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Trieste

Amplified Emission of a Soft-X Ray Free-Electron Laser Based on Echo-Enabled Harmonic Generation

E. Allaria
on behalf of the **FERMI team**
and **EEHG collaboration**

Outline

FERMI Free-Electron Laser

- Spectral and temporal control
- Coherence and coherent control

EEHG at FERMI

- Evidence of EEHG
- FEL gain
- Spectral quality

Conclusions

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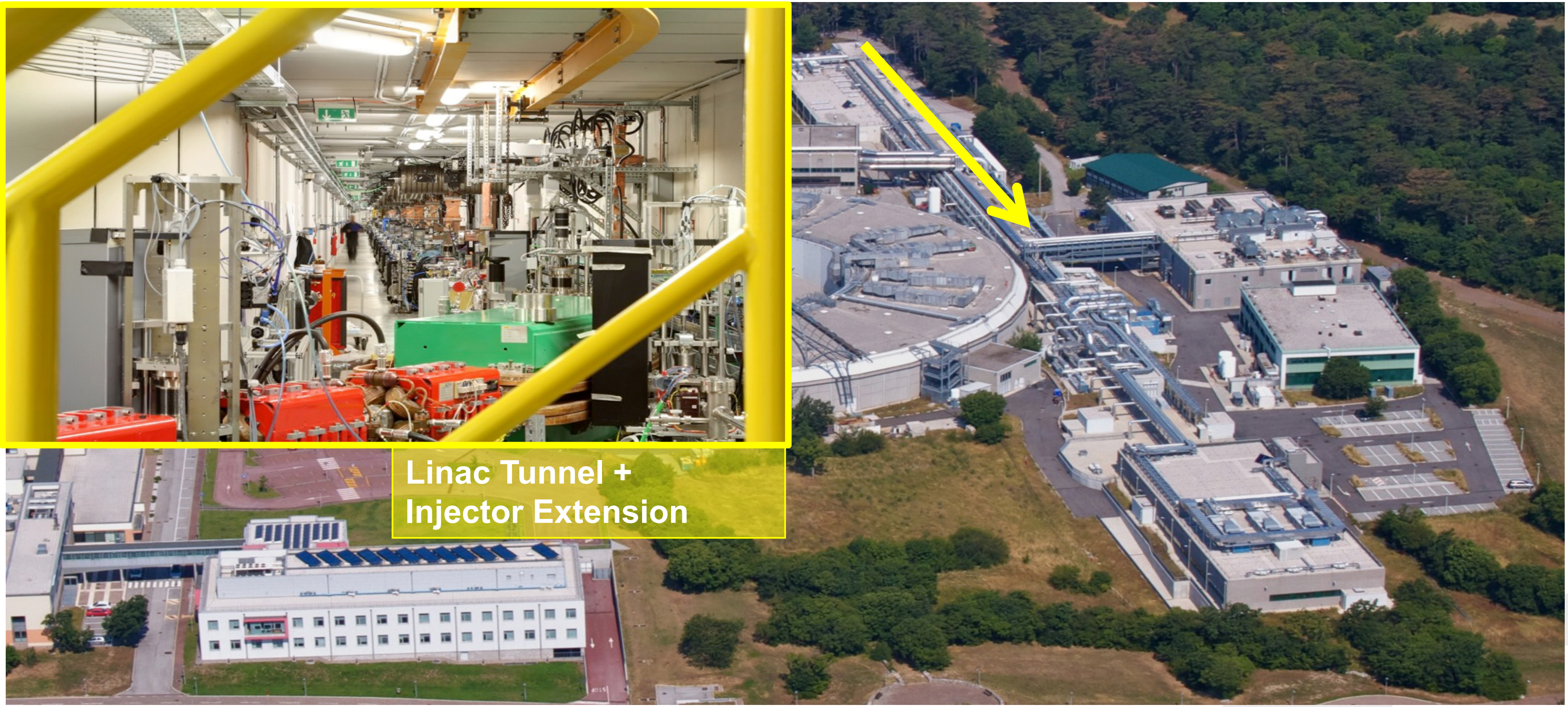
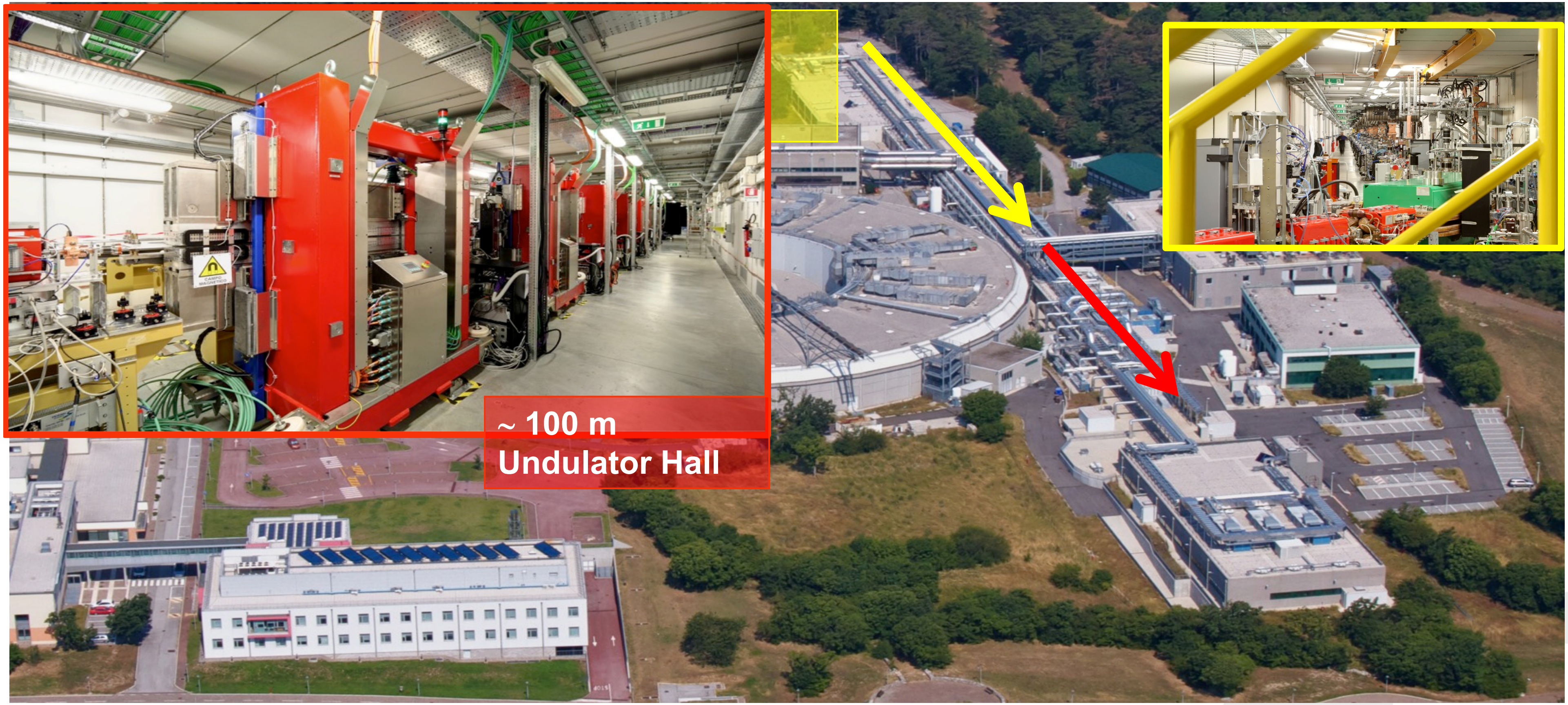
FERMI Free Electron Laser

FERMI Free Electron Laser



FERMI Free Electron Laser



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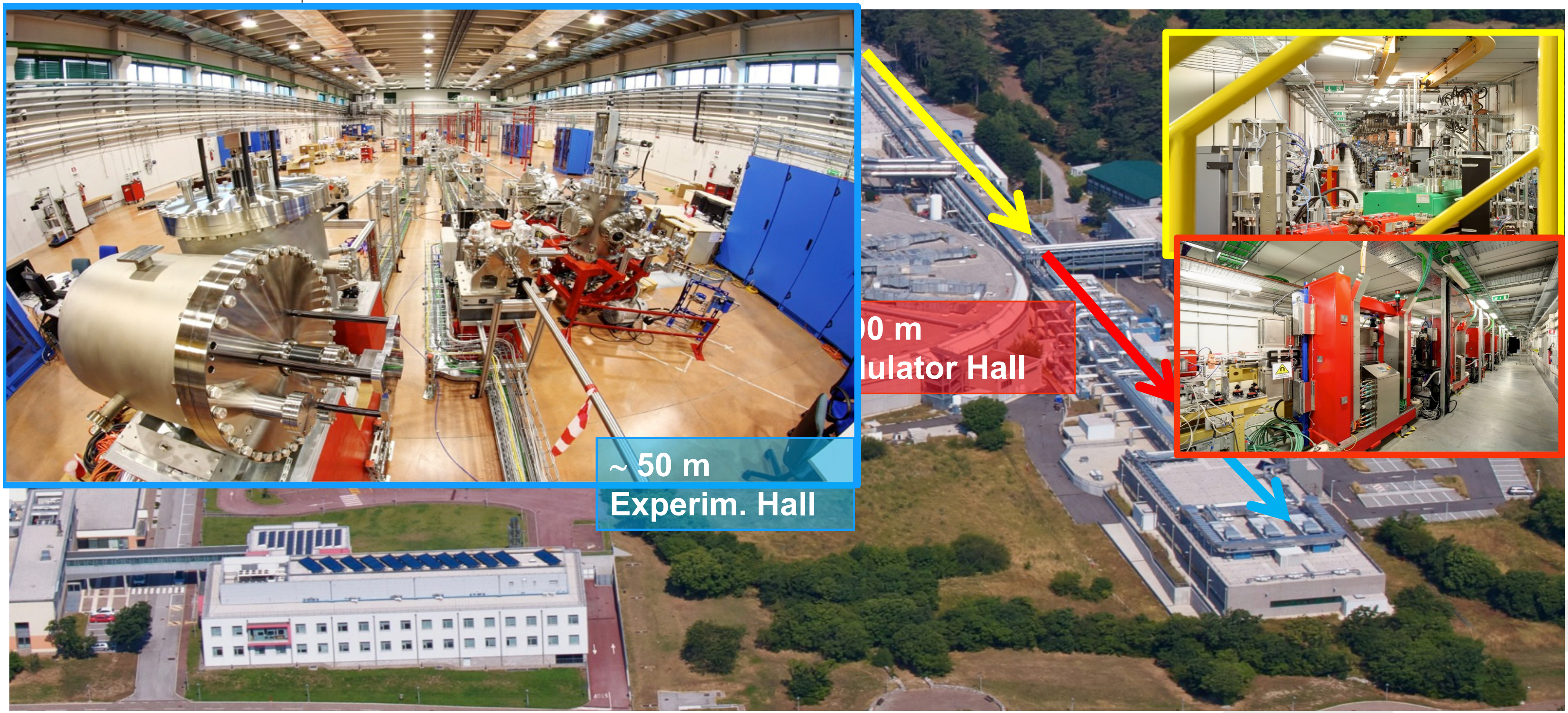

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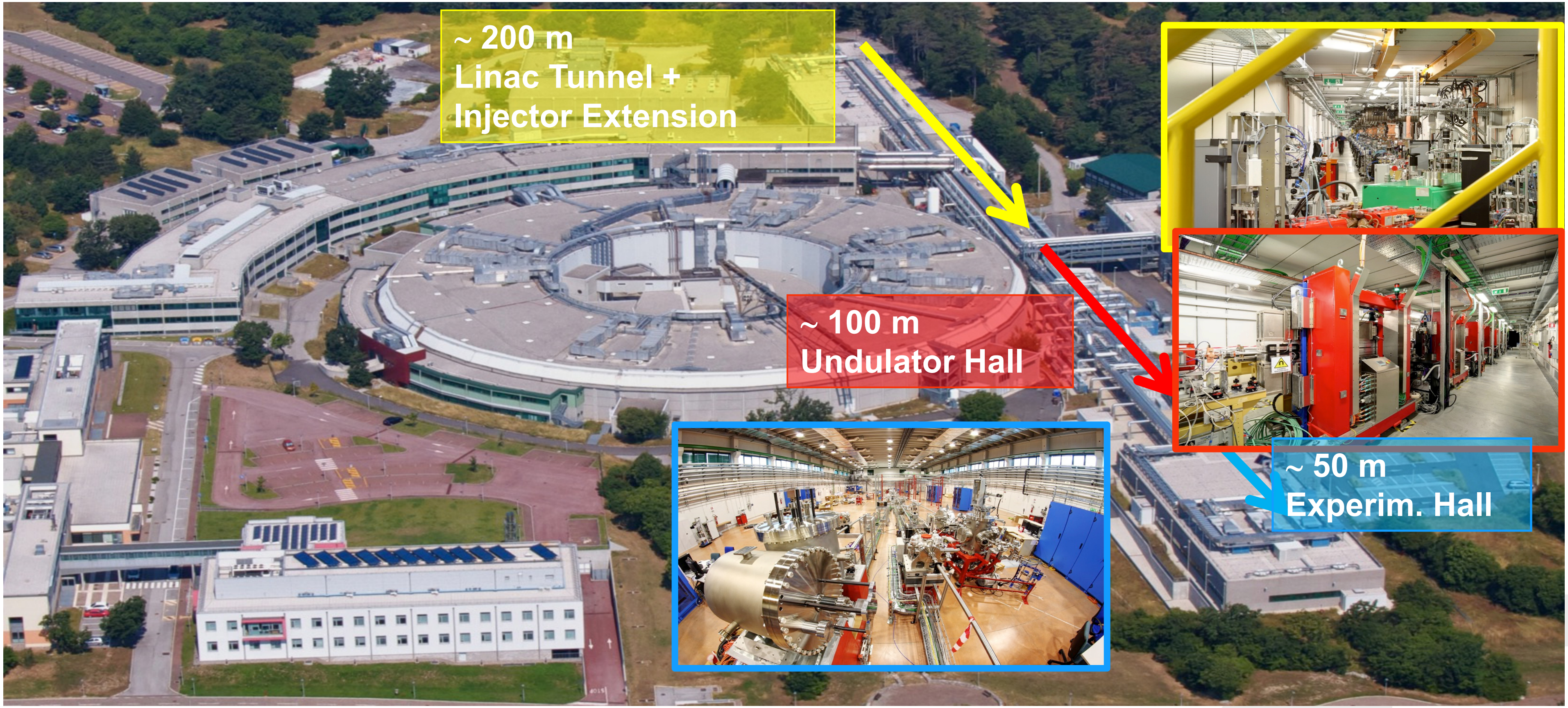
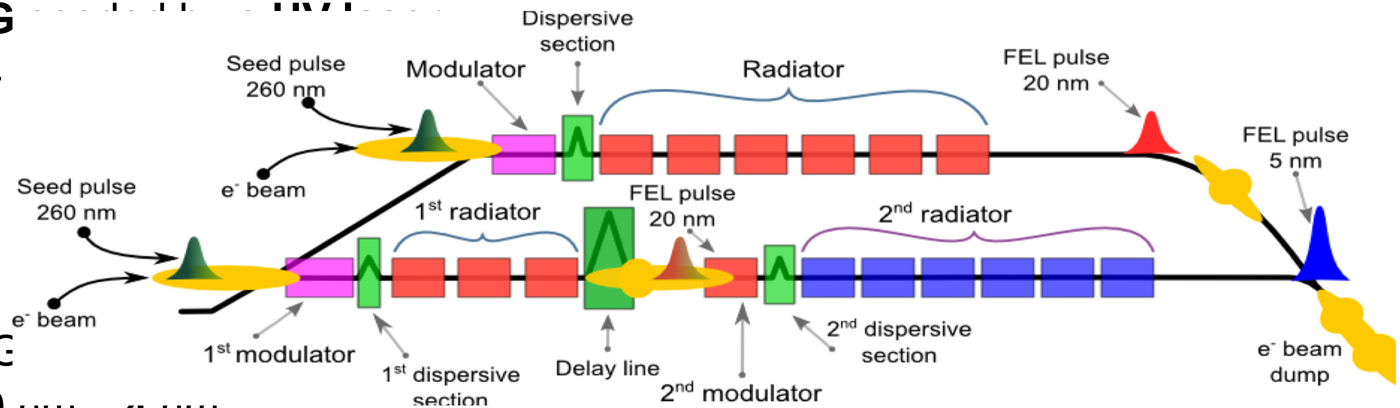


FERMI FELs: FEL-1 & FEL-2

FEL-1: **single** stage **HGHG**
covers the range **100** nm –



FEL-2: **double** cascade HG
to reach the wavelength **20** nm – 4 nm.

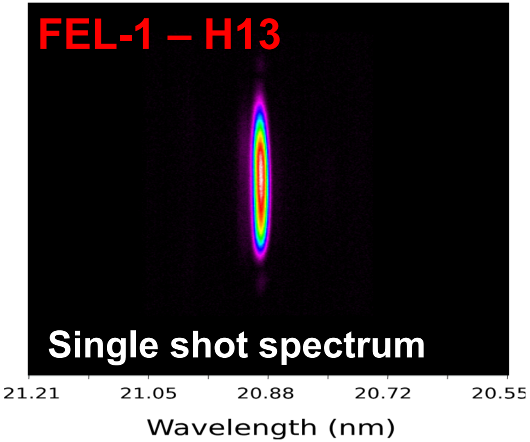
FEL-1 (Nat. Photon. **6**, 699 (2012))	
Tuning range	100-20 nm (12-60eV)
Relative bandwidth	1x10^{-3} (FWHM)
Pulse length	<100 fs
Pulse energy	20-100 μJ

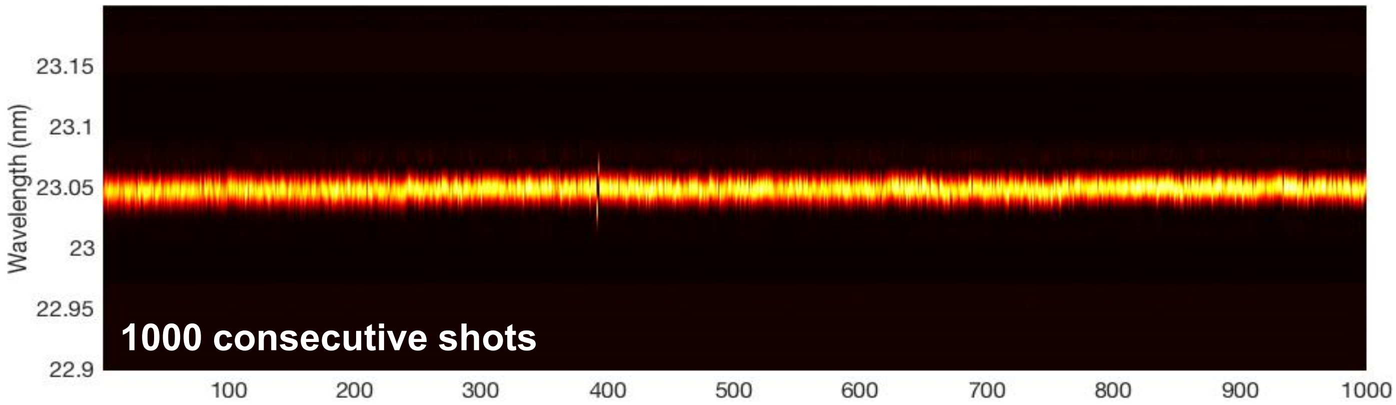
FEL-2 (Nat. Photon. **7**, 913 (2013), Journal of Synchrotron Radiation 22 (2015))	
Tuning range	20-4 nm (60-300eV)
Relative bandwidth	1x10^{-3} (FWHM)
Pulse length	~50 fs
Pulse energy	10-70μJ

Both FELs have APPLE-II undulators in the final radiator allowing **polarization control**.

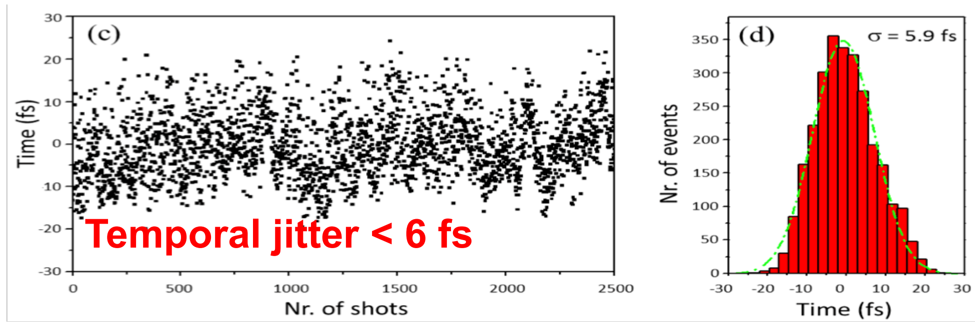
Spectral and temporal properties

Single spectral mode up to **H13 on FEL1** and **H65 on FEL2** (*linewidth ~ 2 10^{-4} rms, depending on wavelength & seed*). High wavelength stability set by the seed (10^{-5} rms)



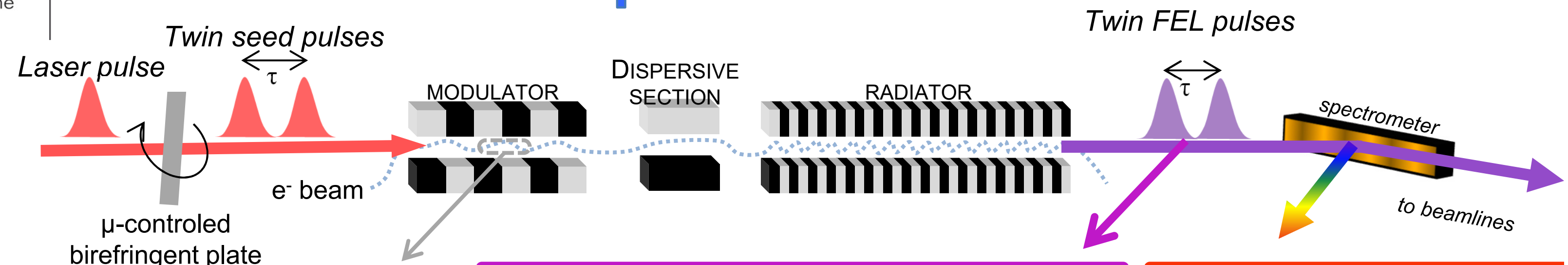


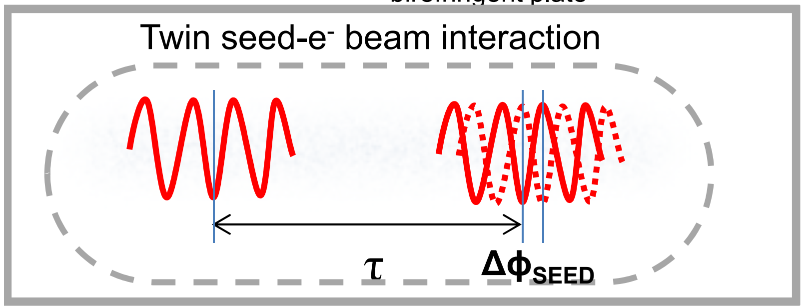
Thanks to the the seeding, the temporal **jitter** of the FEL with the **external laser** is very low.

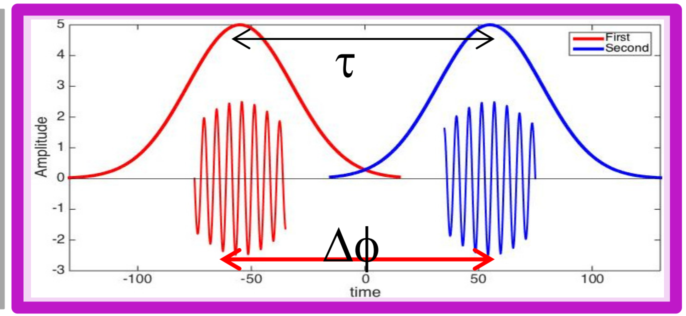


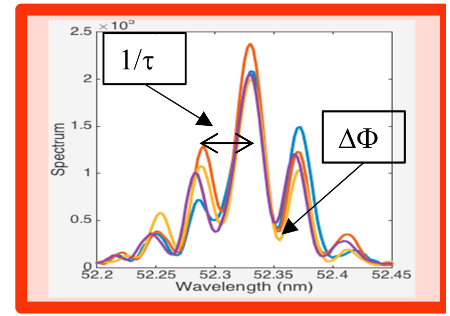
M. Danailov *et al.* Optics Express, Vol. 22, Issue 11, 12869 (2014)

Phase-locked FEL pulses



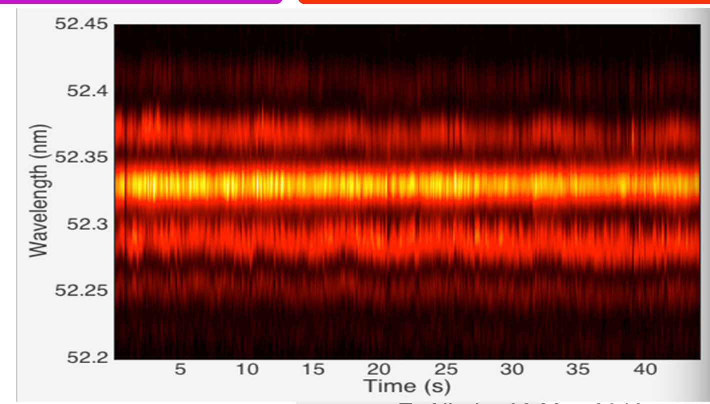






Using two seed lasers we can control and change the **relative time** between **two FEL** pulses. For coherent pulses, a fine tuning **control** the **relative phase** between the two **FEL pulses**.

Interference between two **coherent** and **phase-locked** pulses is evident in the spectral domain.



D. Gauthier et al., Phys. Rev. Lett. **116**, 024801 (2016)

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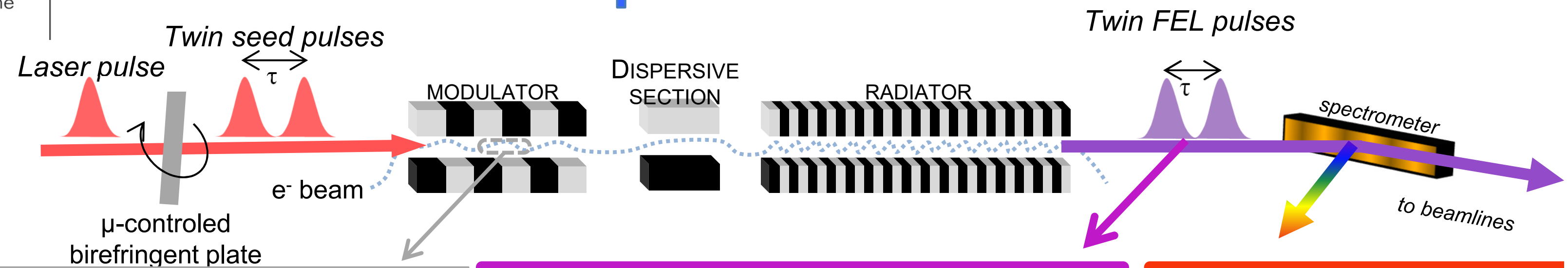
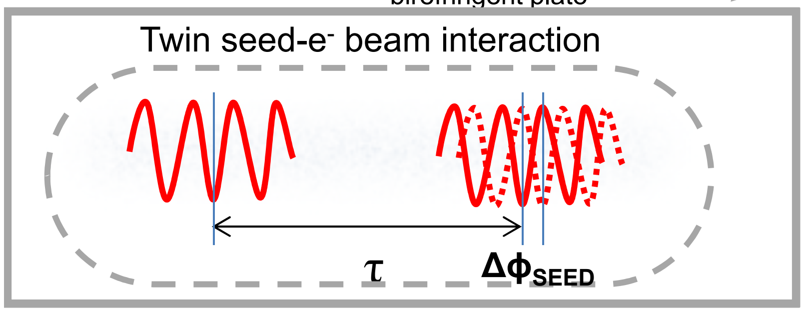
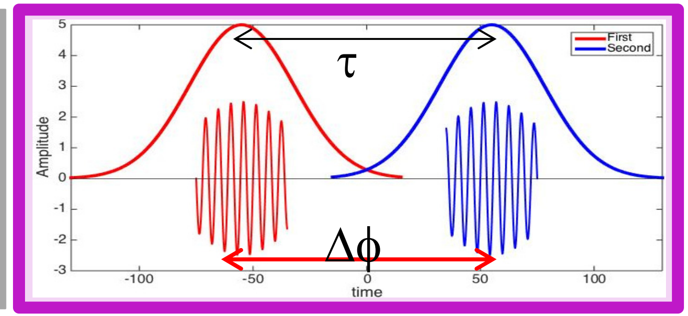
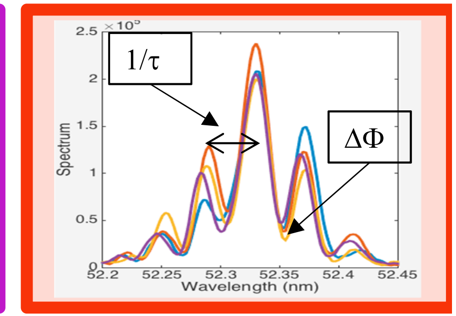
Phase-locked FEL pulses









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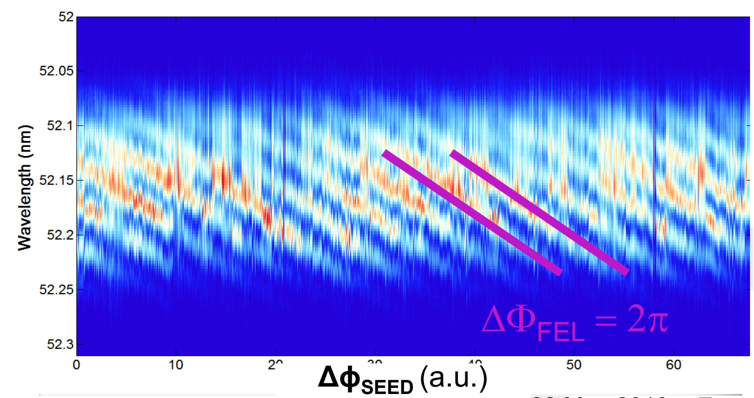

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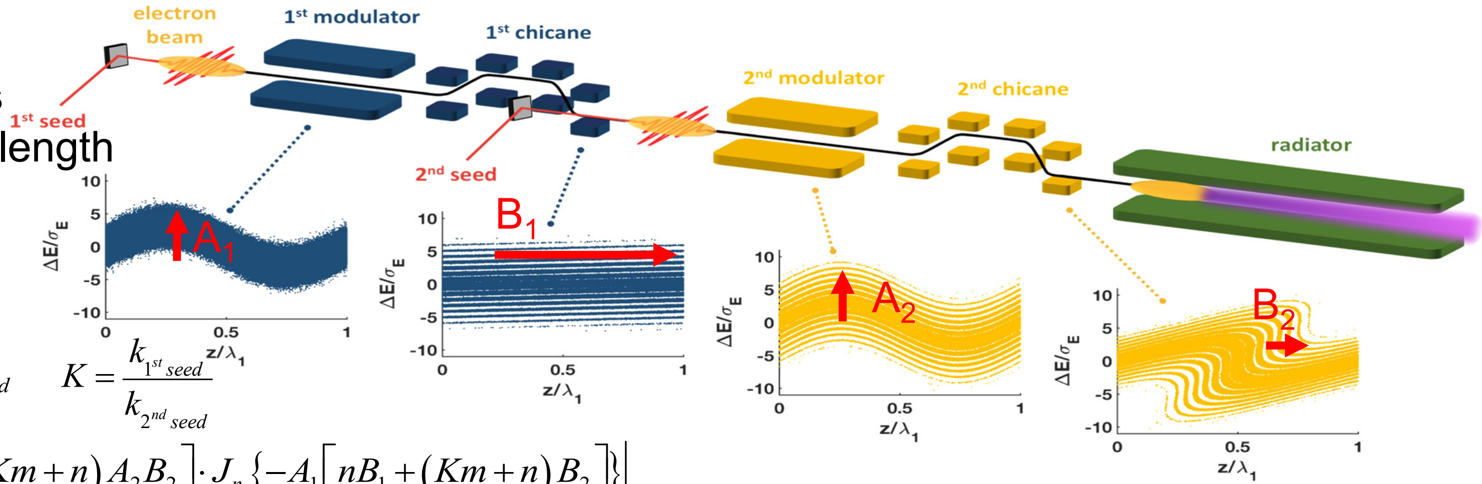
EEHG scheme

G. Stupakov, PRL, 2009

A new scheme allows reaching FEL-2 wavelength with a single stage harmonic generation seeded in the UV.



$$k_{EEHG} = n \cdot k_{1^{st}\,seed} + m \cdot k_{2^{nd}\,seed} \qquad K = \frac{k_{1^{st}\,seed}}{k_{2^{nd}\,seed}}$$

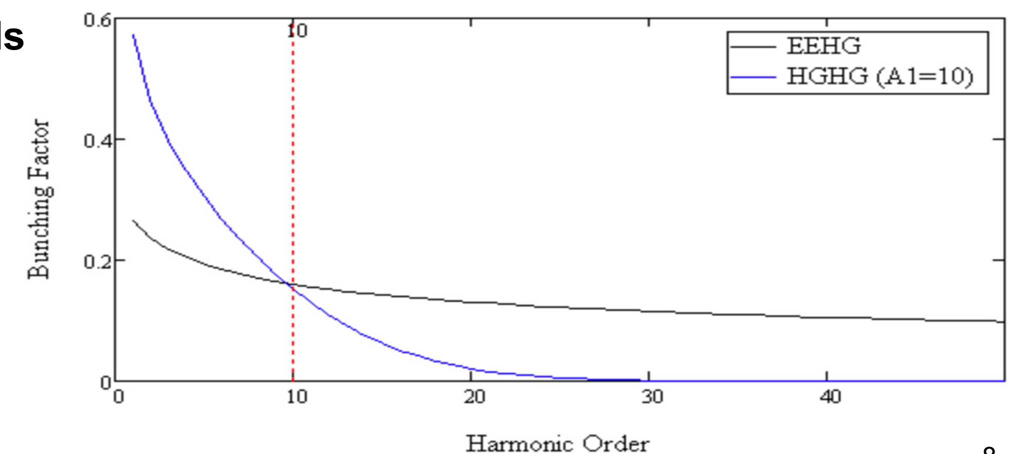
$$b_{n,m} = \left| e^{\frac{1}{2}\left[nB_1 + (Km+n)B_2\right]} \cdot J_m\left[-(Km+n)A_2B_2\right] \cdot J_n\left\{-A_1\left[nB_1 + (Km+n)B_2\right]\right\} \right|$$

EEHG **bunching** at the desired harmonic **depends** on 4 parameters and **slowly decreases** with harmonic number.

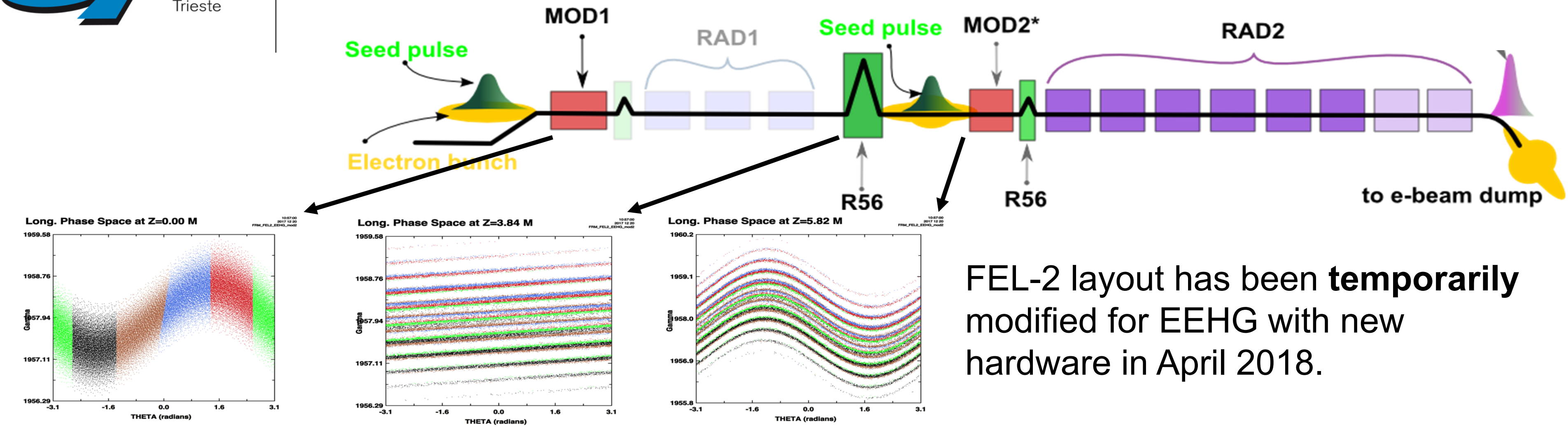
Bunching is maximized for $B_2 \approx \frac{|n|}{H} B_1$.

Higher bunching requires $n = -1$

and slightly decreases for $n = -2, -3$



FEL-2: from HGHG-FB to EEHG

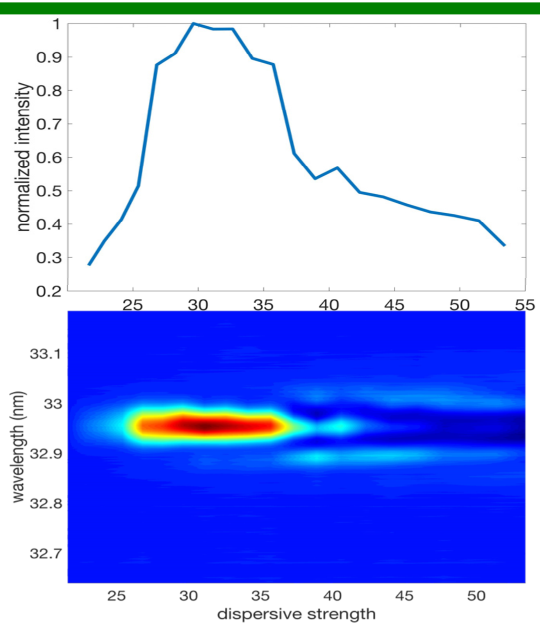


FEL-2 layout has been **temporarily** modified for EEHG with new hardware in April 2018.

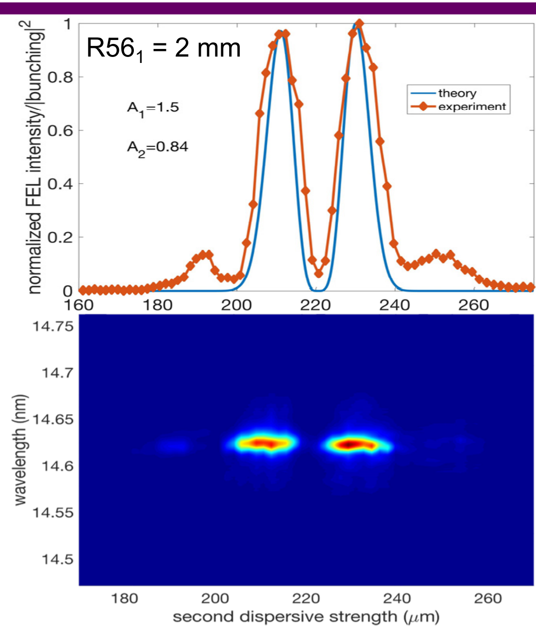
- **Delay line**: changed position of the magnets and new power supply for increasing R56.
- **Second modulator**: changed the undulator.
- **Seed laser**: new seed laser for EEHG.
- **Diagnostic**: new optical table for seed and electron diagnostic.
- **Photon diagnostic**: VUV CCD on PRESTO

Signature of EEHG

HGHG



EEHG



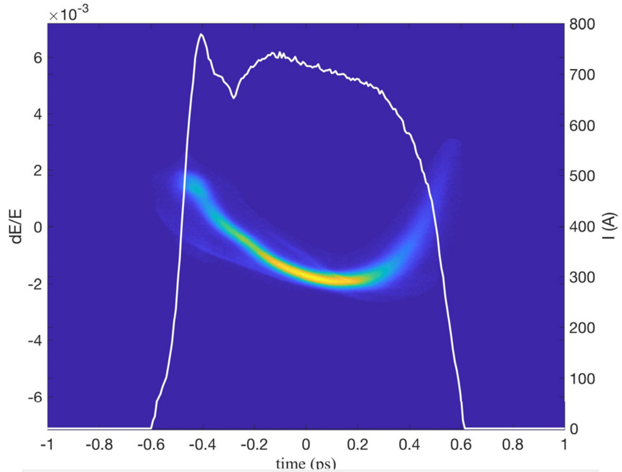
FEL intensity and spectra show **different response** to the dispersive strength **R_{56}** in **HGHG** and **EEHG**.

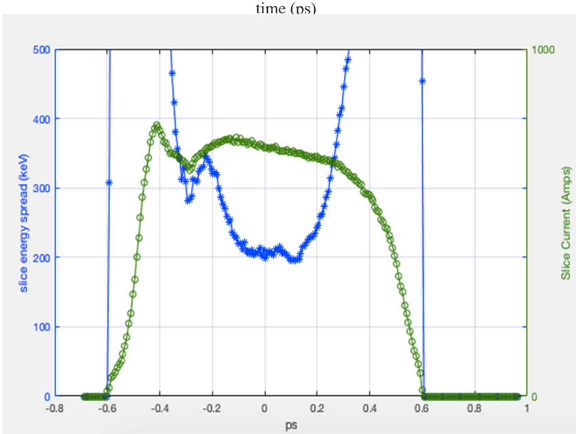
HGHG presents **one maximum**; for **larger R_{56}, power** slowly **decreases** and **spectrum splits** as a result of the over-bunching.

EEHG is maximized in **two** very **narrow regions** determined by the bunching equations.

For this case at H = 36 optimized for n=-2, a minimum is found for $R56_2 \equiv \frac{2}{18} R56_1$ with two adjacent maxima.

E-beam phase space at E = 1.1 GeV

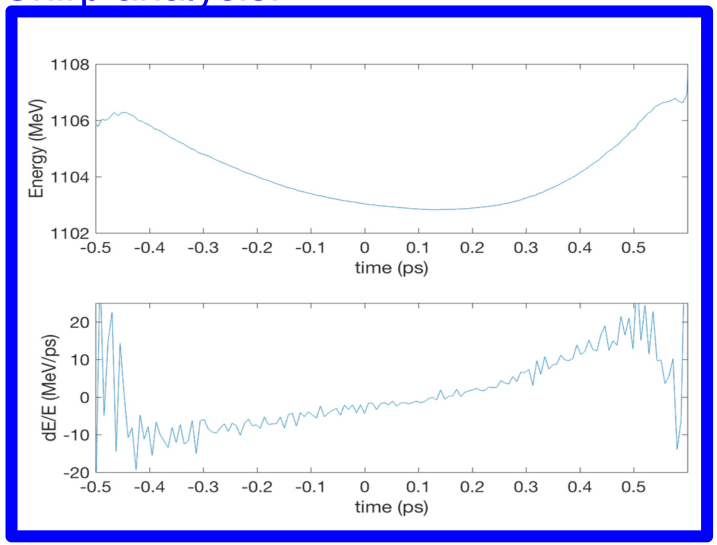




The **same** electron beam has been used for **both EEHG** and **HGHG** to investigate the sensitivity to electron beam properties.

E-beam properties are measured at the end of the linac.

Chirp analysis:

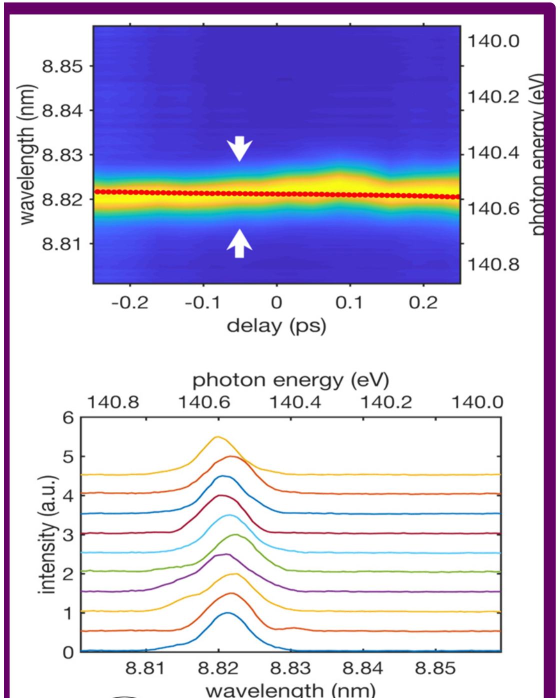


A not negligible **quadratic chirp** characterizes the phase space of FERMI elctron beam.

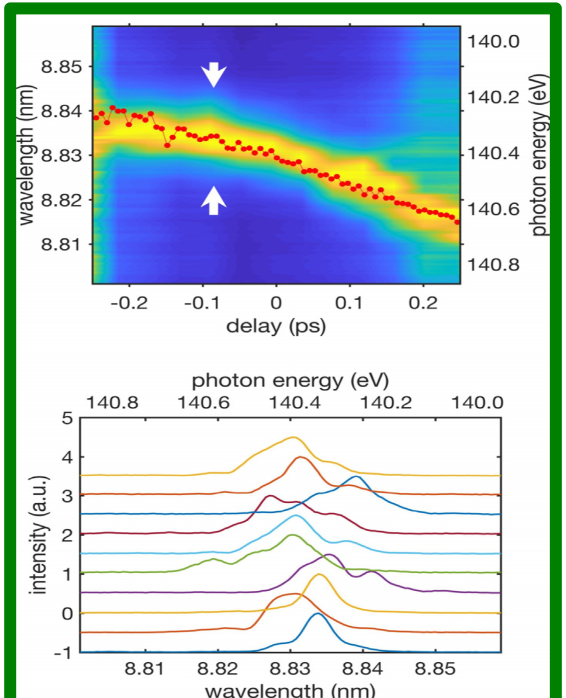
FEL behavior vs. e-beam properties

From bunching equation one gets that **FEL wavelength** is **affected** by e-beam **energy chirp** according to: $\frac{d\lambda}{\lambda} \approx \frac{1}{E}\left(R56_2 + \frac{n}{H} R56_1\right)\frac{dE}{dz}$

EEHG



HGHG



The value of **$R56_2$** is **comparable** for **EEHG** and **HGHG**.

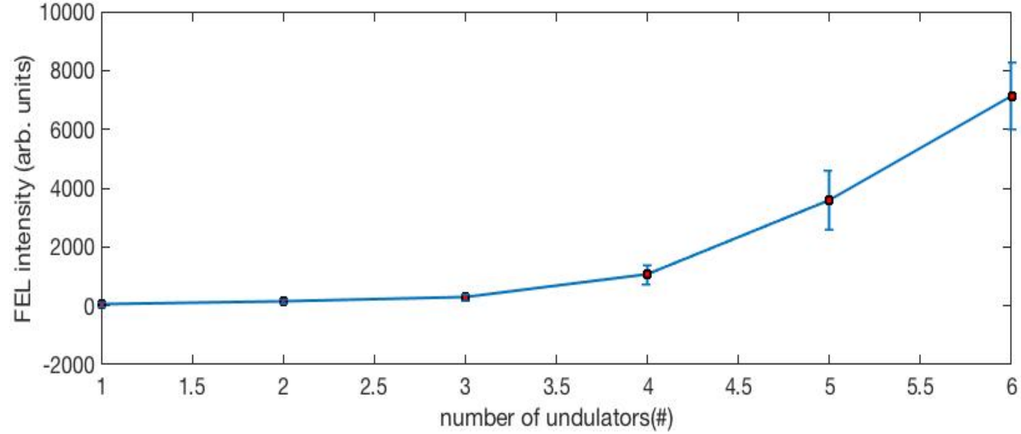
EEHG takes **advantage** of the **combined** effects of **two R56**.

Maximum EEHG bunching when $R56_2 \approx \frac{|n|}{H} R56_1$ with negative n.

Sensitivity to **e-beam** phase space almost **cancelled**.

Much more stable FEL central wavelength and spectra with **less structures**.

Amplification of EEHG



EEHG bunching at high harmonics 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** has been measured and characterized down to **~5nm**.

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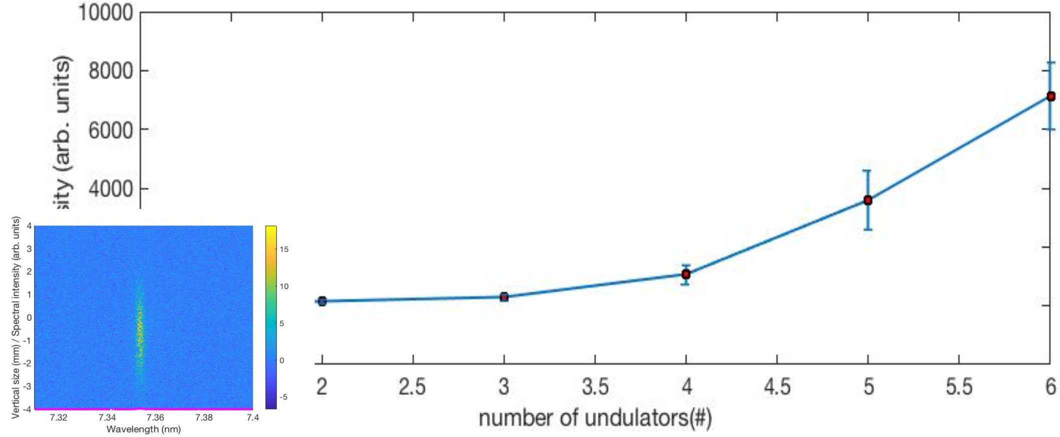

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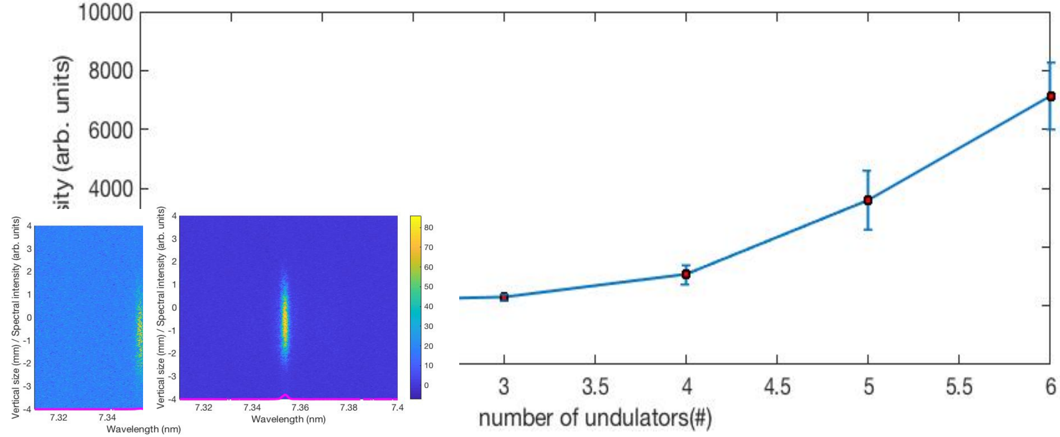

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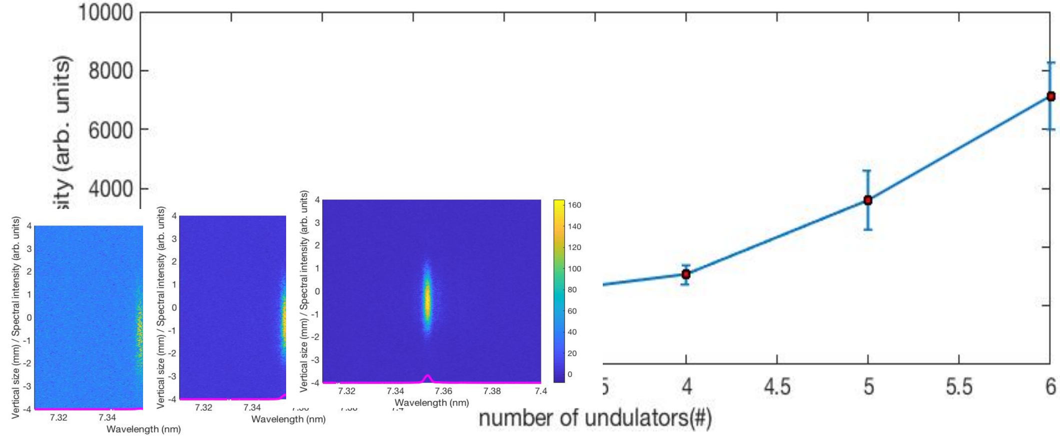

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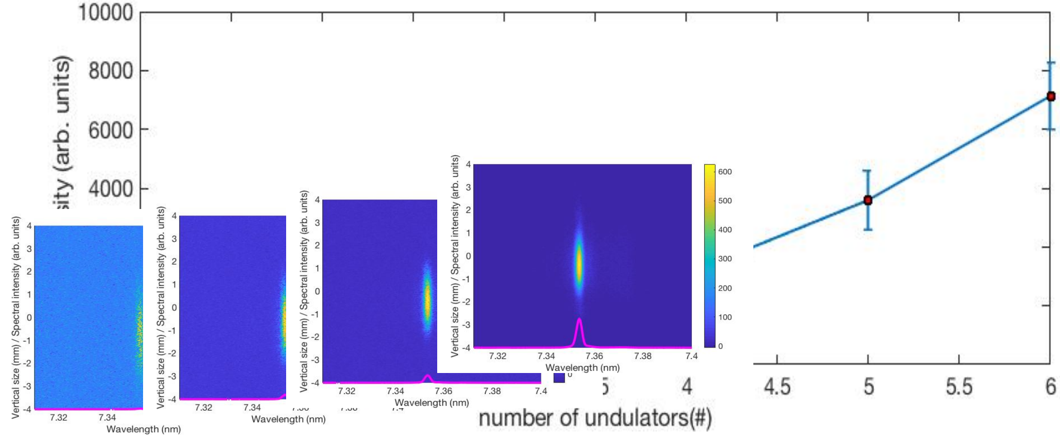

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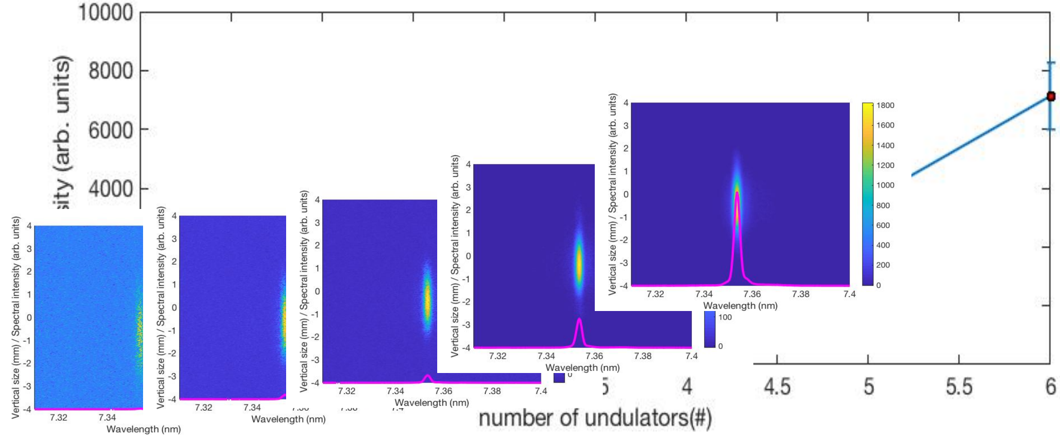

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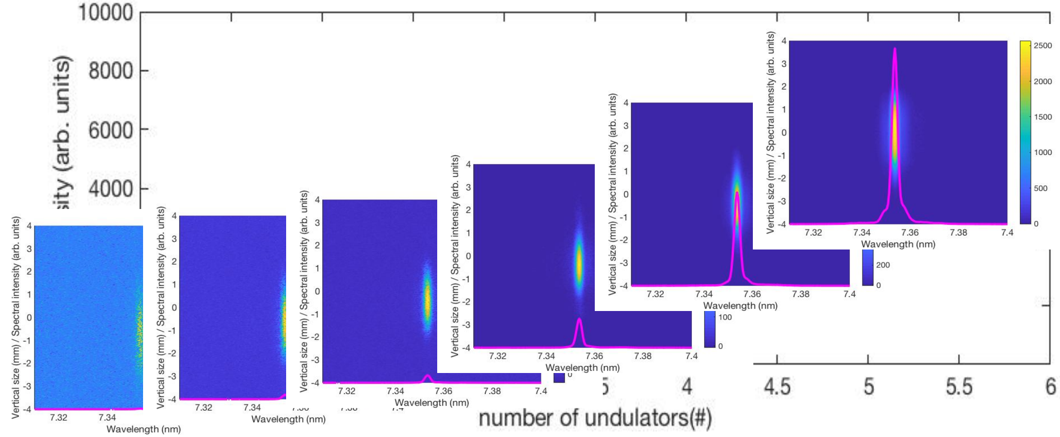

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Amplification of EEHG

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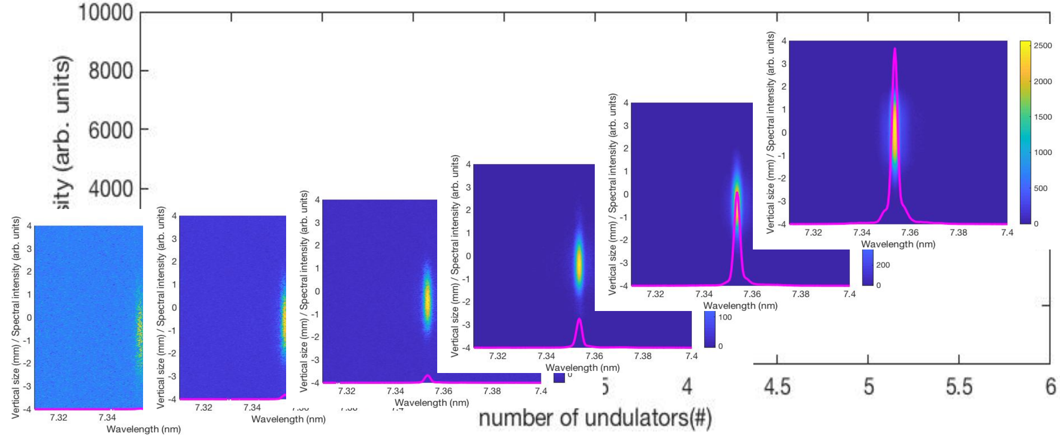

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Generation of **usable** radiation in the soft-X ray region critically **depends** on the **exponential growth** of FEL radiation in the **long radiator**.

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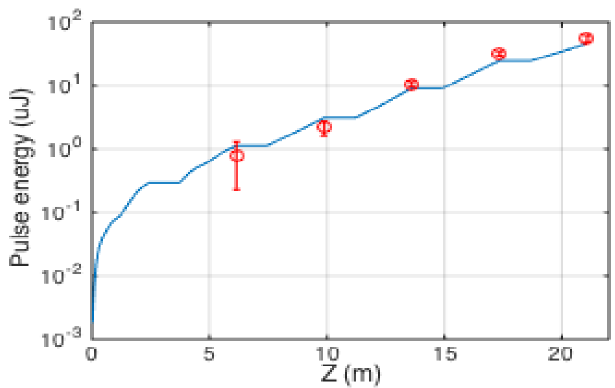
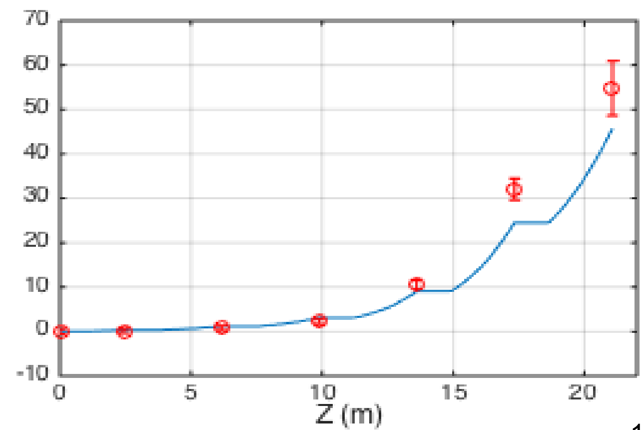
Experimental exponential **growth rate matches** results of **numerical simulations** with our parameters.



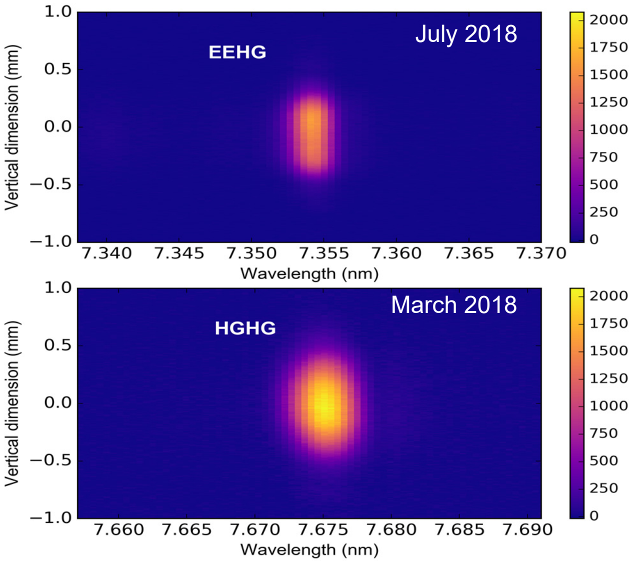


Red dots: rescaled experimental FEL intensity

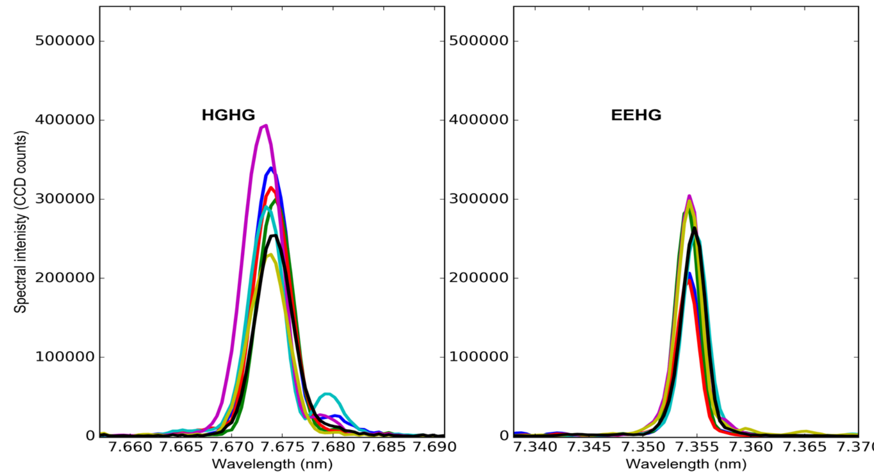
Blue line: numerical simulation

EEHG pulse energies

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



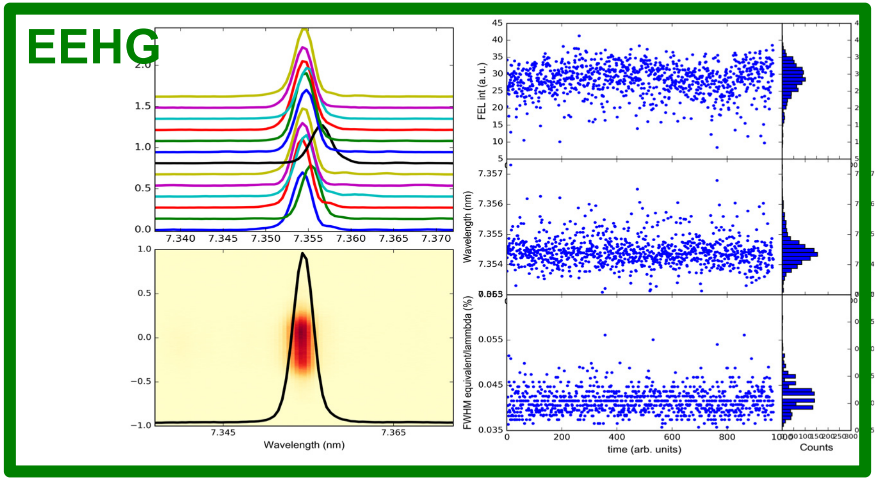
At 7.3 nm direct comparison of the CCD intensity from the **best EEHG** results and a **good FEL** from **HGHG** shows a **similar level** of intensity.

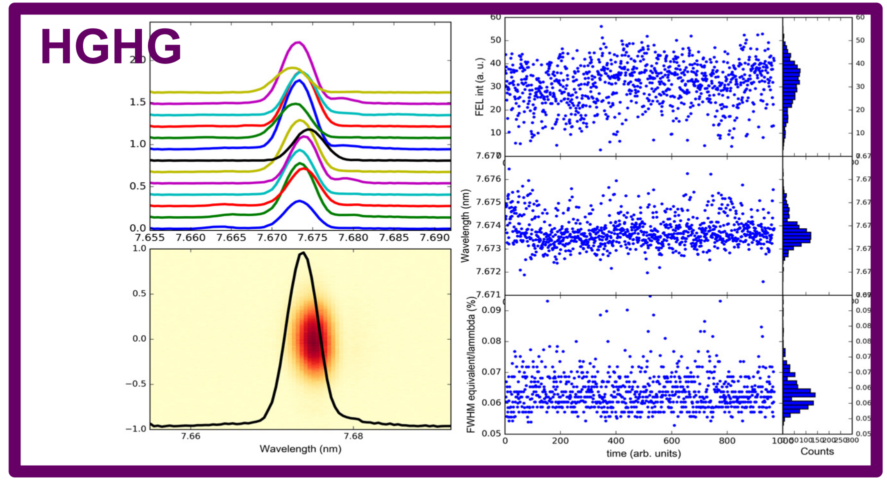


Relaxing requirements on **spectral purity**, **HGHG** can generally **increase** the **energy** per pulse. At **shorter wavelengths HGHG** has **higher energy** per pulse due to the higher flexibility in maximizing bunching (stronger seed).

EEHG spectral control (7nm)

Best EEHG vs. a very good HGHG-FB (**not** same beam **not** same seed laser):





Both cases FEL **optimized** for **clear spectra**.

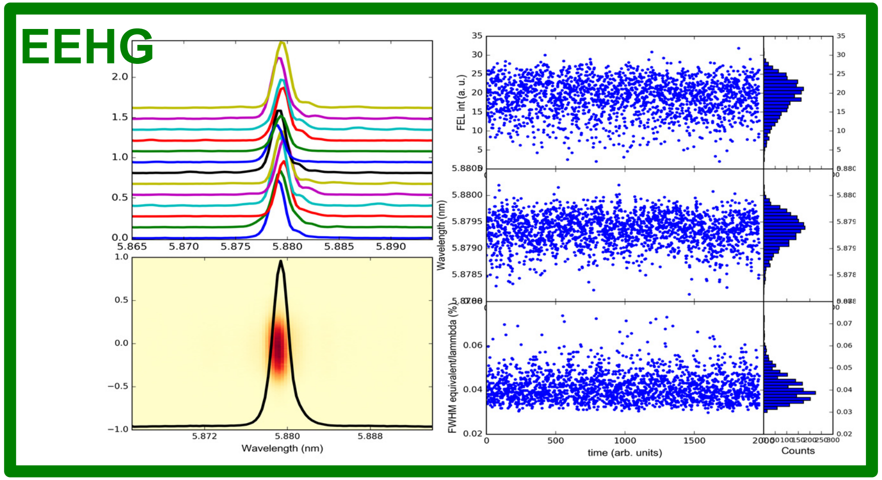
FWHM spectral width **might** be related to slightly **different seed** laser pulses.

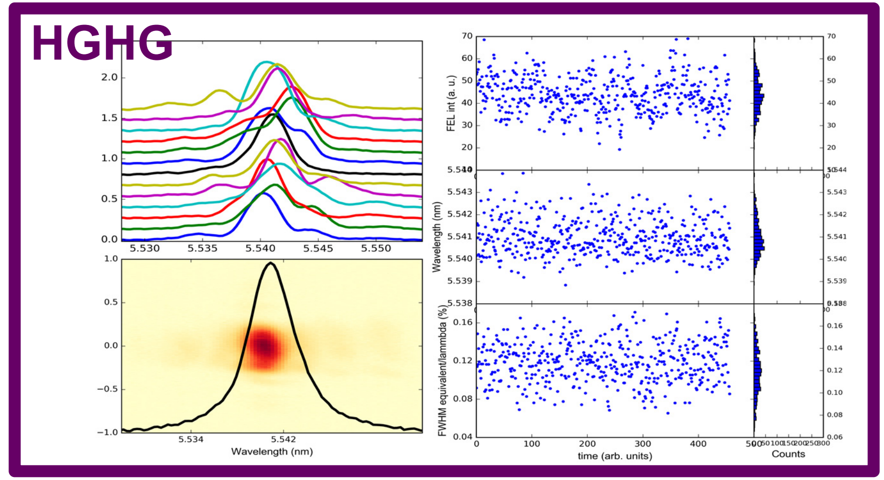
$FW_{76\%}$ (width containing 76% of the energy) is affected by **sidebands** that are more evident in HGHG.

Spectral **reproducibility** is **higher** in **EEHG**.

EEHG spectral control (5nm)

Best EEHG vs. a very good HGHG-FB (**not** same beam **not** same seed laser):





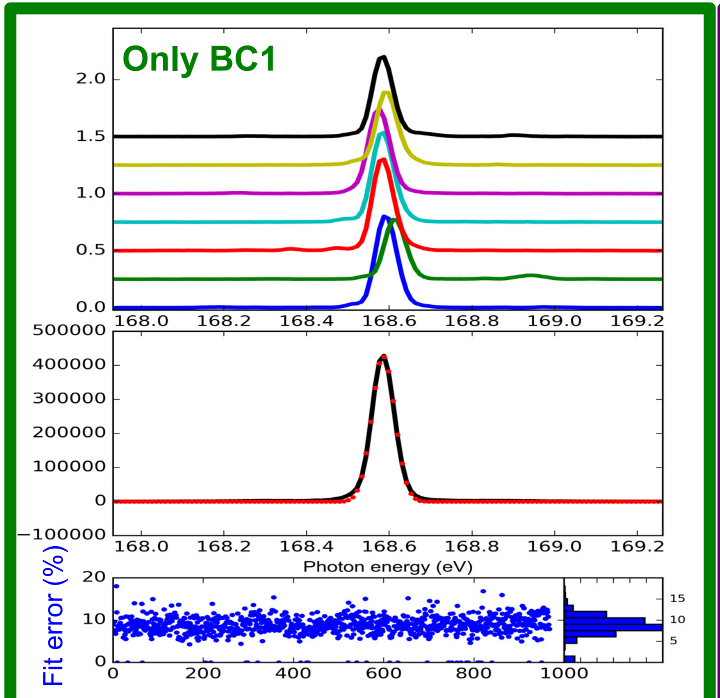
Difference is more pronounced at higher harmonics.

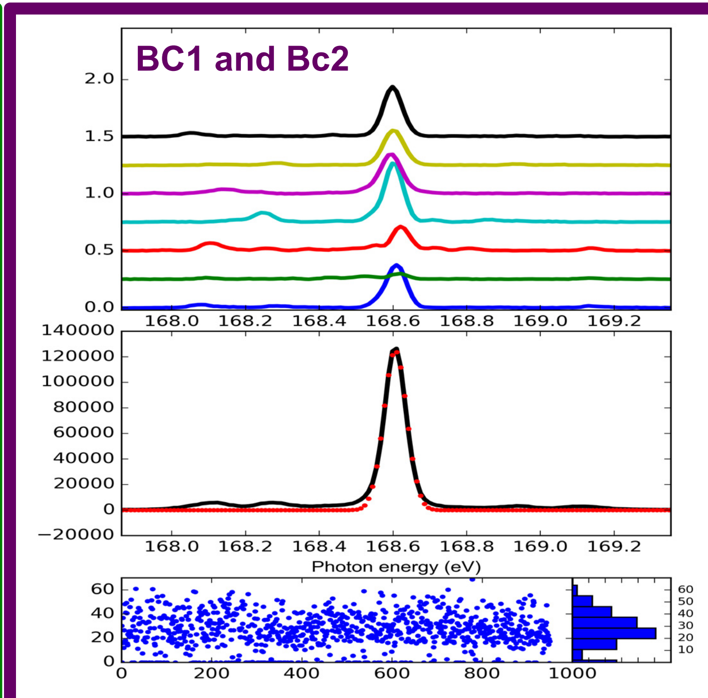
For **HGHG cleaner spectral** can generally be obtained by **reducing t**he overall FEL **intensity**.

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

EEHG sensitivity to mB

Using **2 bunch compressors** in the linac has an impact on the μ**B**.





Higher μ**B** has a clear **impact** on the **spectral purity** also for **EEHG** as seen from the Gaussian fit error.

EEHG at very high harmonics

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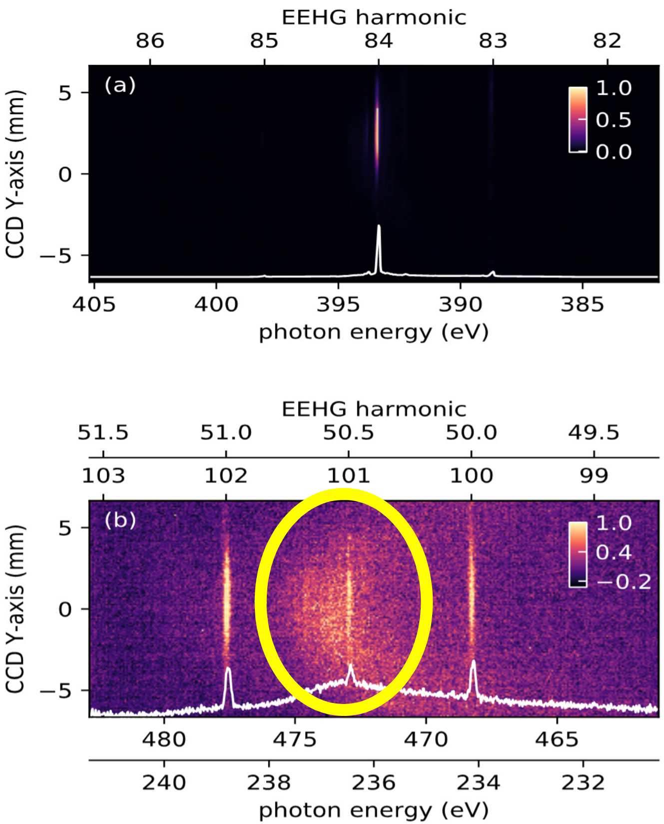
With the e-beam energy at **1.5 GeV** harmonic 84 (**3.1 nm**) and h=101 (**2.6nm**) have been measured.



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Limits in the experimental setup forced us to operate at ***n*=-3,-4** and **low** undulator ***k***.

Nevertheless we have acquired **single** shot spectra with the EUV CCD (Andor) at **3 nm** (shortest wavelength for first order of diffraction)

Measurements at **2.6 nm** required second order of diffraction and few seconds CCD integration time.

FERMI EEHG results just published on Nature Photonics:
https://www.nature.com/articles/s41566-019-0427-1

Conclusions

- Capabilities of EEHG have been fully demonstrated down to harmonic 45 (5.8 nm).
  - Good agreement between simulations and experiment, work to be continued.
- From the limited experience EEHG operations at short wavelengths (limited gain) appears more critical than HGHG-FB.
  - EEHG strongly relies on exponential amplification.
- EEHG confirms promises of producing bunching at very high harmonics
  - H =101 clearly visible in a non optimized setup.
- New FEL capabilities can become available with EEHG in the 20 – 4 nm spectral range.

An optimized EEHG configuration **appears** a viable **option** for extending the tuning range of **FEL-2 to shortest wavelengths** if a **suitable FEL gain** can be **provided**.

Work started at FERMI for a possible upgrade based on EEHG.

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Acknowledgements

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

PAUL SCHERRER INSTITUT PSI

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Thank you!