FEL experiments at FLASH

E. Schneidmiller and M. Yurkov
for FLASH team

Hamburg, January 15, 2019

Outline

- Harmonic lasing self-seeded (HLSS) FEL
- Reverse taper
- Two-color operation
- Frequency doubler
- Post-saturation taper
- Coherence properties

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

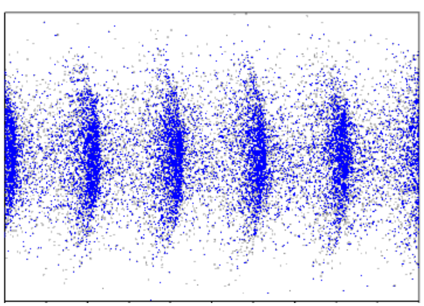
- There are two basic mechanisms in FELs:
  - Nonlinear harmonic generation
  - Harmonic lasing

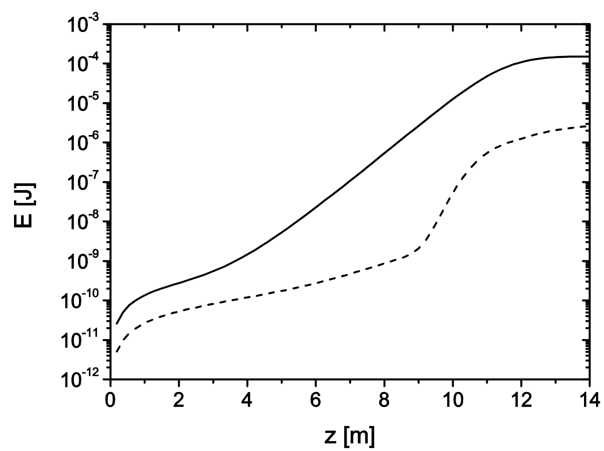
We consider SASE process in a baseline XFEL undulator

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
- Low intensity, poor coherence, strong fluctuations

Microbunching at saturation





1^{st}: solid

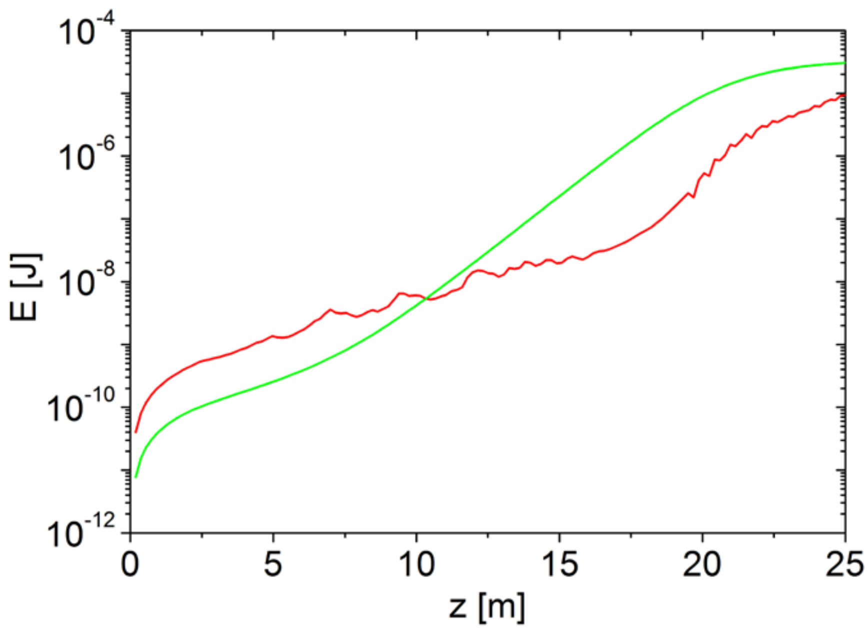
3^{rd}: dash

3^{rd} harmonic is driven by the fundamental

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

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



1st: red

3rd: 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)
- Good transverse coherence

Brilliance is comparable to that of the fundamental!

Suppression of the fundamental

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

Harmonic lasing: status

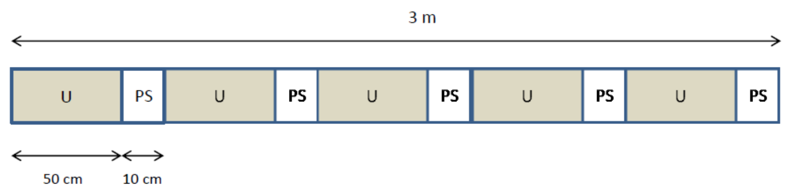
- Known theoretically since 1980s (Colson 1981; Murphy, Pellegrini, Bonifacio 1985)
- Experiments with infrared FEL oscillators
- No prospects for XFEL facilities
- This was changed in 2012 (Schneidmiller and Yurkov, Phys. Rev. ST-AB 15(2012)080702), proposals for European XFEL, FLASH, LCLS …
- First experimental results from FLASH2 (4.5-15 nm) in 2016
- PAL XFEL down to 1nm (FEL’17)
- Activities at the European XFEL started last year

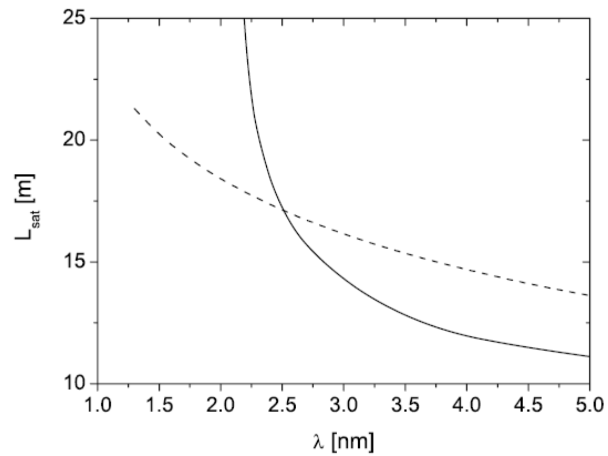
Possible upgrade of FLASH

Lasing down to 1.3 nm is desirable. Making use of 3rd harmonic lasing we can reach this WL with present accelerator energy of 1.25 GeV.

Electron beam	Value
Energy	1.25 GeV
Charge	150 pC
Peak current	2.5 kA
Rms normalized slice emittance	0.5 μm
Rms slice energy spread	250 keV
Rms pulse duration	24 fs

Undulator	Value
Period	2.3 cm
Minimum gap	9 mm
K_{rms} (at minimum gap)	1
Beta-function	7 m
Net magnetic length	25 m
Total length	34.5 m



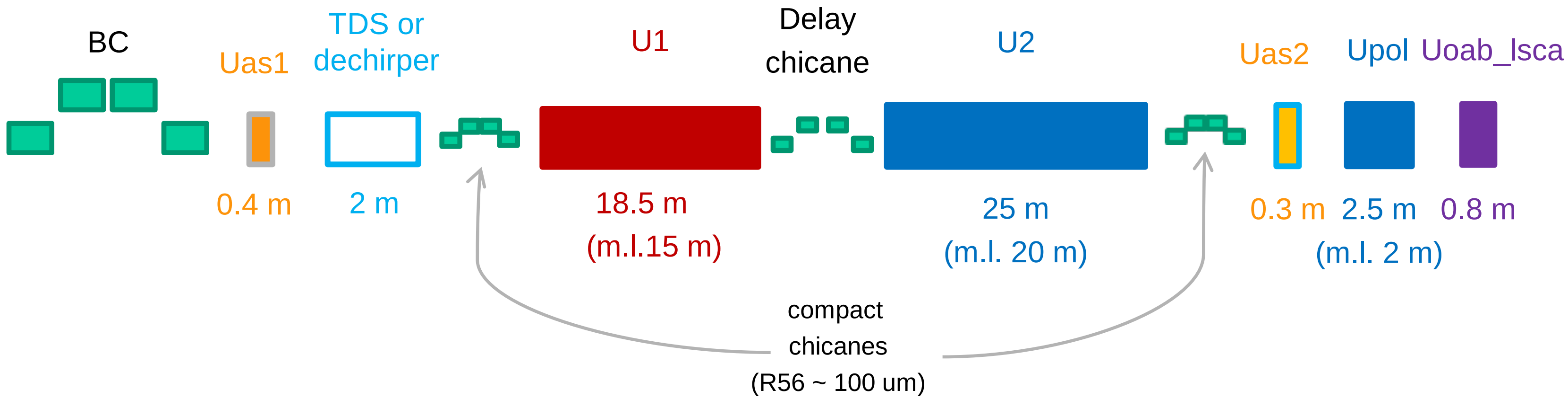


1^{st}: solid

3^{rd}: dash

Schneidmiller, Yurkov, NIMA 717(2013)20

FLASH2020+



U1: period 3.5 cm, Krms = 2.55

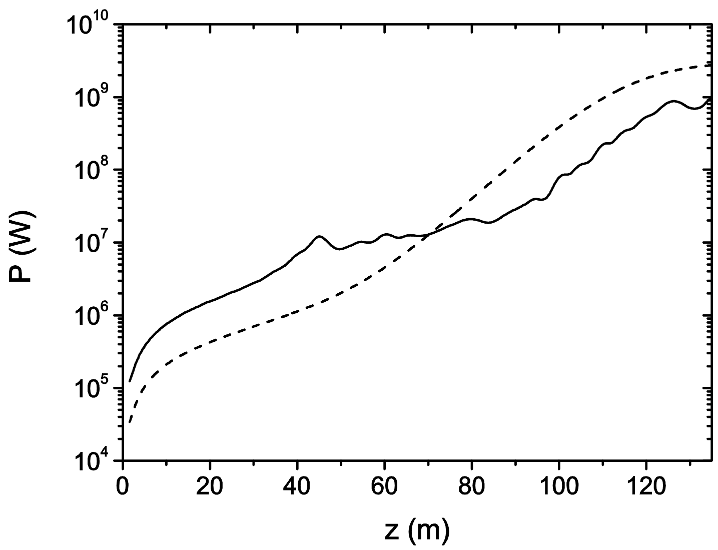
U2: period 2.7 cm, Krms = 1.45

Main FEL modes (for fixed energy 1.35 GeV):

- Harmonic lasing (5^{th} in U1 and 3^{rd} in U2): 1.2 – 2.3 nm
- Frequency doubling or reverse taper with harmonic afterburner: 1.2 – 2.3 nm
- HLSS: 2.2 – 6 nm
- SASE: 2.3 – 18 nm
- Two colors (SASE): 4.5 – 18 nm (U1) and 2.3 nm – 6 nm (U2+Upol)

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.

CW upgrade of the European XFEL

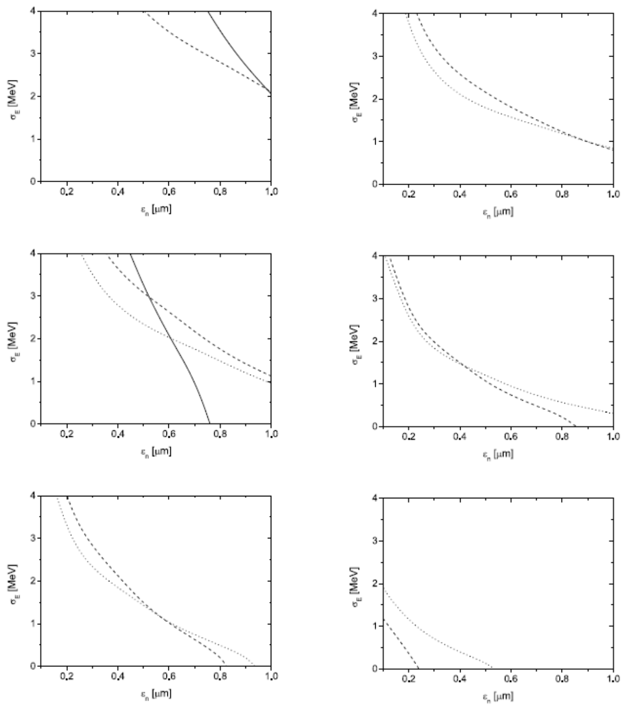
It is expected to have 7 GeV in CW mode and 10 GeV in long pulse mode with 35% duty factor.

10 GeV 7 GeV

1 A

0.75 A

0.5 A



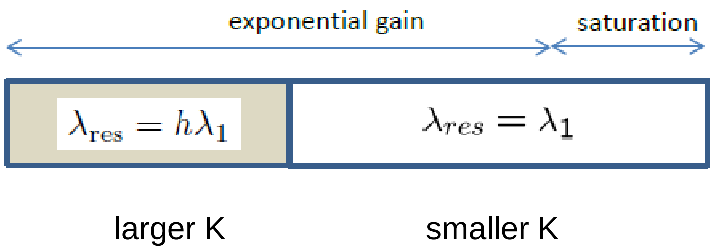
1st: solid
3rd: dash
5th: dot

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

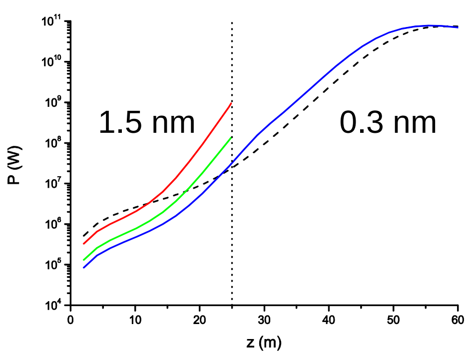


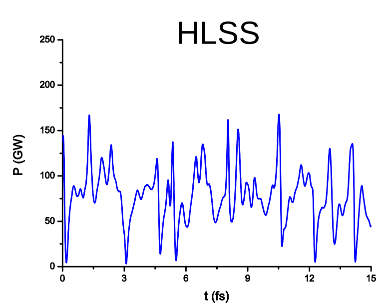
Bandwidth reduction factor:

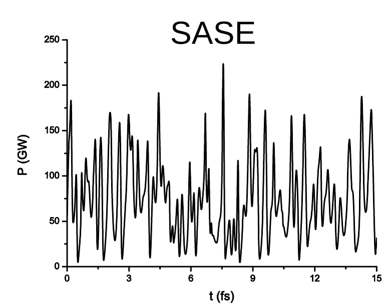
$$R \simeq h \frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{{\rm sat},1}}$$

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.

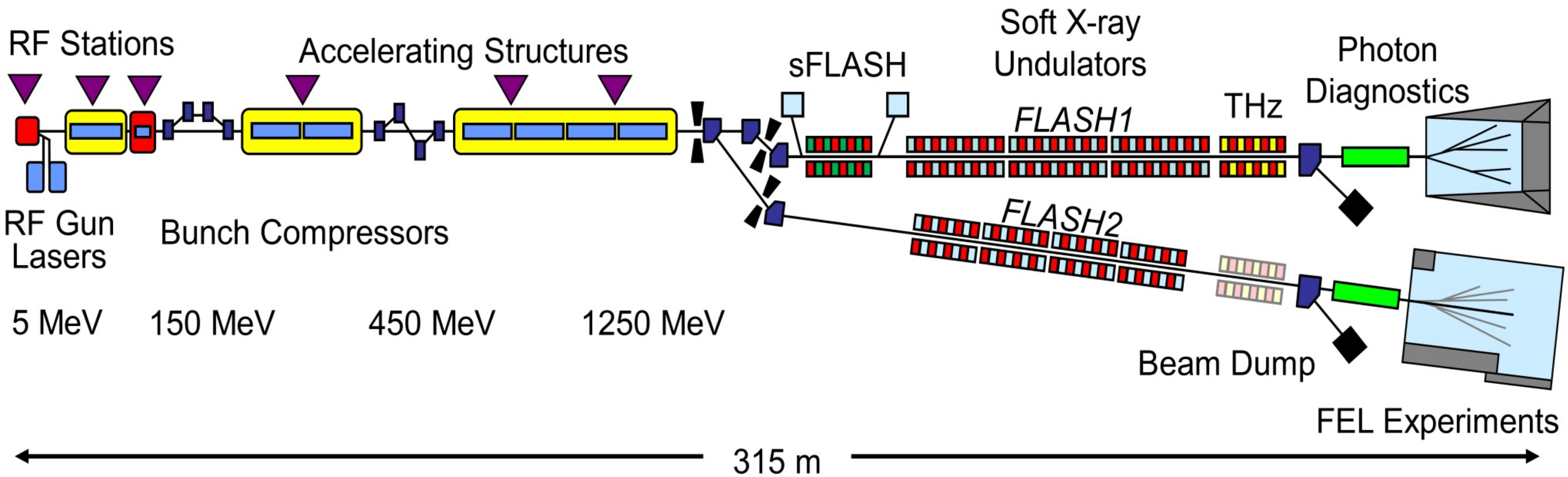






E. Schneidmiller and M. Yurkov, FEL'13

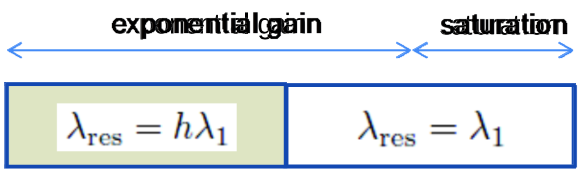
FLASH layout



- Undulators

	Period	Length	
FLASH1:	2.73 cm	27 m (6 x 4.5 m modules)	fixed gap
FLASH2:	3.14 cm	30 m (12 x 2.5 m modules)	variable gap

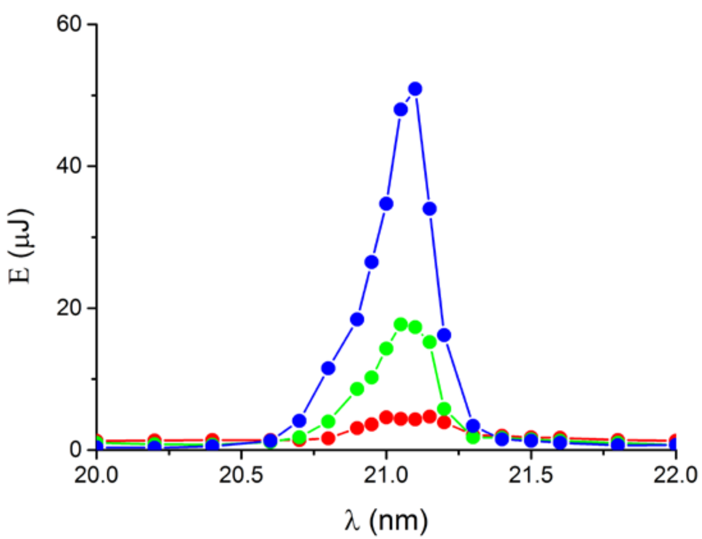
HLSS at FLASH2: 7 nm (May 1, 2016)



(actually, no saturation)

3 undulators	7 undulators
21 nm	7 nm

K-scan of the undulators: only 1st (red); 1st and 2nd (green) ; 1st, 2nd and 3rd (blue)



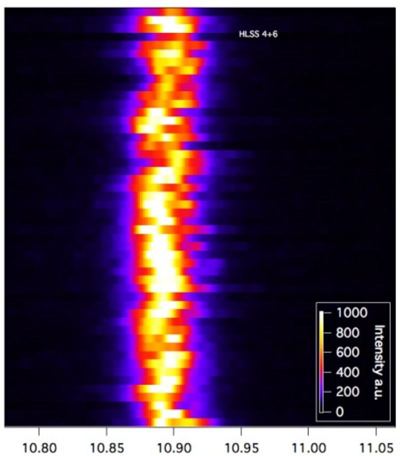
- Normal SASE at 7 nm in 10 undulators: 12 uJ (exponential gain)
- Detuning first (first two, first three) undulator sections: sharp intensity drop
- Coming close to 21 nm: sharp increase, resonant behavior
- With 3 undulators we have 51 uJ instead of 12 uJ; gain length of the 3rd harmonic is shorter than that of the fundamental at 7 nm!
- Nonlinear harmonic generation in the first part is absolutely excluded: pulse energy at 21 nm after 3 undulators was 40 nJ (but about 200 uJ at saturation): 4 orders of magnitude
- Results can only be explained by 3rd harmonic lasing at 7 nm

Schneidmiller, Faatz, Kuhlmann, Roensch-Schulenburg, Schreiber, Tischer, Yurkov, Phys. Rev. ST-AB 20(2017)020705

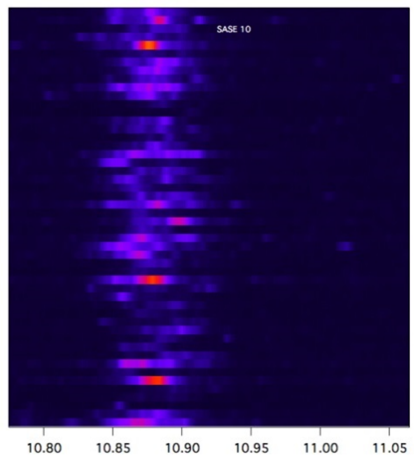
a. HLSS at FLASH2: 11 nm (June 6-7, 2016)

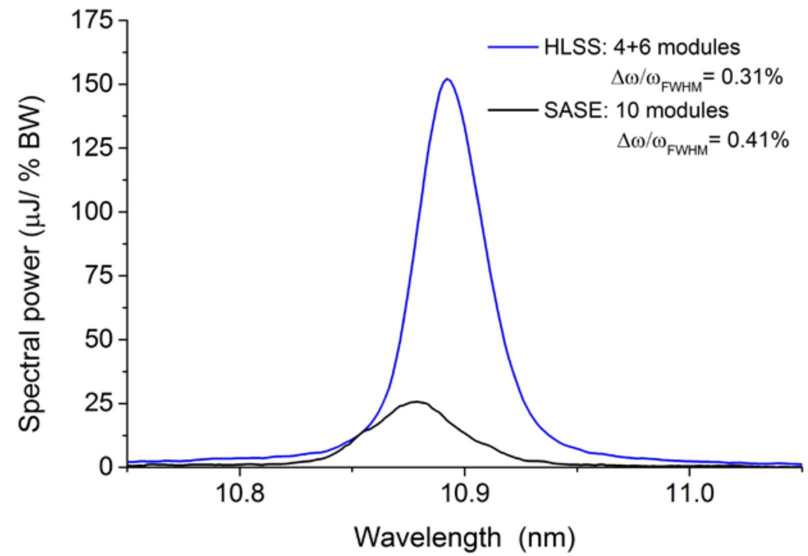
Spectral measurements

HLSS (4+6)



SASE (10)





Expectations

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

R = 1.7

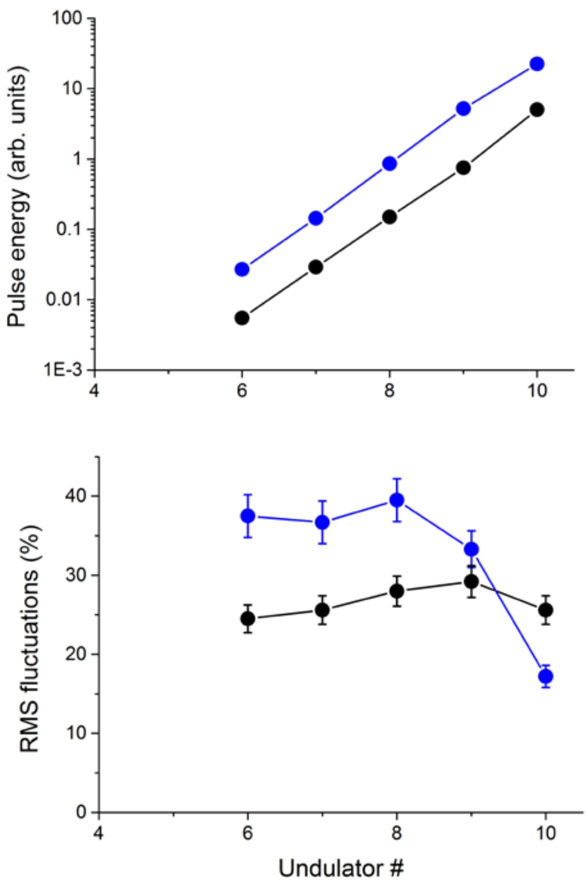
Measured: R = 1.3

Energy chirp!

Schneidmiller, Faatz, Kuhlmann, Roensch-Schulenburg, Schreiber, Tischer, Yurkov, Phys. Rev. ST-AB 20(2017)020705

b. HLSS at FLASH2: 11 nm (June 6-7, 2016)

Statistical determination of an increase of the coherence time



SASE (black) and HLSS (blue)

$$M_l \propto 1/L^{coh}$$

$$M_l = 1/\sigma^2$$

$$\frac{L^{coh}_{HLSS}}{L^{coh}_{SASE}} = \frac{\sigma^2_{HLSS}}{\sigma^2_{SASE}} \simeq 1.8$$

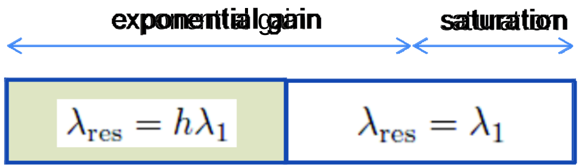
Expectations

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

R = 1.7

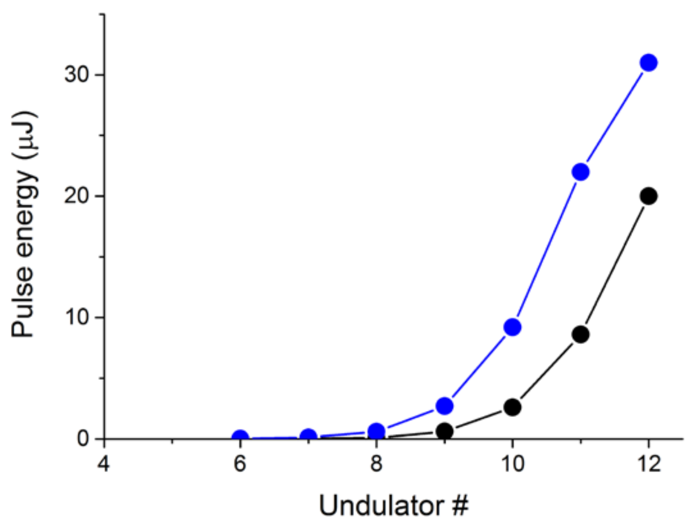
Schneidmiller, Faatz, Kuhlmann, Roensch-Schulenburg, Schreiber, Tischer, Yurkov, Phys. Rev. ST-AB 20(2017)020705

HLSS at FLASH2: 15 nm (Nov. 11, 2016)



4 undulators
45 nm

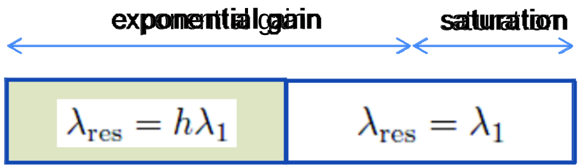
8 undulators
15 nm



Post-saturation taper is applied:
SASE (black) and HLSS (blue)

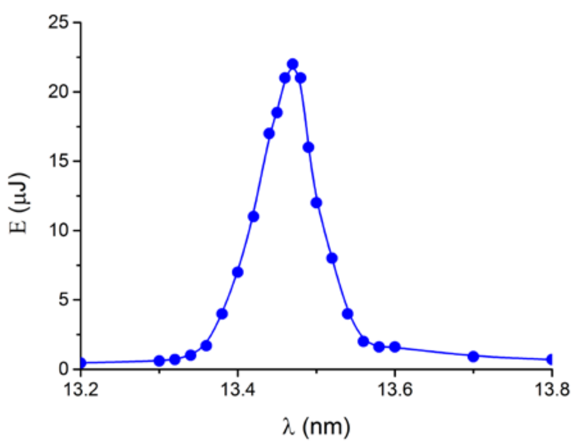
Schneidmiller, Faatz, Kuhlmann, Roensch-Schulenburg, Schreiber, Tischer, Yurkov, Phys. Rev. ST-AB 20(2017)020705

HLSS at FLASH2: 4.5 nm (Sep. 18, 2016)

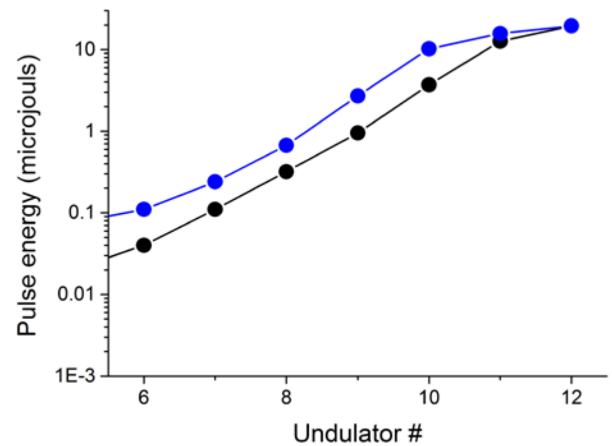


3 undulators
13.5 nm

9 undulators
4.5 nm



K-scan of the first 3 undulators



Gain curve:

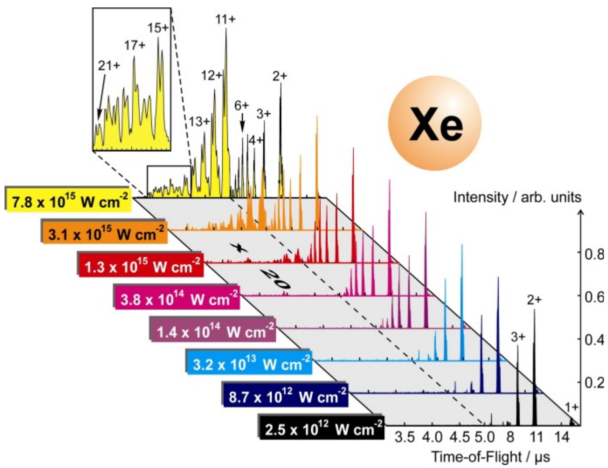
SASE (black) and HLSS (blue)

Schneidmiller, Faatz, Kuhlmann, Roensch-Schulenburg, Schreiber, Tischer, Yurkov, Phys. Rev. ST-AB 20(2017)020705

HLSS for FLASH users (2018)

Proposal: Influence of the coherence of FEL radiation on the multiphoton ionization of highly correlated quantum systems

K. Tiedtke, A.A. Sorokin, M. Richter et al.



A. A. Sorokin, S. V. Bobashev, T. Feigl, K. Tiedtke, H. Wabnitz, and M. Richter, *Photoelectric effect at ultra-high intensities,* Phys. Rev. Lett. **99**, 213002 (2007

- Use SASE and HLSS;
- Keep the same pulse energy, pulse duration, source position etc. but change coherence time.

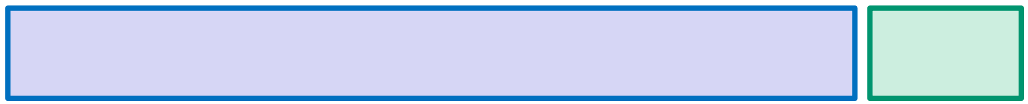
Outline

- Harmonic lasing self-seeded (HLSS) FEL
- Reverse taper
- Two-color operation
- Frequency doubler
- Post-saturation taper
- Coherence properties

Circular polarization production

- Main SASE undulator is planar
- Install helical afterburner
- Try to get rid of powerful linearly polarized radiation from the main undulator

Recent idea: reverse taper



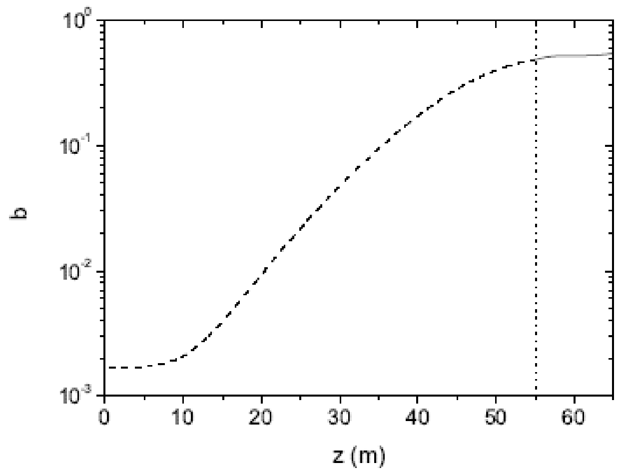
reverse-tapered planar undulator (K increases)

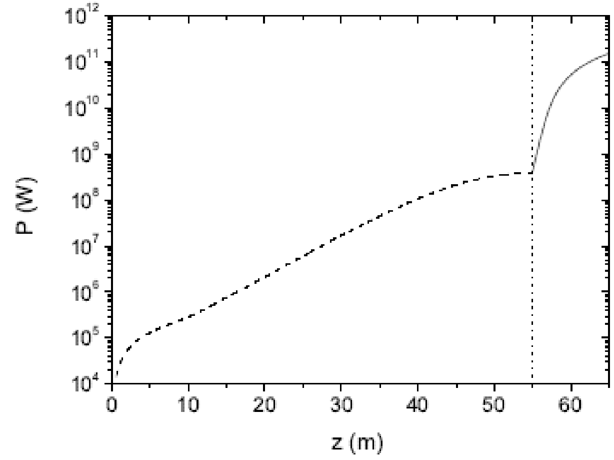
helical afterburner

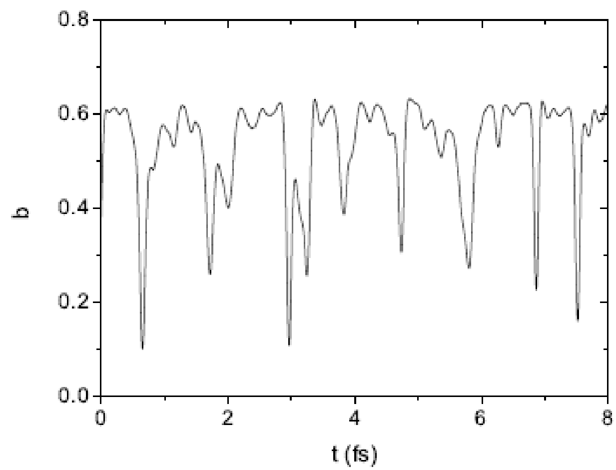
- Fully microbunched electron beam but strongly suppressed radiation power at the exit of reverse-tapered planar undulator
- The beam radiates at full power in the helical afterburner tuned to the resonance

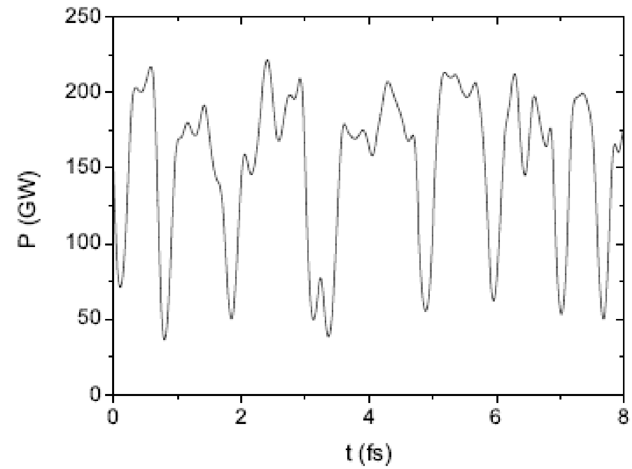
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 110702(2013)16

Results of simulations for European XFEL (SASE3)









≈ 400

bunching

power

Reverse taper at LCLS

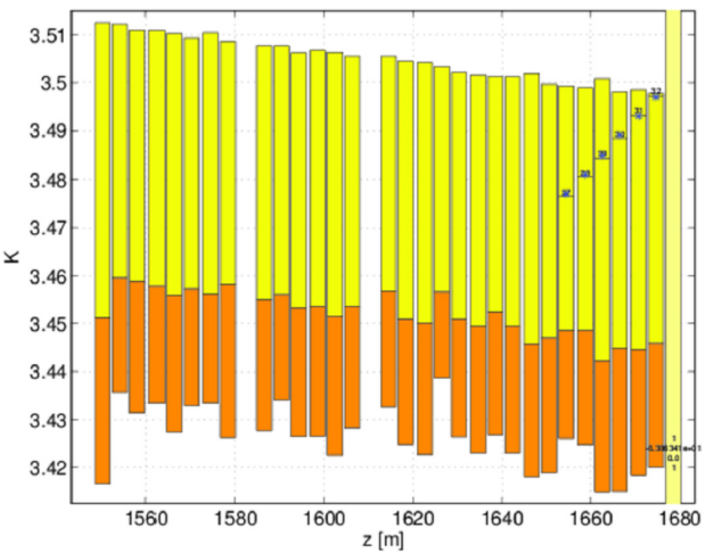
FEL2015 Daejeon Korea, 23rd – 28th August 2015 Heinz-Dieter Nuhn

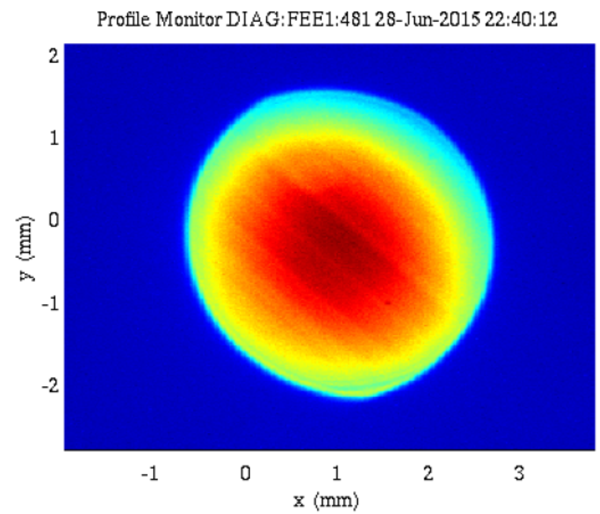
Delta in Enhanced Afterburner Configuration at 710 eV

SLAC

Reverse Taper

E.A. Schneidmiller, M.V. Yurkov, “Obtaining high degree of circular polarization at X-ray FELs via a reverse undulator taper”, arXiv:1308.3342 [physics.acc-ph]





- X-ray growth suppressed during reverse taper

- 30 μJ with Delta off
- 510 μJ with Delta on

Peak Current increased above 4 kA

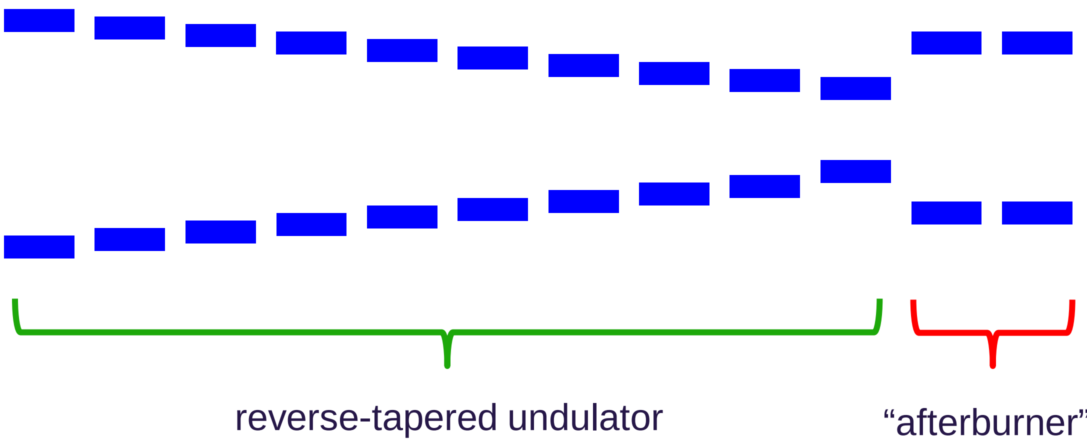
James MacArthur WEP004

24

Courtesy H.-D. Nuhn

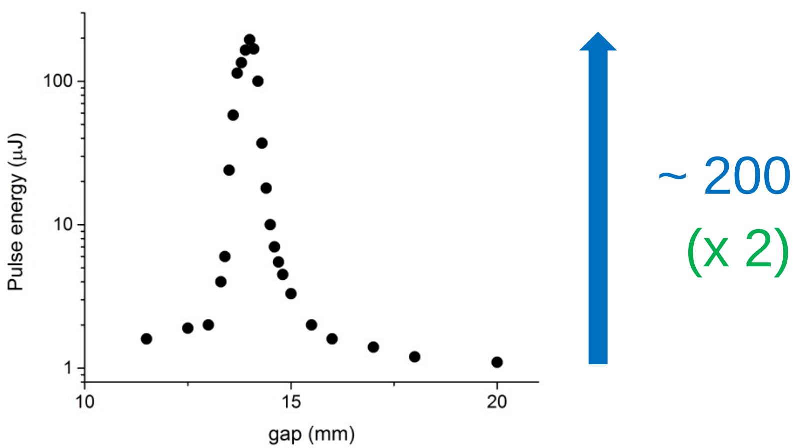
Reverse taper experiment at FLASH2

23.01.2016



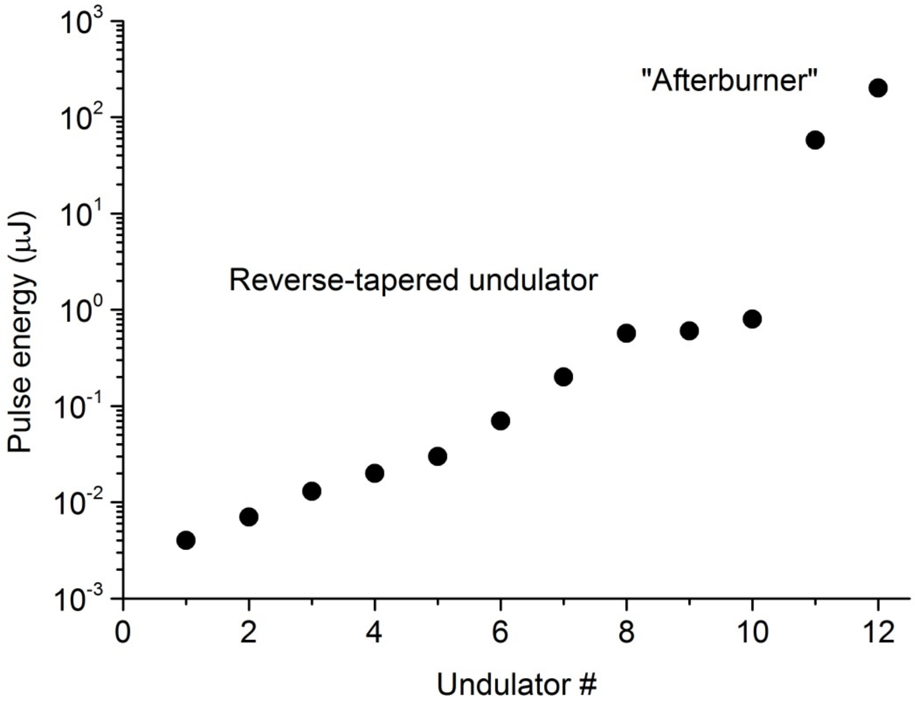
Beam energy 720 MeV, wavelength 17 nm.

Reverse taper was applied to the 10 undulator segments; the gap of the 11th and 12th segments was scanned.



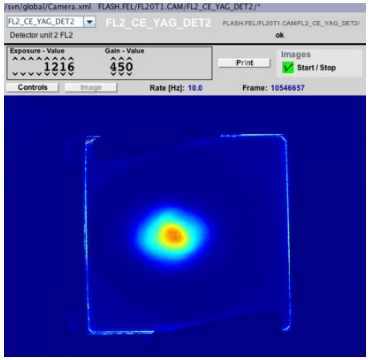
Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.

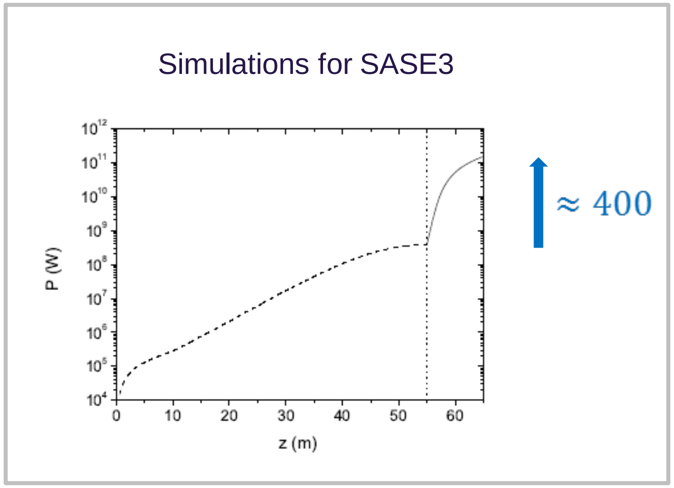
Reverse taper experiment at FLASH2 (cont'd)



~ 200

(x 2)

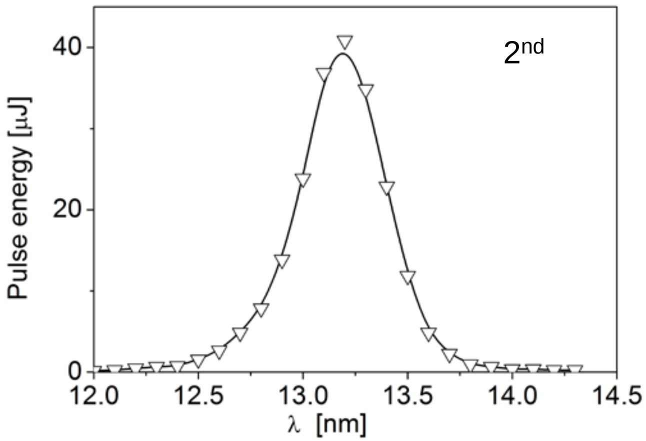


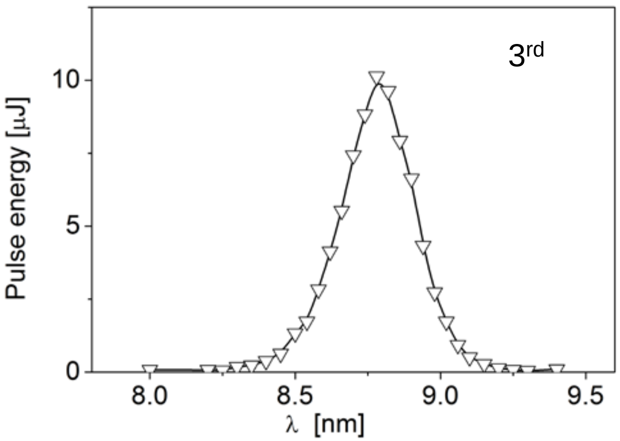


$$\beta = -\frac{\lambda_{\mathrm{w}}}{4\pi\rho^2}\,\frac{K(0)}{1+K(0)^2}\,\frac{dK}{dz}$$

Reverse taper plus harmonic afterburner

- Experiment at FLASH2 on Oct. 10, 2016:
- Main undulator: 9 modules, 26.5 nm, -5% taper.
- Afterburner: 2 modules, 26.5 nm, 13.2 nm, 8.8 nm
- Pulse energy after tapered part: < 1 microjoule
- Afterburner on the fundamental: 150 microjoules
- 2nd harmonic: 40 microjoules
- 3rd harmonic: 10 microjoules





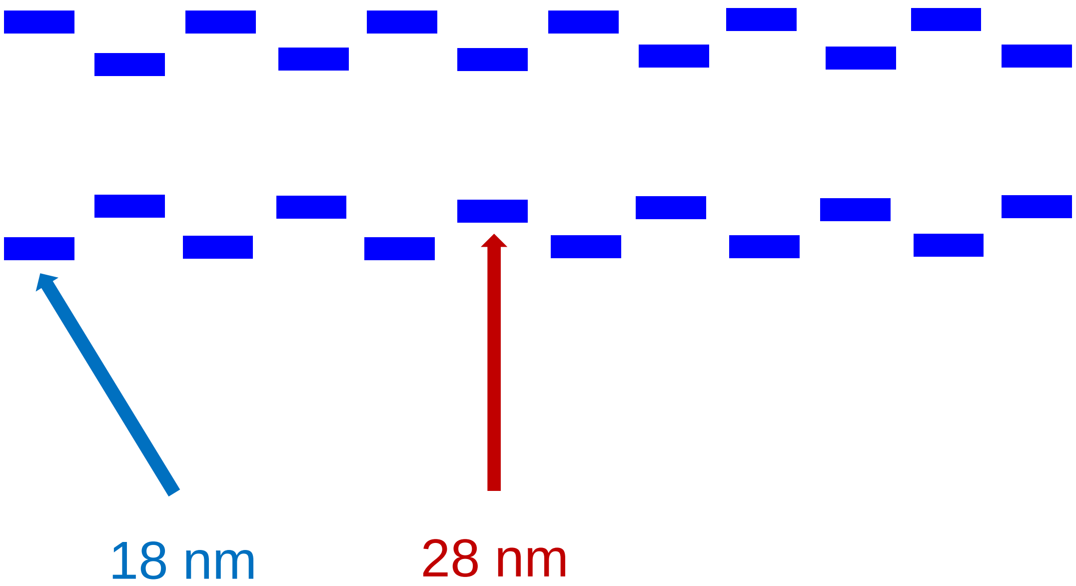
Reverse taper can be used for efficient background-free generation of harmonics in an afterburner;

Outline

- Harmonic lasing self-seeded (HLSS) FEL
- Reverse taper
- Two-color operation
- Frequency doubler
- Post-saturation taper
- Coherence properties

Two-color operation (same bunch)

22.10.2018



Beam energy 675 MeV,
wavelengths 18 and 28 nm.

Segments with “wrong” wavelength are active elements: bunching due to R56

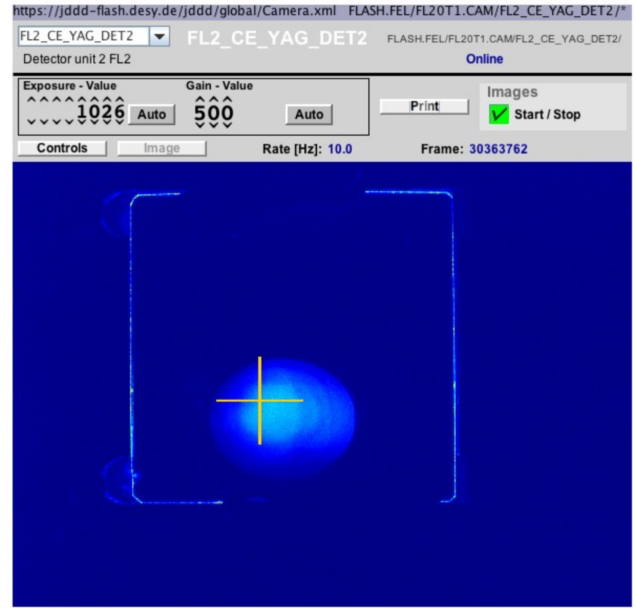
Source positions are close to each other.

In linear regime two colors are independent, in nonlinear regime they are not. We aim at nonlinear regime (possibly close to saturation). One cannot measure intensity of one color by suppressing the other!

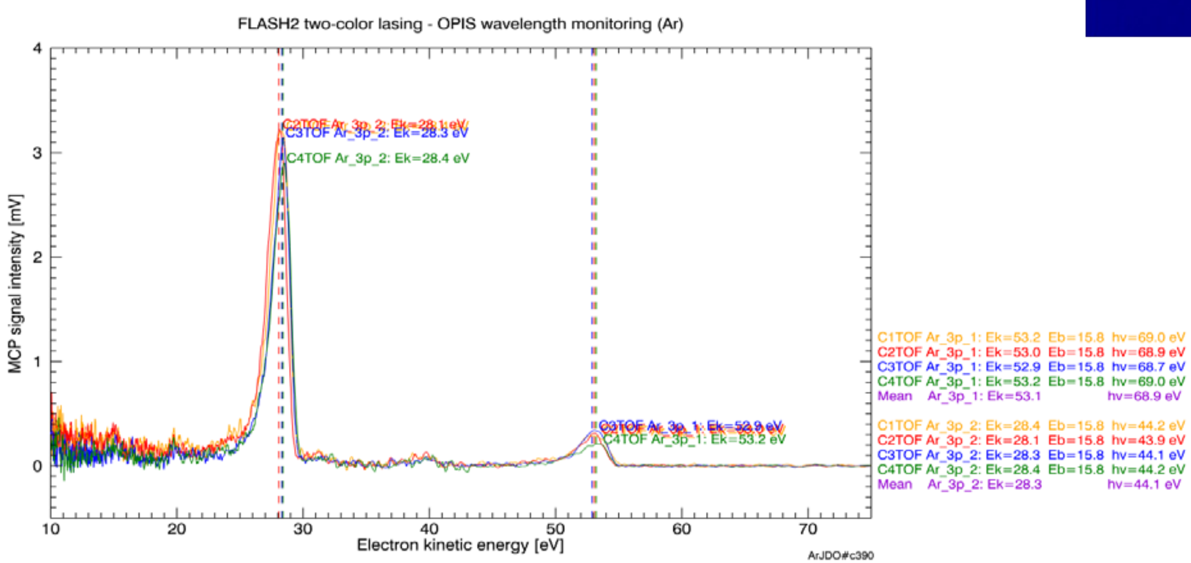
A possible solution: two GMDs (or consequently two gases in the same GMD), cross-sections are known, two linear equations with two unknowns.

Or GMD and OPIS.

Two-color operation (cont'd)



From GMD and OPIS measurements the pulse energies can be estimated at ~ 5 uJ for 18 nm and ~ 20 uJ for 28 nm



Measurement by M. Braune

Summary for part 1

- Harmonic lasing was demonstrated at FL2: first time in a high-gain FEL and at a short wavelengths
- Harmonic lasing self-seeded (HLSS) FEL allows to improve longitudinal coherence; demonstrated at FL2
- Reverse taper is an option for polarization control and background-free production of harmonics: demonstrated at FL2.
- Two-color operation (one bunch, non-multiple colors) tested at FL2
- All these options are considered for FLASH2020+, will be used at EuXFEL

FEL studies at FLASH2 in the period 2016-2018:
Advanced modes of operation and characterization of the radiation properties

E.A. Schneidmiller and M.V. Yurkov (DESY, Hamburg)

Part 1:

- ✓ Studies of the reverse undulator tapering.
- ✓ Harmonic lasing self-seeded FEL.
- ✓ Two color mode of operation.

Part 2:

- ✓ **Frequency doubler at FLASH2 operating in the water window.**
- ✓ **Studies of the post-saturation undulator tapering .**
- ✓ **Studies of the coherence properties of the radiation from SASE FEL using statistical methods.**

Background for advanced developments

Harmonic lasing self-seeded FEL at FLASH2:

E.A. Schneidmiller, and M.V. Yurkov, Harmonic lasing in x-ray free electron lasers, Phys. Rev. ST Accel. Beams 15 (2012) 080702.

E.A. Schneidmiller, and M.V. Yurkov, Studies of harmonic lasing self-seeded FEL at FLASH2, Proc. IPAC2016, MOPOW009.

Studies of the reverse undulator tapering at FLASH2:

E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 16 (2013) 110702.

E.A. Schneidmiller and M.V. Yurkov, Reverse undulator tapering for polarization controls at XFELs, Proc. IPAC2016, MOPOW008

Studies of the post-saturation undulator tapering at FLASH2:

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, The Physics of Free Electron Lasers (Springer-Verlag, Berlin, 1999).

E.A. Schneidmiller, and M.V. Yurkov, Optimization of a high efficiency free electron laser amplifier, Phys. Rev. ST Accel. Beams 18 (2015) 030705.

E.A. Schneidmiller, and M.V. Yurkov, The universal method for optimization of undulator tapering in FEL amplifiers, Proc. SPIE Vol. 9512, 951219 (2015).

Efficient frequency doubler at FLASH2 operating in the water window:

J. Feldhaus, M. K¨orfer, T. M¨oller, J. Pfl¨uger, E.L. Saldin, E.A. Schneidmiller, M.V.Yurkov, Efficient frequency doubler for the soft X-ray SASE FEL at the TESLA Test Facility, Nucl. Instrum. and Methods A 528 (2004) 471-475.

Studies of the coherence properties of the radiation from SASE FEL using statistical methods:

E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Statistical properties of radiation from VUV and X-ray free electron lasers, Optics Communications 148(1998)383.

V. Ayvazyan et al., Study of the statistical properties of the radiation from a VUV SASE FEL operating in the femtosecond regime, Nucl. Instrum. and Methods A507(2003)368.

C. Behrens et al., Constraints on photon pulse duration from longitudinal electron beam diagnostics at a soft x-ray free-electron laser, Phys. Rev. ST Accel. Beams 15 (2012) 030707.

S. Duesterer et al., Development of experimental techniques for the characterization of ultrashort photon pulses of extreme ultraviolet free-electron lasers, Phys. Rev. ST Accel. Beams 17 (2014) 120702.

E.A. Schneidmiller, and M.V. Yurkov, Application of Statistical Methods for Measurements of the Coherence Properties of the Radiation from SASE FEL, Proc. IPAC2016, MOPOW013.

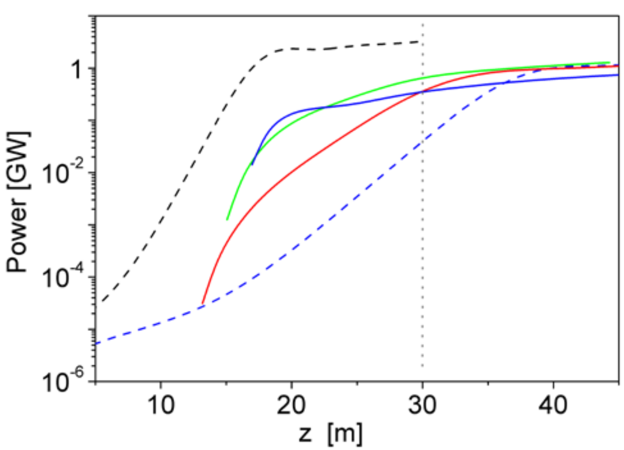
Frequency doubler

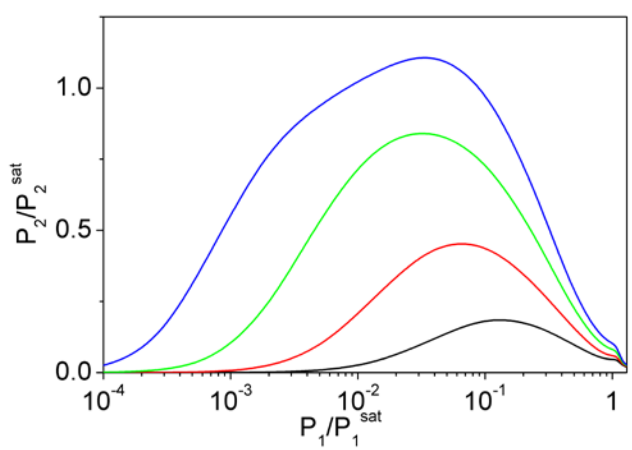
- Undulator is divided in two parts. The second part is tuned to the double frequency of the first part.
- Amplification process in the first undulator part is stopped at the onset of the nonlinear regime, such that nonlinear higher harmonic bunching in the electron beam density becomes pronouncing, but the radiation level is still small to disturb the electron beam significantly.
- Modulated electron beam enters the second part of the undulator and generates radiation at the 2^{nd} harmonic.
- Frequency doubler allows operation in a two-color mode and operation at shorter wavelengths with respect to standard SASE scheme.

Frequency doubler

Left plot: Dashed curves correspond to SASE FEL operating at 8 nm (black) and at 4 nm (blue). Solid curves correspond to frequency doubler 8 nm to 4 nm for different lengths of the 1w undulator section (red, green, and blue colors).

Right plot: Parameter space of radiation powers from frequency doubler at FLASH2. P1 is radiation power at 1ω (8 nm) at the exit of the first section, and P2 is radiation power at 2ω (4 nm) at the exit of the doubling section. Radiation powers are normalized to the saturation powers of SASE FEL: 2.3 GW and 1 GW for 8 nm, and 4 nm, respectively. Different colors (black, red, green, and blue) denote lengths of the doubling section in terms of the saturation length: 1/6 z_{sat}, 1/3 z_{sat}, 1/2 z_{sat}, and 2/3 z_{sat}.





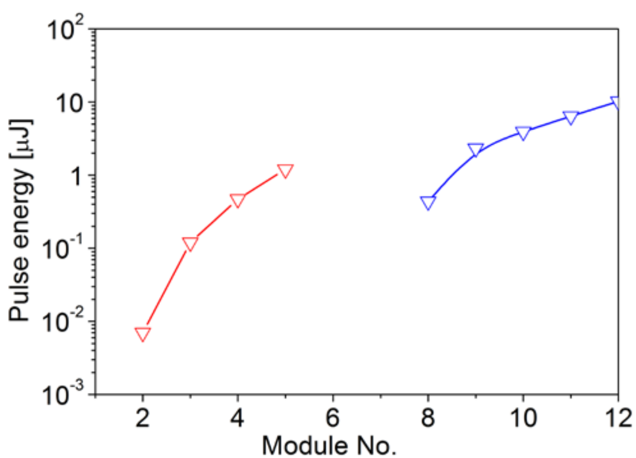
FAST simulations: electron energy is 1080 MeV, beam current is 1500 A, normalized rms emittance 1 mm-mrad, and rms energy spread 0.15 MeV.

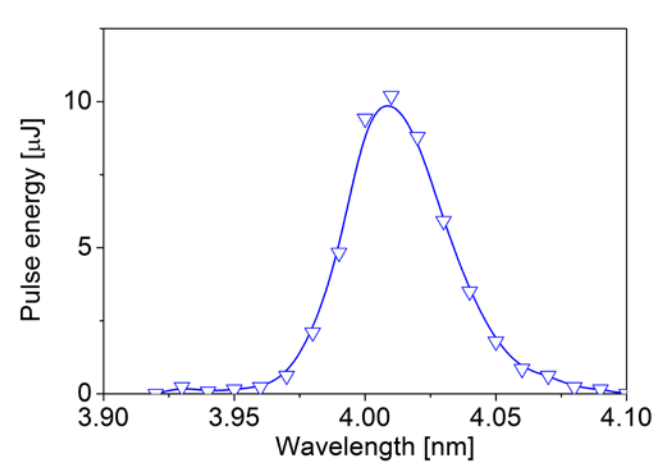
Frequency doubler

- We had three successful shifts for tuning frequency doubler:
  - September 15, 2016 (1080 MeV)
  - September 23, 2016 (1230 MeV)
  - November 15, 2018 (1224 MeV)

SASE configuration: 12 modules

Doubler configuration: 5u x ω + 7u x 2ω





Example: experimental results for frequency doubler 8 nm ➔ 4 nm at 1080 MeV.

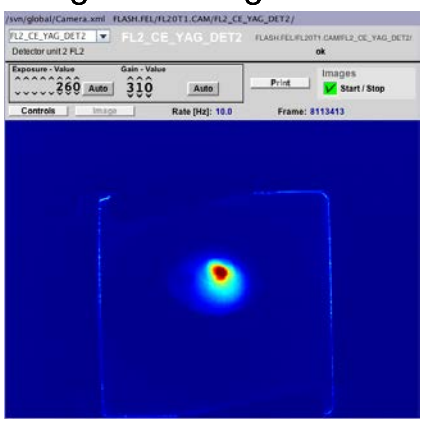
Frequency doubler: two color mode of operation

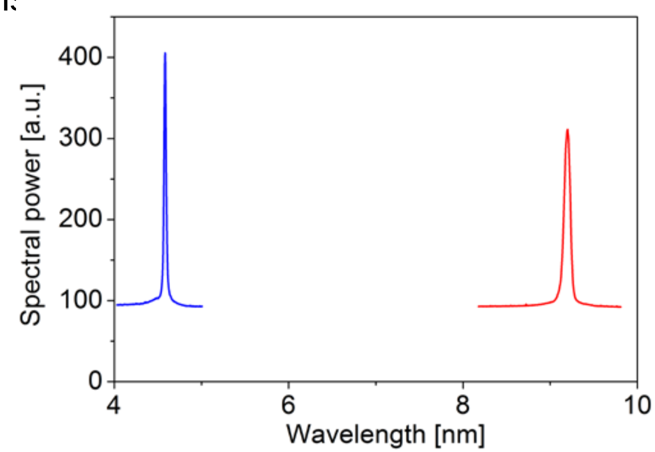
14.09.2016 22:59 Schneidmiller/Yurkov/ **Summary on frequency doubler operation at FLASH2**

FLASH2: Electron energy 1073.8 MeV, bunch charge 350 pC, 160 uJ SASE @ 9 nm, 120 uJ SASE @ 8 nm.
Doubler configuration: 5u x ω + 7u x 2ω

Successful demonstration of frequency doubler and two-color operation in the water window:
- 10 uJ at 9 nm and 10 uJ at 4.5 nm (4 uJ SASE at 4.5 nm and 12 modules)
- 3 uJ at 8 nm and 4 uJ at 4 nm (~ 0.1 uJ SASE at 4 nm and 12 modules)

Extrapolation of obtained results to the energy of 1.25 GeV: it would be possible to operate FLASH2 at the wavelength down to 3 nm. Radiation pulse energy will depend on quality of electron bunch. With good tuning 10 uJ level seems to be possible.



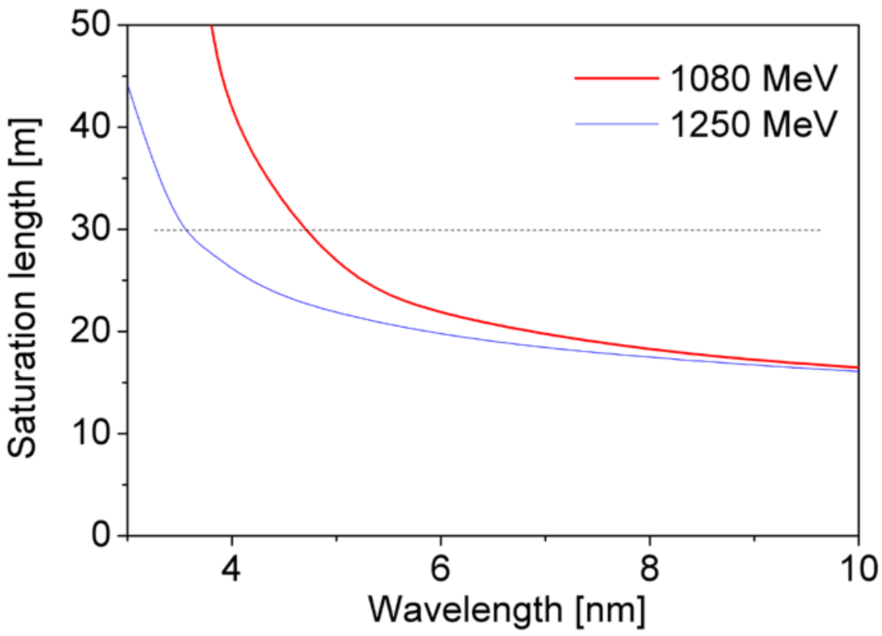


Courtesy to Marion Kuhlmann

Example: frequency doubler, two color mode of operation with 9 nm and 4.5 nm.
Small red spot is 4.5 nm (2nd harmonic) radiation, 10 uJ. Larger blue spot is 9 nm radiation, 10 uJ.

Shortest wavelengths at FLASH2

Challenging problem: lasing of SASE2 at the photon energies of 400 eV (3.2 nm) – Nitrogen K-edge.



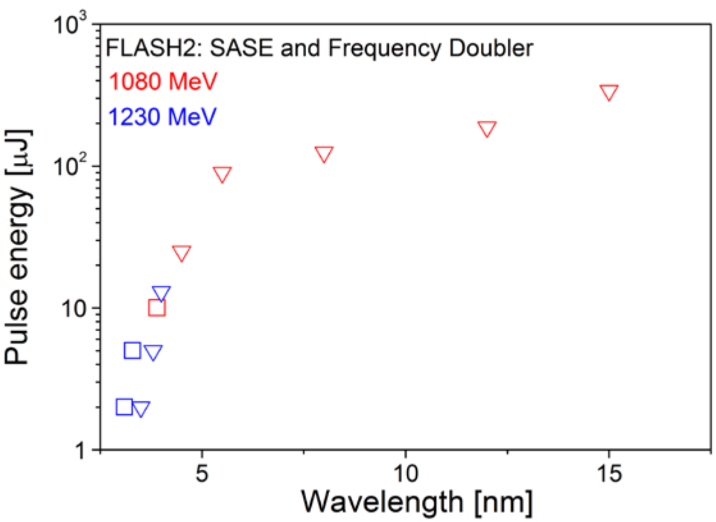
Saturation length of SASE FEL at FLASH2 versus radiation wavelength (blue curve). Gray dashed line at z = 30 m shows magnetic length of FLASH2 undulator. Electron energy is 1080 MeV and 1250 MeV, beam current is 1500 A, normalized rms emittance 1 mm-mrad, and rms energy spread 0.15 MeV.

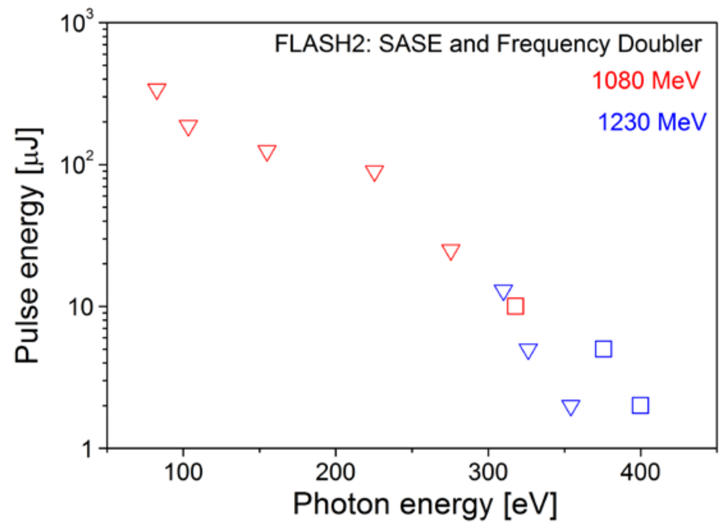
Shortest wavelengths at FLASH2

On September 15 and 23, 2016 accelerator operated with the energy of 1080 MeV and 1230 MeV. We got dedicated shifts within the FLASH studies program for the topic "Efficient frequency doubler at FLASH2 operating in the water window".

SASE configuration: 12 modules

Doubler configuration: 5u x ω + 7u x 2ω





Triangles - SASE

Squares - doubler

For "usable" range of the radiation pulse enrgies above 1 uJ, FLASH2 demonstrated operation down to 3.5 nm in the SASE mode, and down to 3.1 nm in the frequency doubler mode.

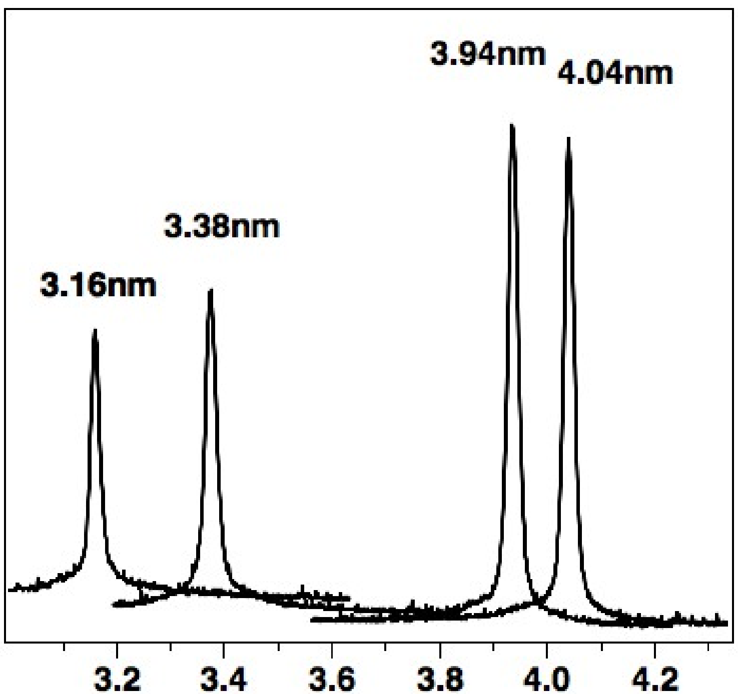
Shortest wavelengths at FLASH2

Doubler configuration: 5u x ω + 7u x 2ω

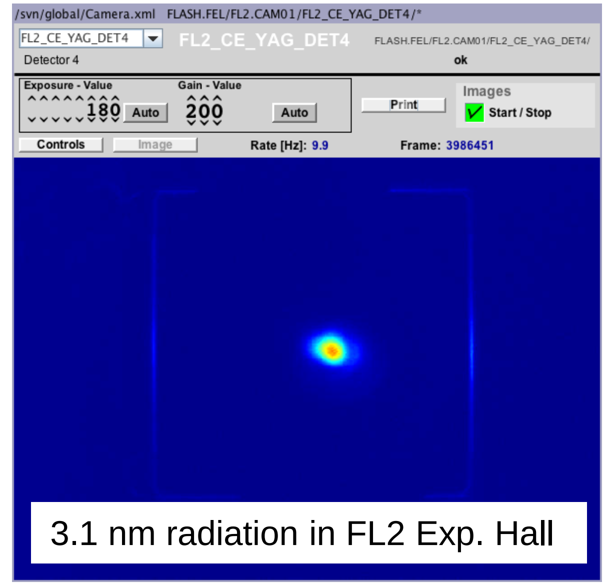
Minimum wavelength of frequency doubler:

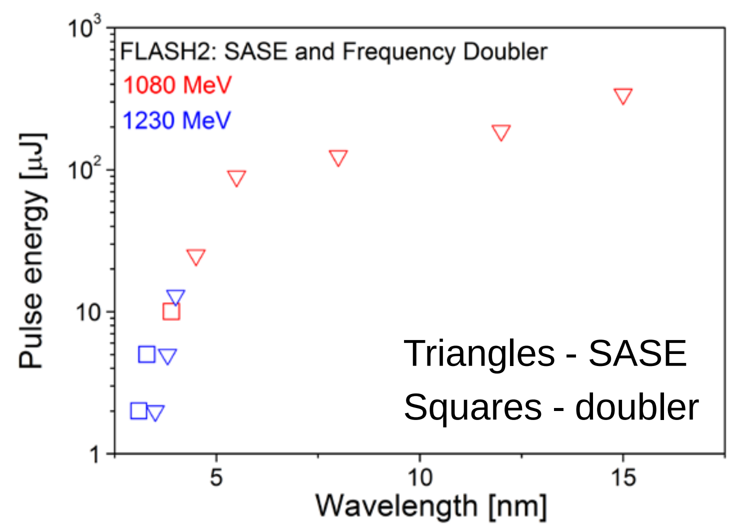
3.9 nm at 1080 MeV

3.1 nm at 1230 MeV



Courtesy to Marion Kuhlmann





Spectrum bandwith of the radiation from frequency doubler is 0.5% FWHM.

Frequency doubler and SASE at maximum electron energy: 2016 vs 2018

Shifts: September 15, 2016 (1080 MeV)

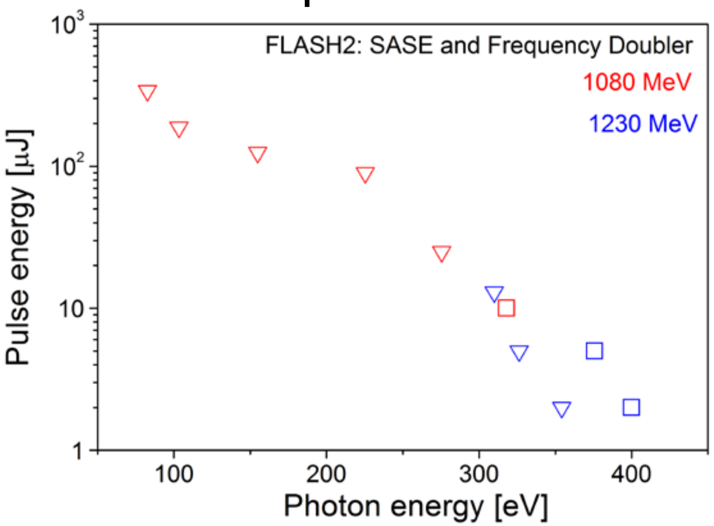
September 23, 2016 (1230 MeV)

November 15, 2018 (1224 MeV)

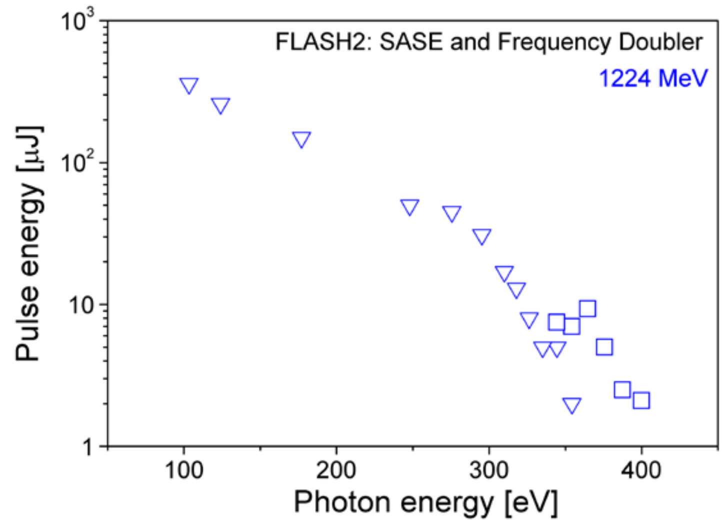
SASE configuration: 12 modules

Doubler configuration: 5u x ω + 7u x 2ω

September 2016



November 2018



Triangles - SASE

Squares - doubler

Reproducible results for both: SASE and frequency doubler

With present maximum electron energy of 1.23 GeV we just touch Nitrogen K-edge (400 eV). For reliable operation for users we need to increase electron energy.

Post saturation undulator tapering for efficiency increase

- Application of post saturation undulator tapering allows to preserve resonance interaction of electrons and radiation and increase FEL efficiency.

- Resonance condition: Electromagnetci wave advances the electron by one wave-length when electron passes one undulator period:

$$\frac{\lambda_{\mathrm{w}}}{v_{\mathrm{z}}} = \frac{\lambda}{c - v_{\mathrm{z}}} \ , \qquad \lambda \simeq \frac{\lambda_{\mathrm{w}}}{2\gamma_{\mathrm{z}}^2} = \lambda_{\mathrm{w}} \frac{1 + K^2}{2\gamma^2} .$$

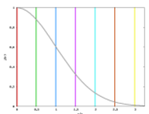
- Undulator tapering: originally proposed by [N.M. Kroll, P.L. Morton, and M.N. Rosenbluth, IEEE J. Quantum Electronics, QE-17, 1436 (1981)] for increasing the radiation power in the post-saturation regime preserving resonance condition:

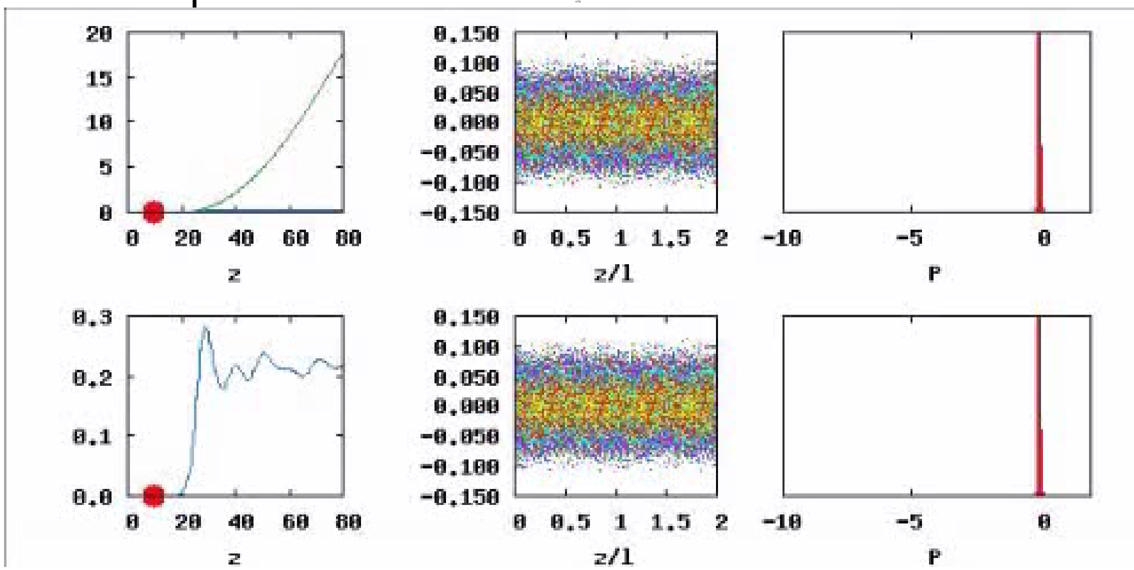
$$\lambda \simeq \lambda_{\mathrm{w}}(z) \frac{1 + K^2(z)}{2\gamma^2(z)} .$$

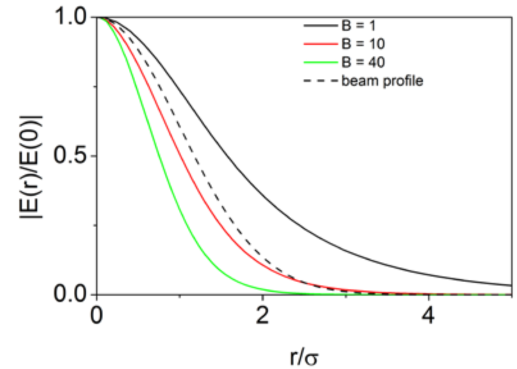
Seeded FEL, optimum tapering: how it works

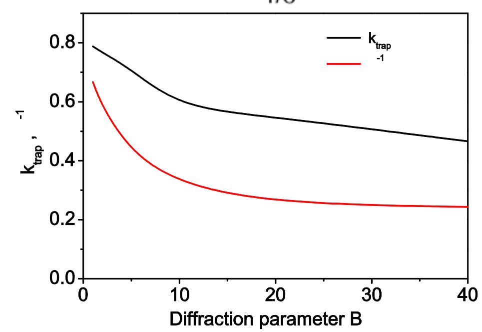
Top: tapered

Bottom: untapered









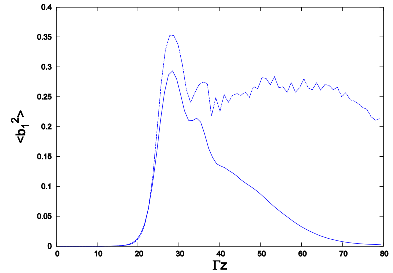
$$\hat{C} = \alpha_{tap}(\hat{z} - \hat{z}_0)\left[\arctan\left(\frac{1}{2N}\right) + N\ln\left(\frac{4N^2}{4N^2+1}\right)\right] , \qquad N = \frac{\beta_{tap}}{(\hat{z} - \hat{z}_0)}$$

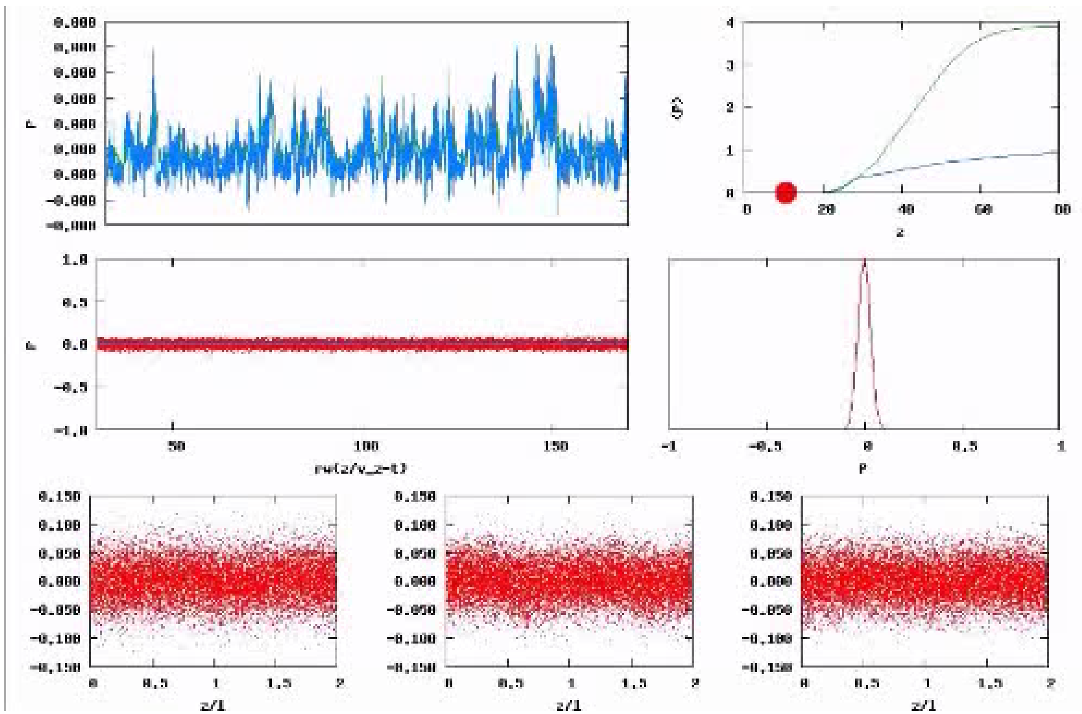
- The particles in the core of the beam (red, green, blue color) are trapped most effectively. Nearly all particles located at the edge of the electron beam (braun, yellow color) leave the stability region very soon. The trapping process lasts for a several field gain lengths when the trapped particles become to be isolated in the trapped energy band for which the undulator tapering is optimized further. Non-trapped particles continue to populate low energy tail of the energy distribution.

E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST AB 18 (2015) 030705

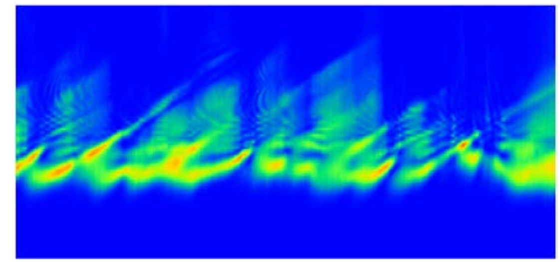
SASE FEL, optimum tapering: how it works

- Left: slice radiation power and energy loss; phase space
- Right: bunching, average power, particle energy spectrum

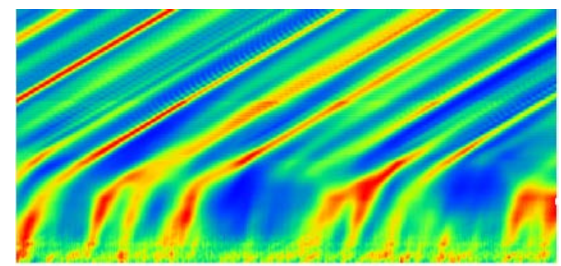




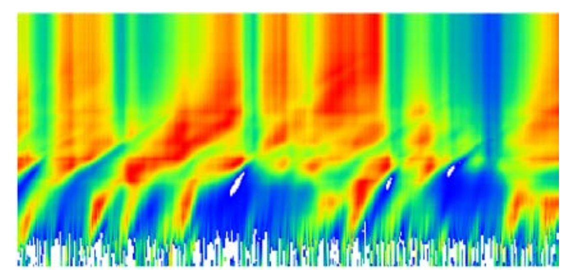
Bunching



Radiation power



Energy loss



z

z

$$\hat{C} = \alpha_{tap}(\hat{z} - \hat{z}_0) \left[\arctan\left(\frac{1}{2N}\right) + N \ln\left(\frac{4N^2}{4N^2+1}\right) \right] , \qquad N = \frac{\beta_{tap}}{(\hat{z} - \hat{z}_0)}$$

$$\hat{s} = \rho\omega(z/v_z - t)$$

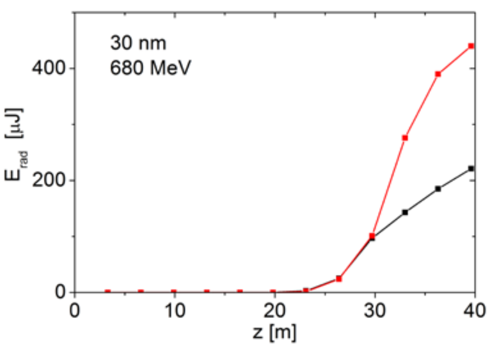
E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST AB 18 (2015) 030705

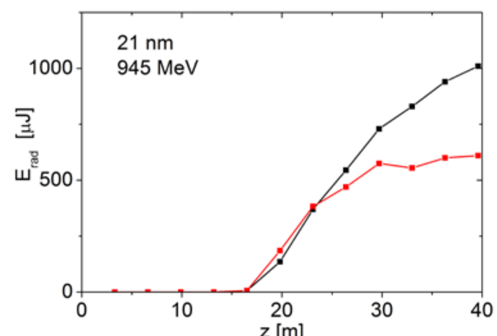
Post-saturation undulator tapering for efficiency increase

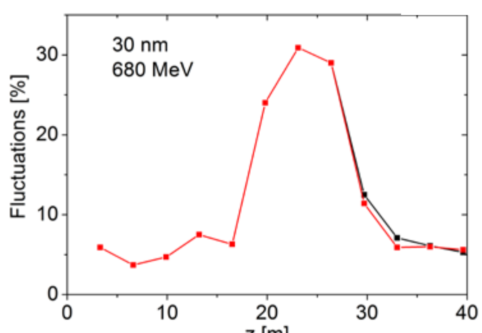
Use of statistical measurements for tuning optimum undulator tapering:

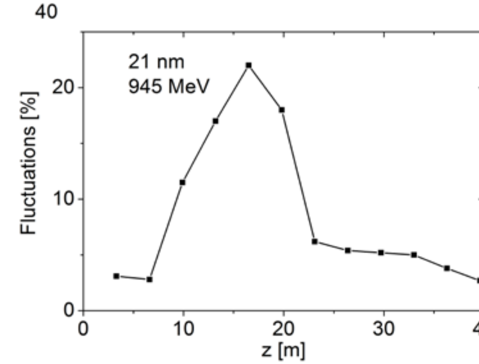
- Optimum conditions of the undulator tapering assume the starting point to be by two field gain lengths before the saturation point (Phys. Rev. ST AB 18, 030705 (2015)) corresponding to the maximum brilliance of the SASE FEL radiation.
- Saturation point on the gain curve is defined by the condition for fluctuations to fall down by a factor of 3 with respect to their maximum value in the end of exponential regime.
- Then quadratic law of tapering is applied (optimal for moderate increase of the extraction efficiency at the initial stage of tapering).

Experimental results from FLASH 2, January-May 2016









Post-saturation undulator tapering for efficiency increase

Logbook entry: /TTFelog/data/2016/17/01.05_a

01.05.2016 22:59 Schneidmiller/Yurkov

FL2 Summary: transverse coherence, tapering, harmonic lasing

Energy 945 MeV
Wavelength 21 nm

Successful developments:

1. Measurements of transverse coherence with pinhole statistical technique.
2. Undulator **tapering** > 1 mJ pulse energy
3. Operation of Harmonic Lasing Self Seeded (HLSS) scheme has been demonstrated.

==============================

1. Measurements of transverse coherence with pinhole statistical technique.

Goal: develop technique of pinhole statistical measurements for measurements of the degree of transverse coherence.
Background: In the high gain exponential regime squared ratio of energy fluctuations full to pinhole is degree of transverse coherence.
Fluctuations in 1 mm / 10 mm aperture measured along the undulator.
5 modules correspond to the end of exponential regime.
After 5 undulator modules:
Aperure: 10 mm: energy 2.5 uJ, fluctuations 22%
Aperure: 1 mm: energy 0.12 uJ, fluctuations 24.5%
Degree of transverse coherence at the onset of saturation: 81% = (22/24.5)^2
==============================
2. Undulator **tapering** > 1 mJ pulse energy
Untapered undulator: pulse energy 690 uJ
Tapered undulator: pulse energy 1.02 mJ
Quadratic taper, (n-5)^2, max dK/K = 2.8%
Start of **tapering** is chosen according to the rule of 2 field gain length before saturation
(derived in Phys. Rev. ST AB 18, 030705 (2015)),
see entry http://ttfinfo.desy.de/TTFelog/show.jsp?dir=/2016/05/03.02_a&pos=2016-02-04T22:58:00

Note that saturation point is defined by x3 drop of fluctuations wrt maximum value in the end of exponential regime.

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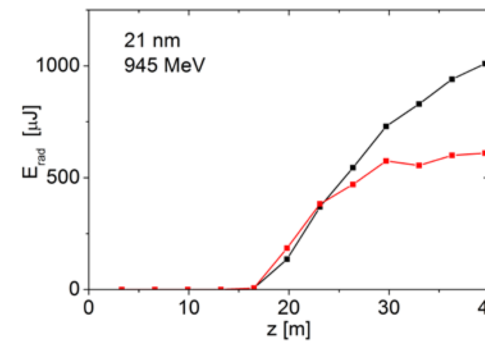
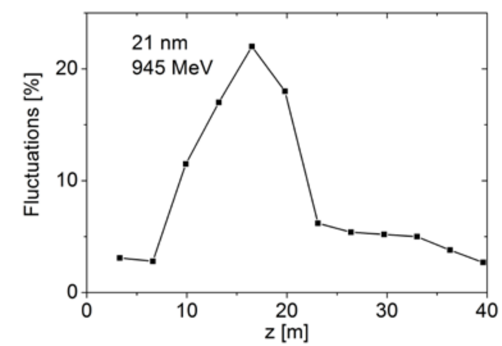




How to: Practical receipts for operators

Statistical fluctuation method

- SASE FEL operating in linear regime holds features of completely chaotic polarized light - fundamenatl statistical object described by gaussian statistics.

- The probability density function of the radiation pulse energy, $p(E)$, follows the gamma distribution:

$$p(E) = \frac{M^M}{\Gamma(M)} \left(\frac{E}{<E>}\right)^{M-1} \frac{1}{<E>} \exp\left(-M\frac{E}{<E>}\right) \ ,$$

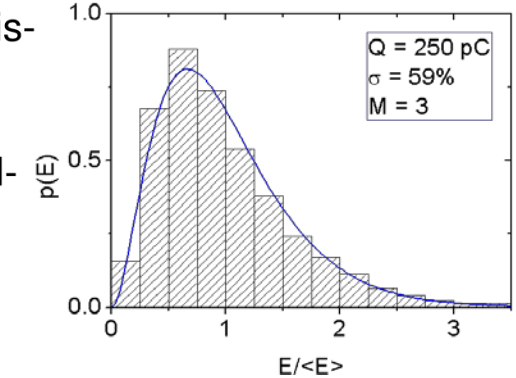
$$M^{-1} = \sigma^2 = < (E - < E >)^2 > / < E >^2$$

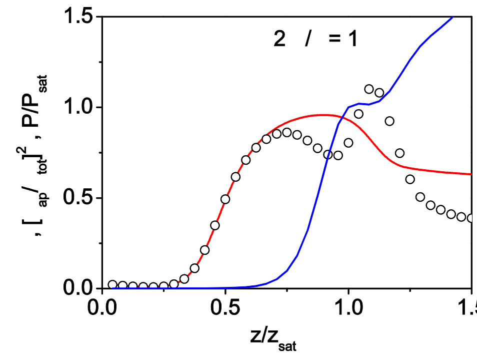
  Parameter M has physical sence of the number of modes in the radiation pulse.

- Total number of modes is product of the number of longitudinal modes by the number of transverse modes.

- Measurements of the fluctuations of the total pulse energy and of the radiaiton energy after a pinhole gives us the number of longitudinal modes, and the total number of modes.

- Their ratio gives the number for the degree of transverse coherence.





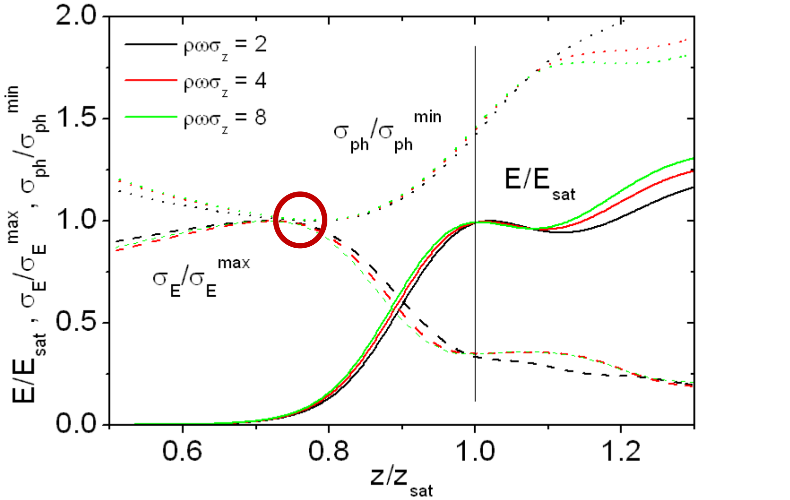
Degree of transverse coherence (red)
FEL power (blue).
Circles: the ratio of fluctuations of the total radiation energy to the fluctuations of the radiation energy in a pinhole.

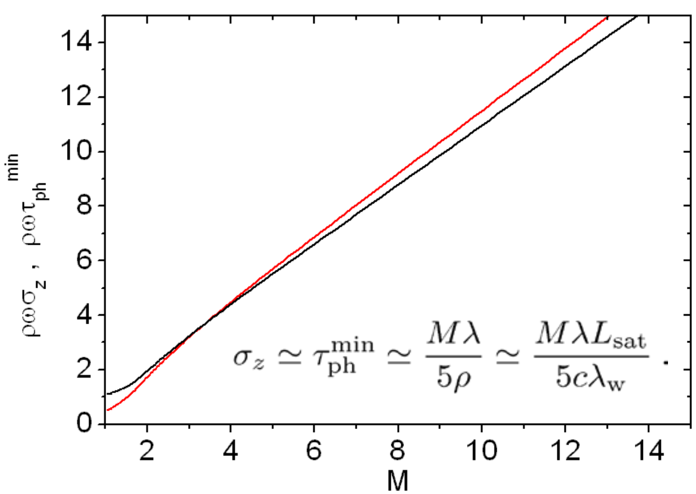
E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Opti. Comm. 148(1998)383.
V. Ayvazyan et al., Pys. Rev. Lett. 2002
S. Ackermann et al., Nature Photonics 1 (2007) 346.

C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)
E.A. Schneidmiller and M.V. Yurkov, Proc. IPAC2016, MOPOW013.

Statistical fluctuation method
Coherence time. Pulse duration

C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 030707 (2012)





Maximum value of the coherence time and saturation length

$$(\tau_{\rm c})_{\max} \simeq \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_{\rm c}}{18}}\,, \qquad L_{\rm sat} \simeq \frac{\lambda_{\rm w}}{4\pi\rho}\left(3+\frac{\ln N_{\rm c}}{\sqrt{3}}\right)\,,$$

are expressed in terms of the FEL parameter ρ and the number of cooperating electrons $N_{\rm c} = I/(e\rho\omega)$. Practical estimate for parameter ρ comes from the observation that in the parameter range of SASE FELs operating in the VUV and x-ray wavelength range, the number of field gain lengths to saturation is about 10. Thus, the parameter ρ and coherence time $\tau_{\rm c}$ relate to the saturation length as:

$$\rho \simeq \lambda_{\rm w}/L_{\rm sat}\,, \qquad \tau_{\rm c} \simeq \lambda L_{\rm sat}/(2\sqrt{\pi}c\lambda_{\rm w})\,.$$

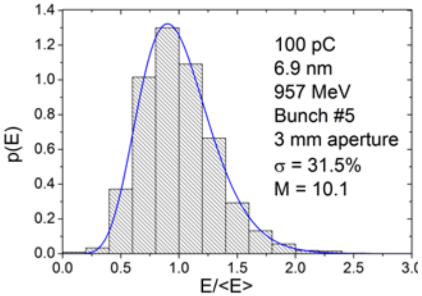
For the number of modes $M \gtrsim$ 2m the rms electron pulse length and minimum FWHM radiation pulse length $\tau_{\rm ph}^{\rm min}$ in the end of the linear regime are given by:

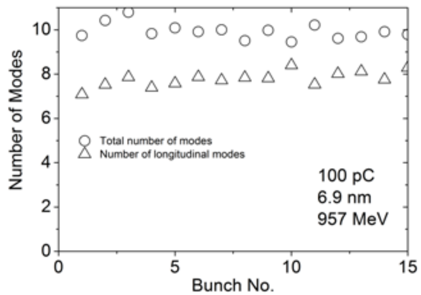
$$\tau_{\rm ph}^{\rm min} \simeq \sigma_z \simeq \frac{M\lambda}{5\rho} \simeq \frac{M\lambda L_{\rm sat}}{5c\lambda_{\rm w}}\,.$$

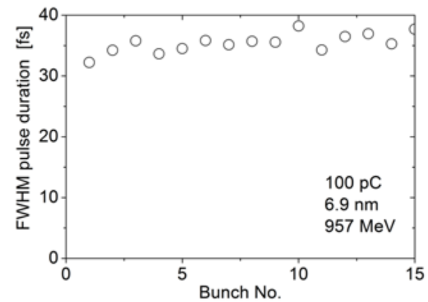
Minimum radiation pulse duration expressed in terms of coherence time is $\tau_{\rm ph}^{\rm min} \simeq 0.7 \times M \times \tau_{\rm c}$.

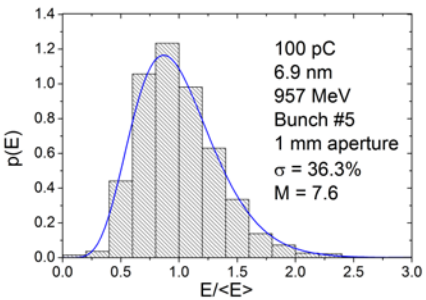
Statistical fluctuation method
Degree of transverse coherence

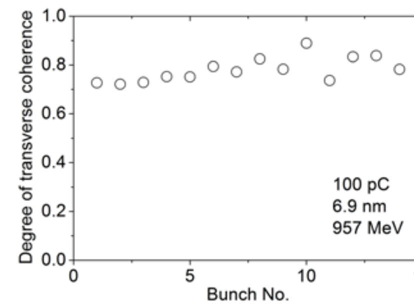
Experimental results from FLASH1, 01.05.2016









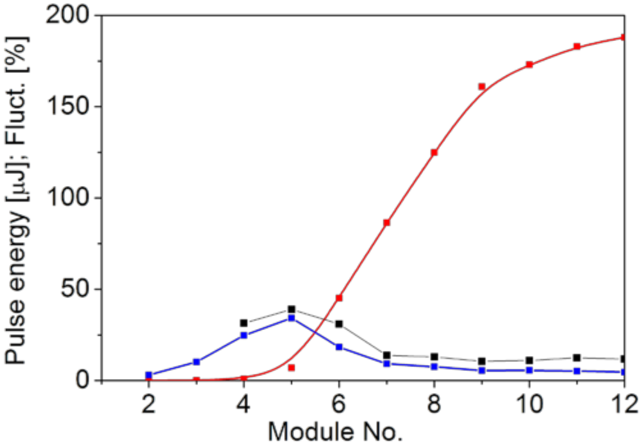


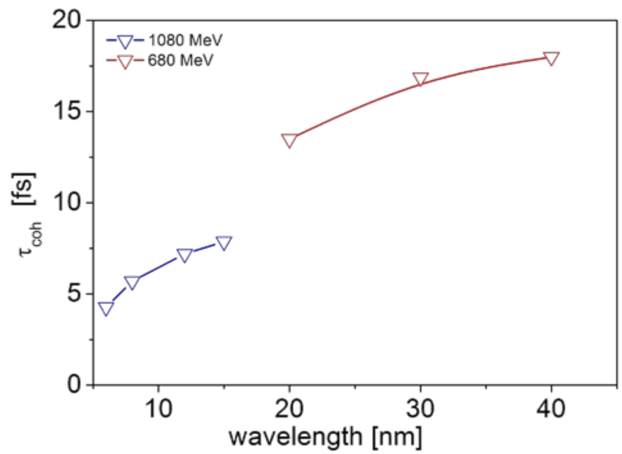
- Fast MCP detector is beig used for radiation energy measurements. The electronics of MCP-detector has low noise, about 1 mV at the level of signal of 100 mV (1% relative measurement accuracy).
- Two measurements: full radiation energy, and the energy after pinhole give us total number of modes, and number of longitudinal modes.
- The degree of transverse coherence is given by $\zeta = M_{ap}/M_{tot}$.
- Knowledge of the number of longitudinal modes gives us the radiation pulse duration.

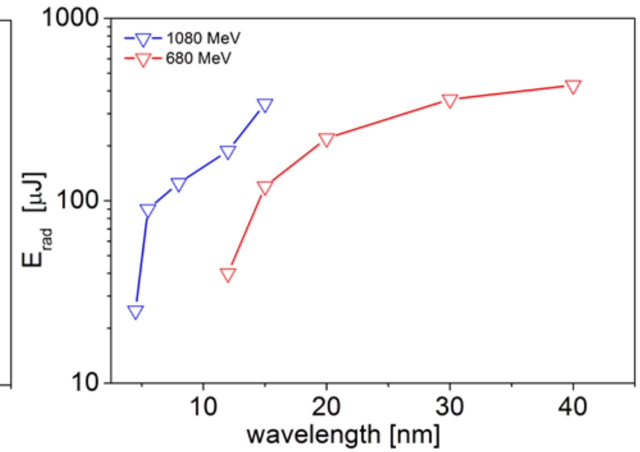
Statistical fluctuation method

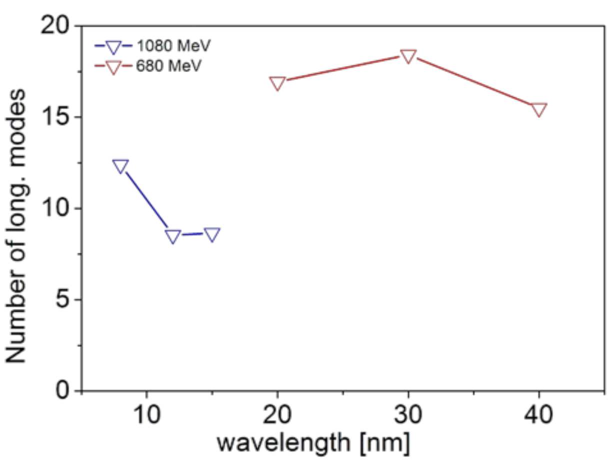
Complete radiation pulse characterization at FLASH2, September 2016:

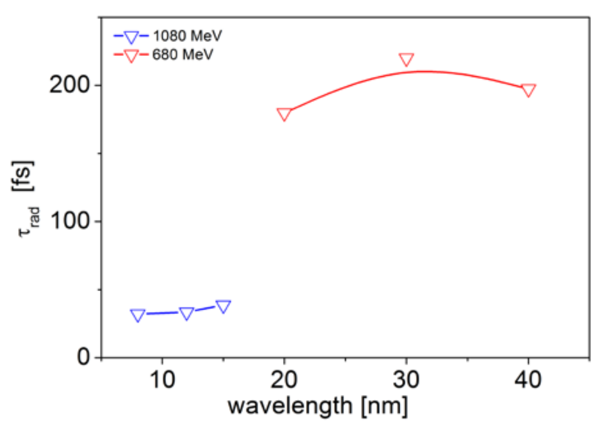
Gain, number of modes, coherence time, degree of transverse coherence, pulse duration.

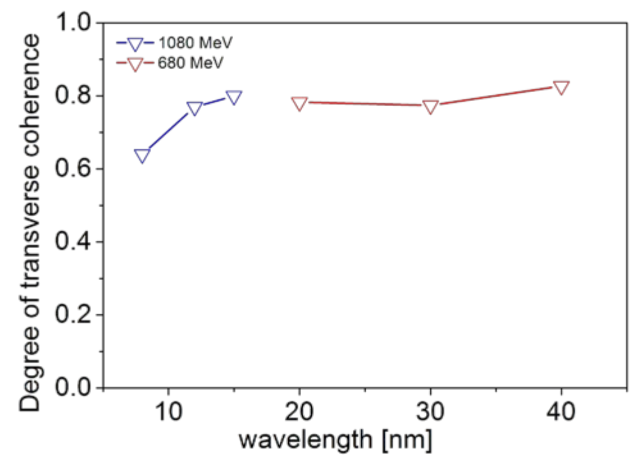












Summary for Part 2

I. Frequency doubler scheme demonstrated operation with the wavelength of 3.1 nm at 1230 MeV electron energy. Operation at shorter wavelengths will benefit a lot with installation of additional undulator modules and increase of electron energy.
II. Two color mode of operation has been demonstrated with frequency doubler scheme.
III. Post-saturation undulator tapering allows to increase the radiation pulse energy by about factor of 2 with respect to SASE at full undulator length.
IV. Statistical techniques have been developed which allow to measure main parameters of the SASE FEL radiation: gain, coherence time, degree of transverse coherence, number of longitudinal and transverse radiation modes, radiation pulse duration. Next task, implementation of this technique for every day use, requires development of scientific software.

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