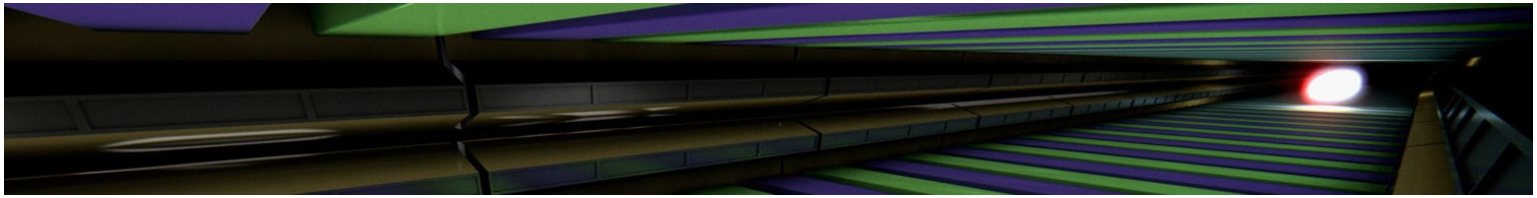
European XFEL



Harmonic lasing experiment at the European XFEL

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FEL’2019, Hamburg, August 27, 2019

DESY

HELMHOLTZ | ASSOCIATION

Harmonics in FELs

- In a planar undulator (K ~ 1 or K >1) the odd harmonics can be radiated on-axis (widely used in SR sources)

- For coherent emission a mechanism is required to create coherent microbunching at harmonic frequencies

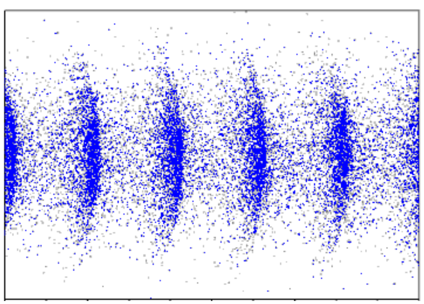
- There are two basic mechanisms in FELs:
  - Nonlinear harmonic generation
  - Harmonic lasing

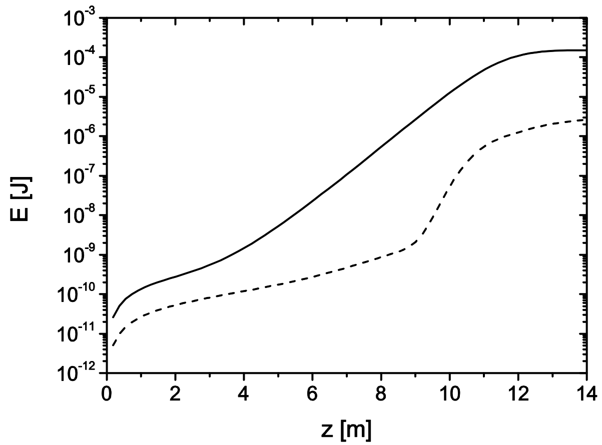
We consider SASE process in a baseline XFEL undulator

Nonlinear harmonic generation

- When lasing at the fundamental frequency approaches saturation, the density modulation becomes nonlinear (contains higher harmonics)
- Odd harmonics are radiated then on-axis
- Well-known process, studied in many papers

Microbunching at saturation





1st: solid

3rd: dash

3rd harmonic is driven by the fundamental

Occurs whenever an FEL reaches saturation; studied and used at FLASH, LCLS etc.

Properties of nonlinear harmonic generation

- Power of 3rd harmonic is about 1% of saturation power of the fundamental (and much smaller for higher harmonics)

- Relative bandwidth is approximately the same (contrary to 1/h in the case of spontaneous emission)

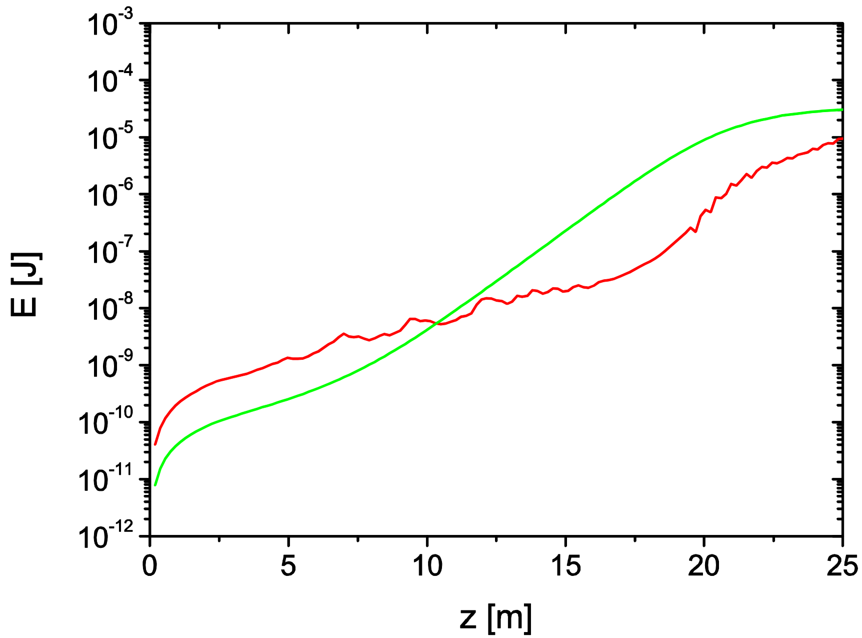
- Shot-to-shot intensity fluctuations are much stronger

- Transverse coherence is worse

In short, nonlinear harmonics are much less brilliant and less stable than the fundamental

Harmonic lasing

- Harmonic lasing is an FEL instability developing independently of the fundamental (in linear regime)
- We have to disrupt the fundamental to let a harmonic saturate



1^{st}: red

3^{rd}: green

the fundamental is disrupted by phase shifters

Properties of harmonic lasing

- Saturation efficiency of h-th harmonic scales as ~ $\lambda_w/(hL_{sat})$

- Relative rms bandwidth scales as ~ $\lambda_w/(hL_{sat})$

- Shot-to-shot intensity fluctuations are comparable (the same statistics)

Brilliance is comparable to that of the fundamental!

Suppression of the fundamental

- Phase shifters
- Spectral filtering
- Switching between 3rd and 5th harmonics

Harmonic lasing: the history

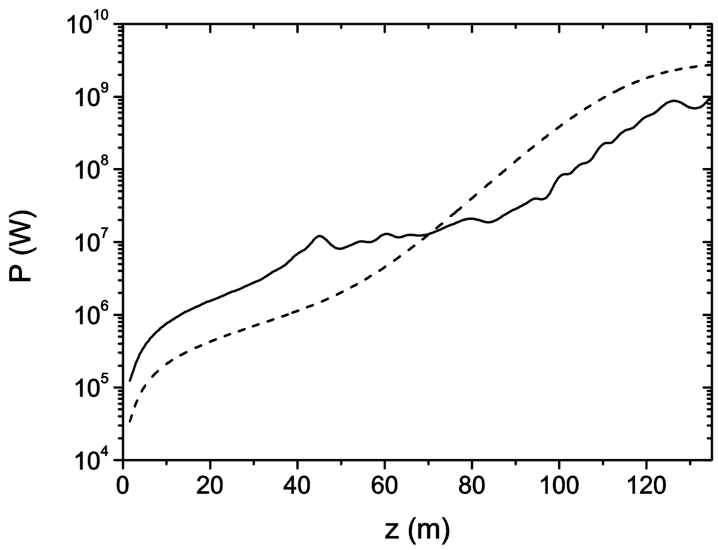
- First theoretical consideration for low-gain FELs almost 40 years ago (Colson, 1981)
- Several successful experiments with FEL oscillators in infrared range (1988-2010)

- High-gain FELs (theoretical works):

  Murphy, Pellegrini, Bonifacio, 1985
  Z. Huang and K.-J. Kim, 2000
  McNeil et al., 2005
  Schneidmiller and Yurkov, 2012

Example for the European FEL

3rd harmonic lasing at 62 keV (0.2 A). Beam parameters for 100 pC from s2e (quantum diffusion in the undulator added), energy 17.5 GeV. With 20 pC bunch one can even reach 100 keV.



1st: solid

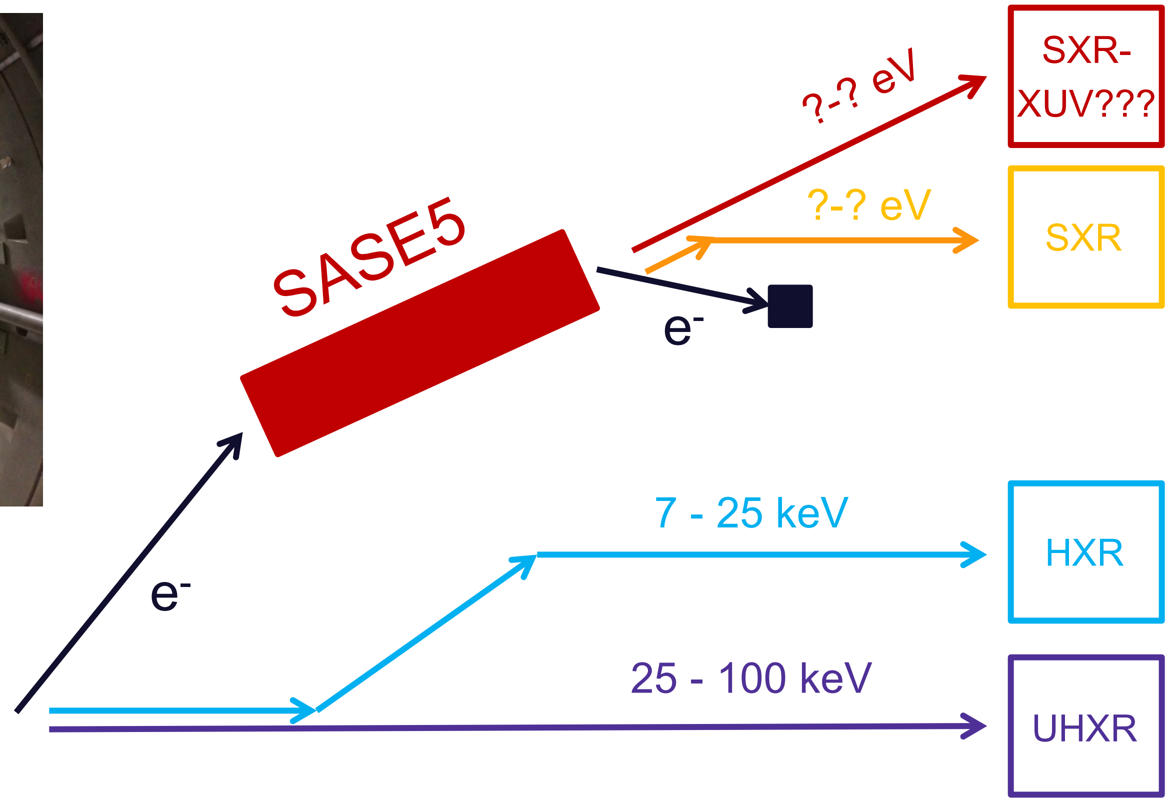
3rd: dash

bandwidth is 2×10^{-4} (FWHM)

Users are interested; MAC recommended.

SASE4 at the European XFEL?

Harmonic lasing can be an option for reaching 100 keV



Posters TUP056, TUP057, TUP060,TUP061

CW upgrade of the European XFEL

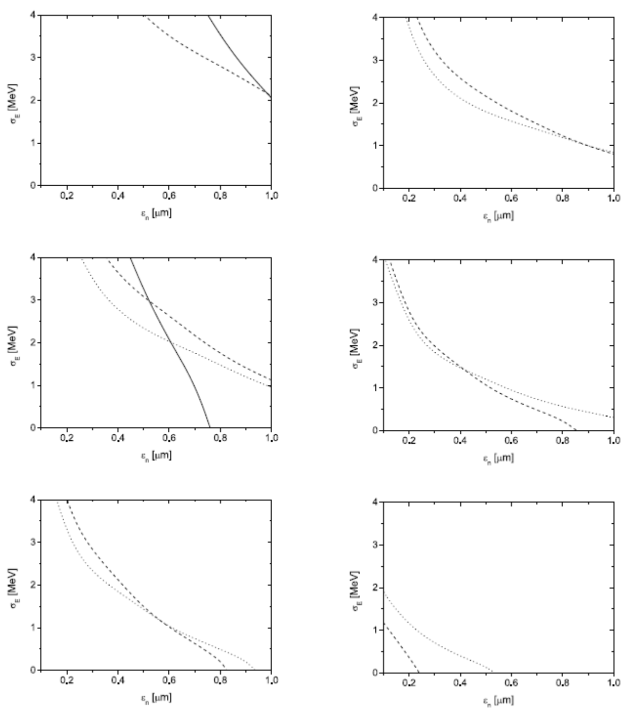
It is expected to have 7 GeV in CW mode and 10 GeV in long pulse mode with 35% duty factor.

10 GeV | 7 GeV

1 A

0.75 A

0.5 A



1st: solid

3rd: dash

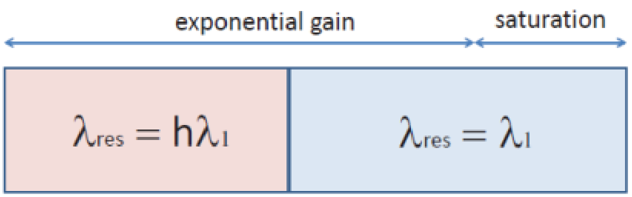
5th: dot

Brinkmann, Schneidmiller, Sekutowicz, Yurkov, NIMA 768(2014)20

HLSS FEL (Harmonic Lasing Self-Seeded FEL)

We proposed a simple trick for improvement of spectral brightness in a gap-tunable undulator: harmonic lasing in linear regime (with narrow bandwidth) in the first part of the undulator, then reducing K and reaching saturation at the fundamental. Then we have high power and narrow BW.

E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702



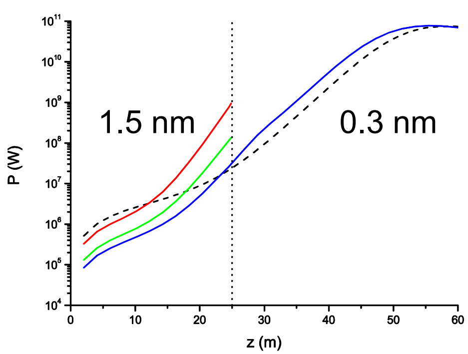
larger K smaller K

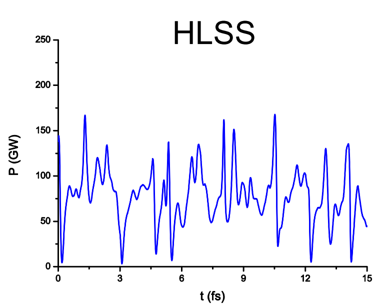
Bandwidth reduction factor:

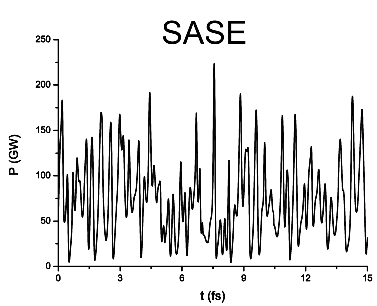
$$R \simeq h \frac{\sqrt{L_{\mathrm{w}}^{(1)} L_{\mathrm{sat},h}}}{L_{\mathrm{sat},1}}$$

Typically R = 0.6-0.9 h

The fundamental and all harmonics have to stay well below saturation in the first part of the undulator. Use of phase shifters in the first undulator is optional.





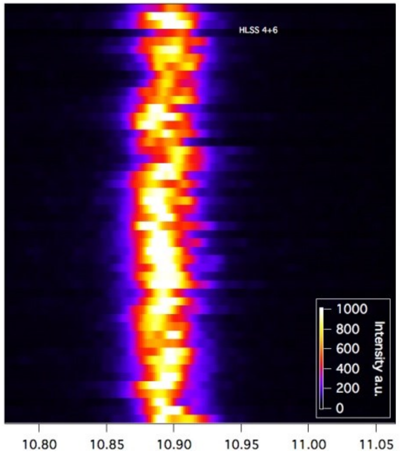


E. Schneidmiller and M. Yurkov, FEL'13

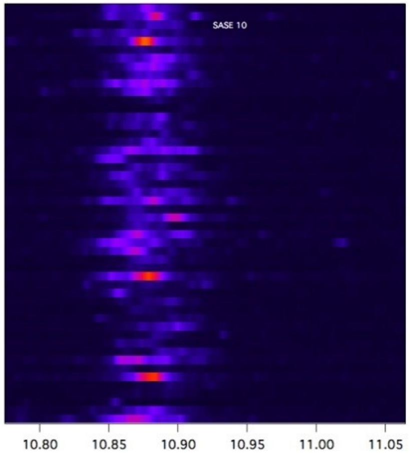
HLSS at FLASH2 (2016): 4.5 – 15 nm

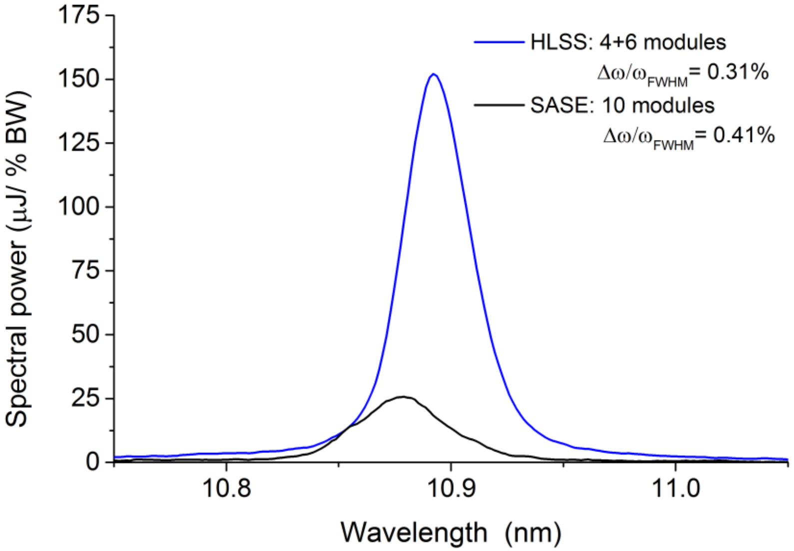
Spectral measurements

HLSS (4+6)



SASE (10)





E. Schneidmiller et al., Phys. Rev. AB 20(2017)020705

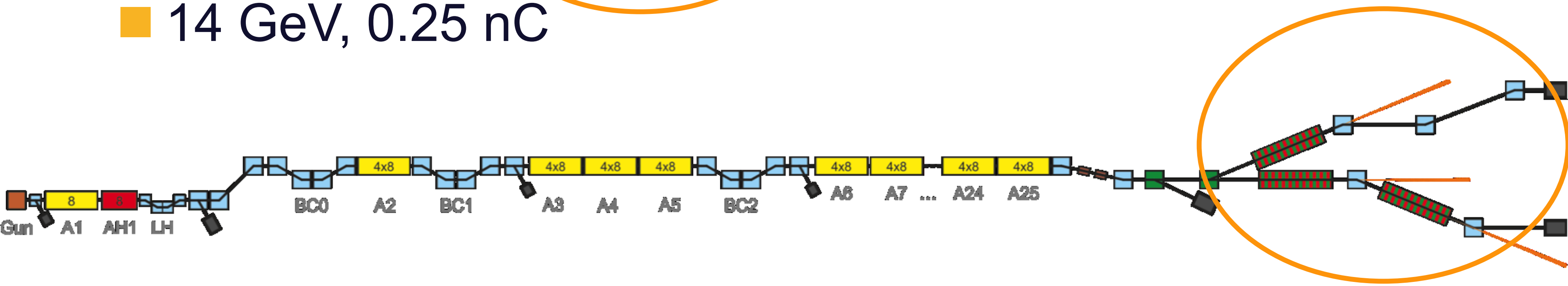
HLSS at PAL XFEL (2017): 1 nm

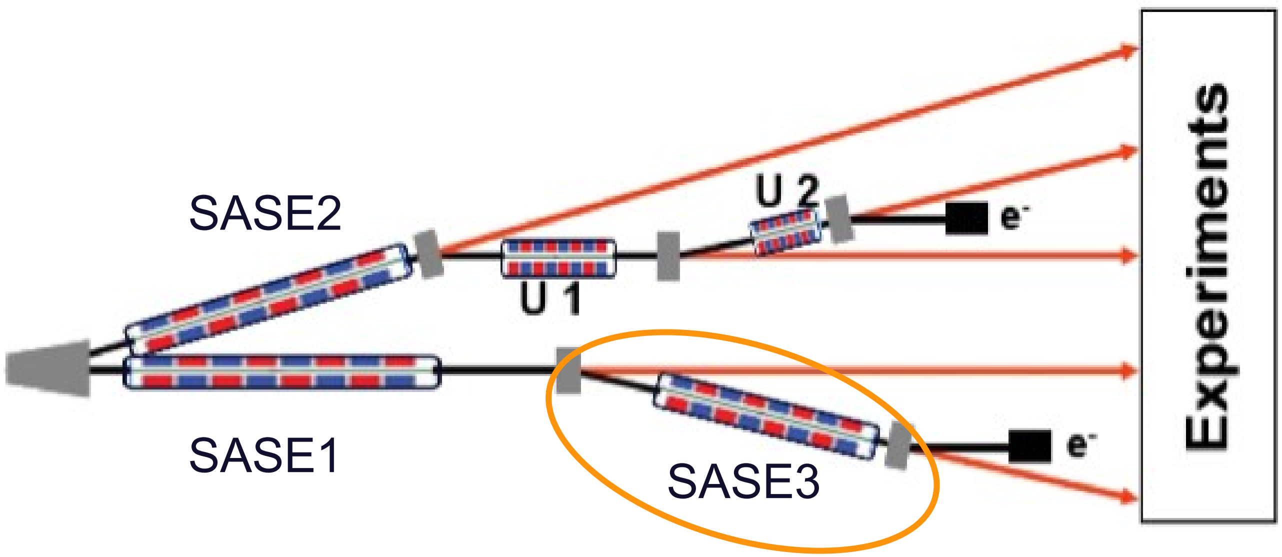
- Soft X-ray undulator was used to test HLSS;
- It worked very well at 1 nm;
- Good agreement with theory.

I. Nam et al., Appl. Phys. Lett. **112**, 213506 (2018)

HLSS at EuXFEL (Apr. and Aug. 2019)

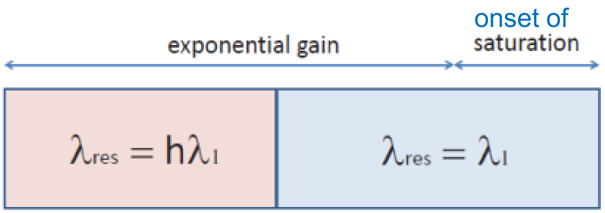
- Soft X-ray undulator (SASE3) was used;
- Period 6.8 cm, K up to 9; 21 segments (5 m each)
- 14 GeV, 0.25 nC





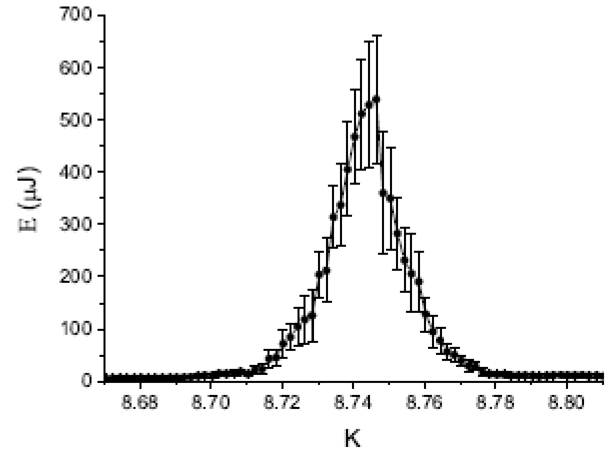
HLSS at EuXFEL: 2.1 keV

Configuration of SASE3 undulator

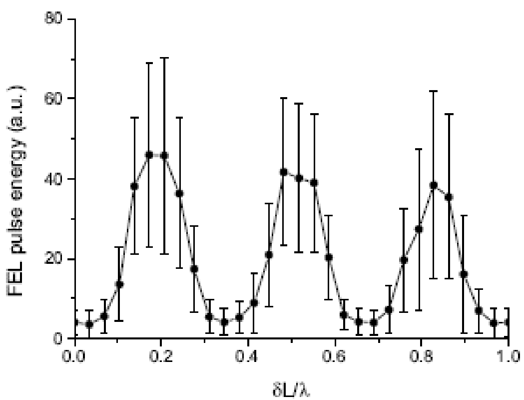


5 undulators | 7 undulators
700 eV | 2.1 keV

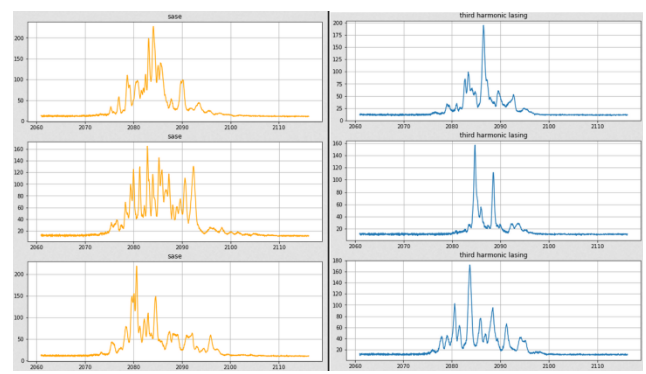
Scan of K-value



Scan of phase shifters



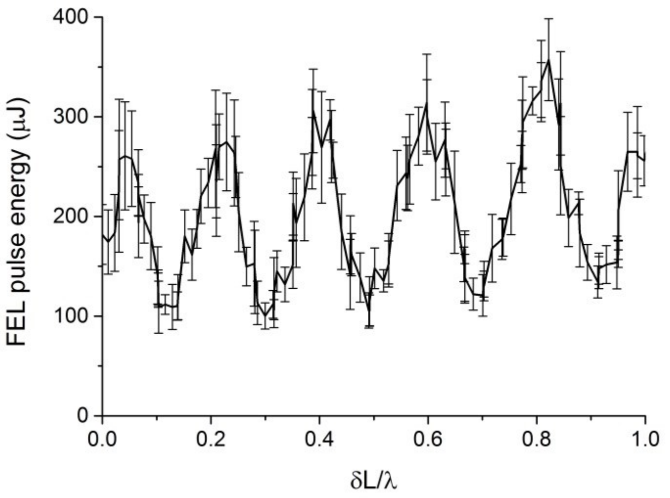
Single-shot spectra



HLSS at EuXFEL: 4.5 keV

- SASE at 4.5 keV was obtained (saturation);
- First five segments were set to 1.5 keV: HLSS with 3rd harmonic
- Then these five segments were set to 0.9 keV: HLSS with 5th harmonic
- Confirmed by the scan of phase shifters after first 4 segments

Scan of phase shifters (5th harmonic seeding)



Conclusions

- Harmonic lasing is a perspective option for XFELs;
- Main application I: extension of photon energy range;
- Main application II: bandwidth reduction and brilliance increase (HLSS);
- Successful demonstration at FLASH2 (2016) and PAL XFEL (2017);
- First demonstration of harmonic lasing in the Angstrom regime (2.8 Angstrom, EuXFEL, 2019);
- Lasing on the 3^{rd} and the 5^{th} harmonics possible;
- The final goal is ~100 keV harmonic lasing!