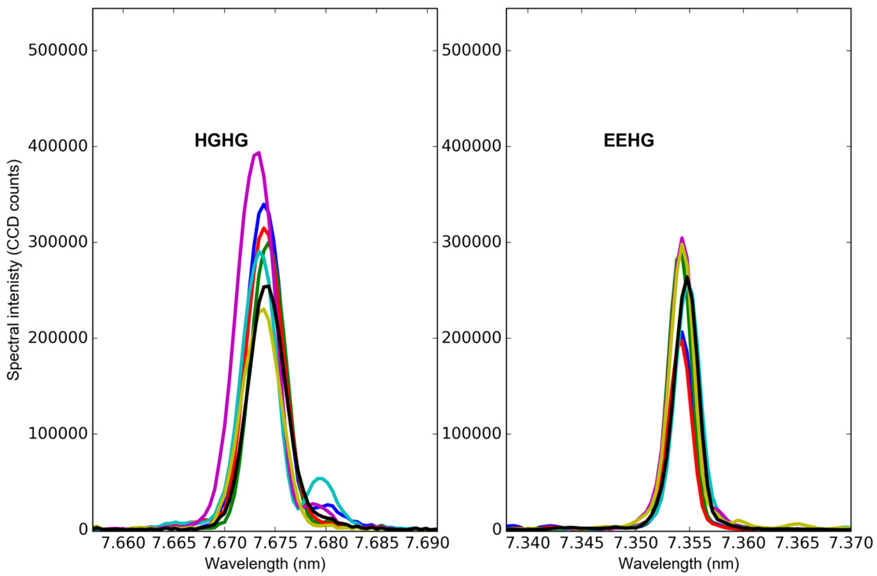


EEHG pulse energies

Measurements with calibrated diagnostics (photodiode, CCDs) **suggests** that **~20μJ** per pulse are generated at **~7nm**.



At 7.3 nm direct comparison of the PRESTO CCD intensity from the **best EEHG** results and a **good FEL** from **HGHG** shows a **similar level** of intensity.



Relaxing requirements on **spectral purity**, **HGHG** can generally provide **more energy** per pulse.

In **our conditions**, at **shorter wavelengths HGHG** provides **higher energy** per pulse due to the higher flexibility in maximizing bunching (stronger seed).

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EEHG vs. HGHG-FB

	EEHG	HGHG-FB
Operability	Requests in terms of e-beam quality are relaxed; **strongly relies on FEL amplification**: optimal e-beam trajectory control is crucial.	Needs to accommodate first and second stage FEL pulses: **stringent requirements in terms of e-beam phase space**.
Spectral purity	**Easy up to H50**; good indications for H >50 but needs more studies. **Fourier limited** pulses **several hundreds of fs** long appear to be **possible.**	Possible for reduced power, **at ~4 nm μB start to be critical**. **Sensitivity to e-beam** and uB suggests that seed laser **~100 fs long** is the **best** working point **for spectral purity**.
FEL intensity	When **sustained** by **gain comparable** to HGHG-FB.	For **limited FEL amplification**, strong seeding allows higher bunching and partially **recover FEL power**.
Two colors similar energy	**Two colors** with **few eV energy separation** is possible.	**Minimum** wavelength **separation** is **few tens of eV** (first stage).
Two color wide separation	A **factor two** wavelength **separation** is **plausible**.	**Large** wavelength **separation** (>x4) can be achieved with **first and second stage**.
Signal at nearby harmonics	A **contamination** ($\sim 10^{-3}$) signal could be generated at the harmonics close to the requested one (**few eV offset**).	A contamination ($\sim 10^{-3}$) signal could be generated at the harmonics close to the requested (**few tens eV offset**).
Two pulses	Single stage allows using **two seeds on the same electron beam**.	Two stages does **not** easily **allow** to generate **two FEL pulses** at the final wavelength.
FEL wavelength tuning	**All harmonics** are **accessible**, limited seed laser wavelength tuning required.	**Only H = n*m** (m ideally = 3-5) are possible. Large tuning range of seed to allow full FEL tunability.