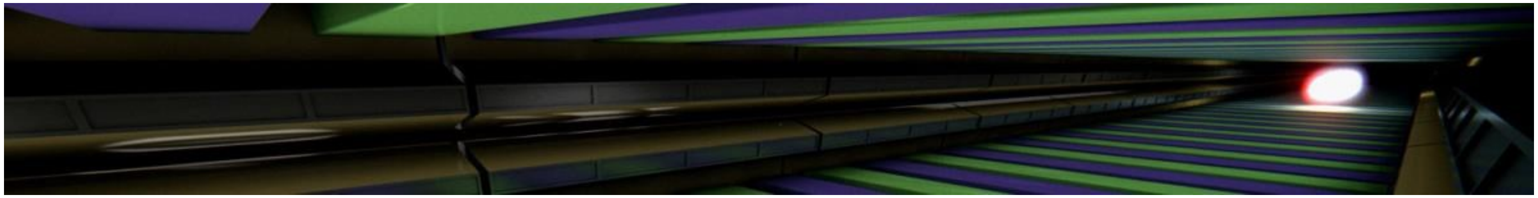


Considerations on a long wavelength FEL beamline with extended user capabilities at the European XFEL

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

- This talk highlights topics related to the design of a long wavelength FEL beamline with extended user capabilities.
- Some options were developed during design stage of the European XFEL project, some of them appeared just recently and tested elsewhere (LCLS, FLASH).
- We aim not to present specific technical design, but to share with you our knowledge and initiate fruitful discussion which (we believe) will form the basis for technical design of an FEL beamline with extended user capabilities.

Extended user capabilities

Features of FEL user facility essential for user experiments:

- Tunability range.
- Control of the radiation pulse duration.
- Coherence control: temporal and spatial.
- Polarization control: linear, circular, elliptical.
- Generation of multiple colors simultaneously: harmonics and independent colors.
- Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
- Control of the photon flux up to ultimate level.

Currently performed user experiments do not use all these features simultaneously.

Available space and technology allows to realize all these features in SASE5 beamline.

Tunability range

Working points and tunability ranges of the European XFEL

	Photon energy range [keV]		Photon wavelength range [nm]	
Energy [GeV]	SASE1/2	SASE3	SASE1/2	SASE3
8.5	1.99 - 7.27	0.24 - 1.08	0.171 - 0.622	1.15 - 5.10
11.5	3.65 - 13.30	0.45 - 1.98	0.093 - 0.340	0.63 - 2.79
14.0	5.41 - 19.71	0.66 - 2.94	0.063 - 0.229	0.42 - 1.88
16.5	7.51 - 27.38	0.92 - 4.08	0.045 - 0.165	0.30 - 1.35
17.5	8.43 - 30.97	1.03 - 4.59	0.040 - 0.147	0.27 - 1.20

Up- to date overview of the parameter space is available:

E.A. Schneidmiller and M.V. Yurkov, Photon beam properties of the European XFEL. Saturation Tables (December 2018 revision)

Currently draft of this document is distributed on request, but we plan to issue an official version soon which will replace report DESY 11-152.

Tunability range

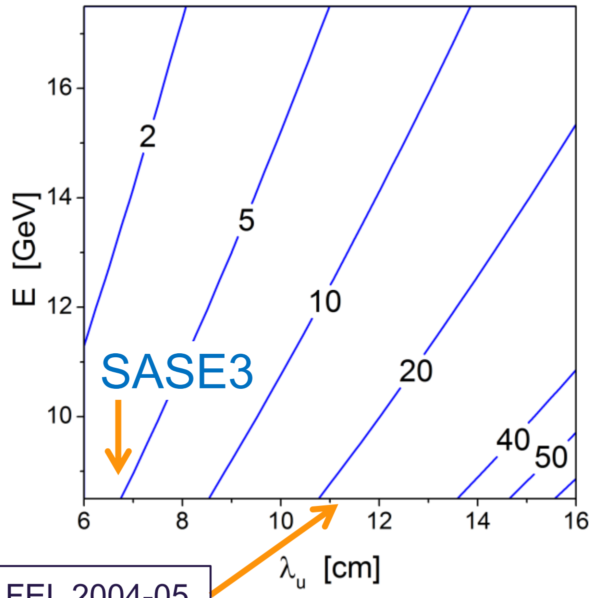
•Tunability range.

•Control of the radiation pulse duration.
•Coherence control: temporal and spatial.
•Polarization control: linear, circular, elliptical.
•Generation of multiple colors simultaneously: harmonics and independent colors.
•Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
•Control of the photon flux up to ultimate level.

Question to user community: Is there strong motivation to extend operating range of the European XFEL in the direction of longer wavelengths?

✓If so, technical solution is rather straightforward – use standard undulator technology with longer period: maximum wavelength and minimum electron energy define the value of undulator period.

Maximum wavelength [nm]



E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov , TTF FEL 2004-05

Tunability range: example for λ_u = 12 cm, Q = 1 nC

Saturation parameters of SASE5 @ E = 17.5 GeV

```
Radiation wavelength               nm         0.5       1         2         6
Pulse energy                       mJ        8.15      11.4      14.0      17.4
Peak power                         GW        76.0      106.      131.      162.
FWHM angular divergence            microrad  4.40      7.71      13.2      29.2
Coherence time                     fs        .421      .666      1.11      2.70
FWHM spectrum width, dw/w          %         .280      .354      .423      .524
Number of longitudinal modes       #         255.      162.      97.2      40.7
Number oh photons per pulse        #         .205E+14  .574E+14  .141E+15  .526E+15
Saturation length                  m         110.      87.7      74.0      60.4
```

Saturation parameters of SASE5 @ E = 8.5 GeV

```
Radiation wavelength                nm         5       10        20        30
Pulse energy                        mJ        9.45     11.0      12.4      13.2
Peak power                          GW        88.1     102.      116.      123.
FWHM angular divergence             microrad  24.0     40.3      65.2      84.3
Coherence time                      fs        2.05     3.54      6.27      8.85
FWHM spectrum width, dw/w           %         .575     .666      .752      .799
Number of longitudinal modes        #         53.4     31.3      18.1      13.1
Number oh photons per pulse         #         .238E+15 .551E+15  .125E+16  .200E+16
Saturation length                   m         54.9     47.8      42.6      40.3
```

Control of the radiation pulse duration

- •Tunability range.
- •**Control of the radiation pulse duration.**
- •Coherence control: temporal and spatial.
- •Polarization control: linear, circular, elliptical.
- •Generation of multiple colors simultaneously: harmonics and independent colors.
- •Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
- •Control of the photon flux up to ultimate level.

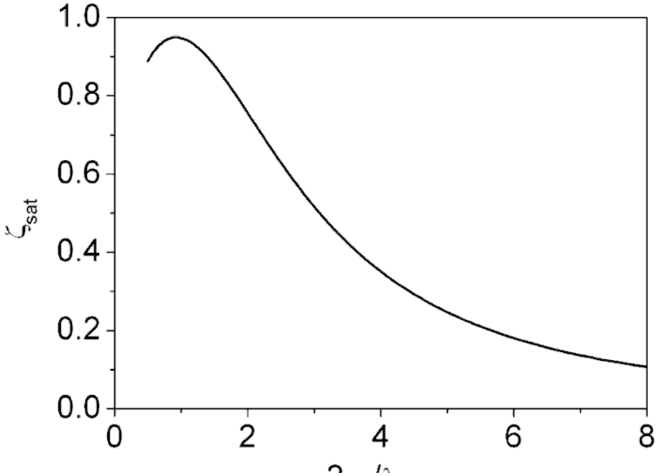
✓ It is not a critical topic: Radiation pulse duration is controlled with standard techniques of the electron beam formation system providing pulse durations down to coherence time (single spike mode of operation).

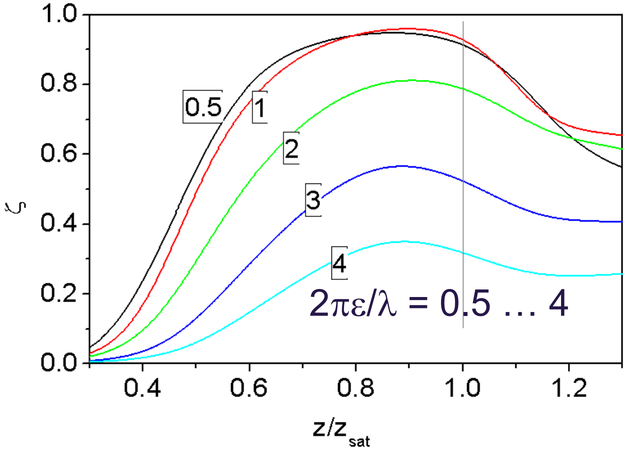
Electron beam at the undulator entrance

Bunch charge	nC	0.02	0.1	0.25	0.5	1
Peak beam current	kA	4.5	5	5	5	5
Normalized rms emittance	mm-mrad	0.32	0.39	0.6	0.7	0.97
rms energy spread	MeV	4.1	2.9	2.5	2.2	2
rms pulse duration	fs	1.2	6.4	16.6	30.6	76.6

Coherence control: temporal and spatial

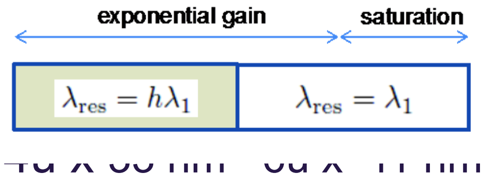
- Tunability range.
- Control of the radiation pulse duration.
- **Coherence control: temporal and spatial.**
- Polarization control: linear, circular, elliptical.
- Generation of multiple colors simultaneously: harmonics and indep
- Wide capabilities for pump-probe experiments involving FEL radia higher harmonics, independent colors), laser and accelerator base
- Control of the photon flux up to ultimate level.





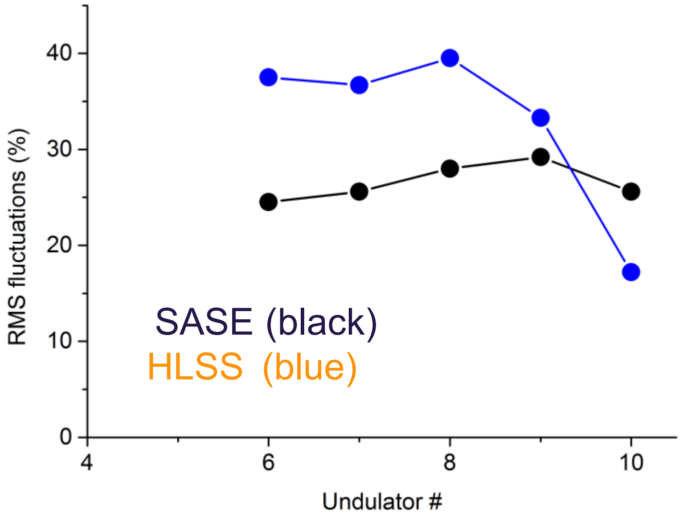
- ✓ For diffraction limited beams ($2\pi\varepsilon/\lambda$ ~1, or, B <~ 1) we expect high degree of transverse coherence in the saturation regime . However, it degrades significantly in the post saturation regime.
- ✓ Temporal coherence can be improved with harmonic lasing self-seeded FEL (HLSS), talk by Evgeny.
- ✓ Improvement of temporal coherence with self-seeding and external seeding at long wavelengths is under discussion, talks by Gianluca and Takanori.

Coherence control: temporal and spatial Harmonic lasing self-seeding (HLSS)



Experiment at FLASH2 on June 6-7, 2016 at 11 nm: demonstration of spectrum width reduction, increase of spectral brightness, and increase of coherence time.

Statistical determination of an increase of the coherence time



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

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

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

Measured increase of the coherence length is in agreement with theory:

$$R \simeq h \frac{\sqrt{L_{\rm w}^{(1)} L_{{\rm sat},h}}}{L_{{\rm sat},1}} = 0.57\ h = 1.7$$

Talk by Evgeny

Polarization control

- Tunability range.
- Control of the radiation pulse duration.
- Coherence control: temporal and spatial.
- **Polarization control: linear, circular, elliptical.**
- Generation of multiple colors simultaneously: harmonics and independent colors.
- Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
- Control of the photon flux up to ultimate level.

✓ Use of APPLE undulator allows to produce any polarization.

Generation of multiple colors

•Tunability range.
•Control of the radiation pulse duration.
•Coherence control: temporal and spatial.
•Polarization control: linear, circular, elliptical.

•Generation of multiple colors simultaneously: harmonics and independent colors.

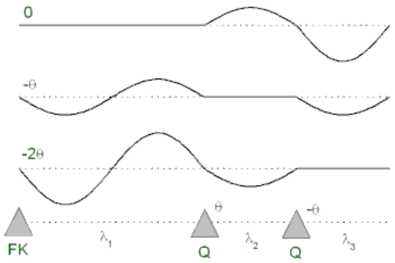
•Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
•Control of the photon flux up to ultimate level.

✓ Odd harmonics in planar undulator (nonlinear harmonic generation and harmonic lasing).

✓ Afterburner for harmonics of the fundamental in combination with reverse tapering of the main undulator.

✓ Frequency doubler.

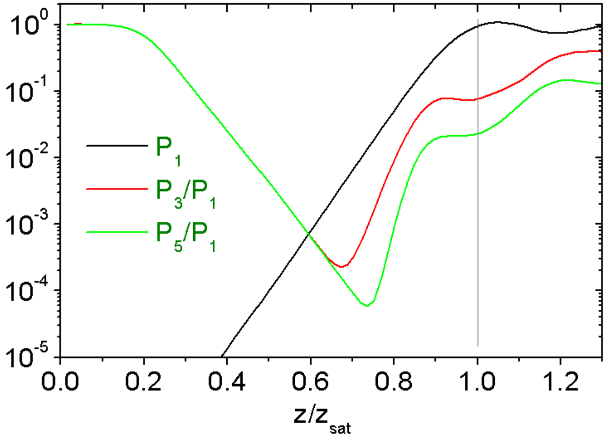
✓ Independent colors using betatron switcher principle (TDS or dechirper) - talk by Evgeny:

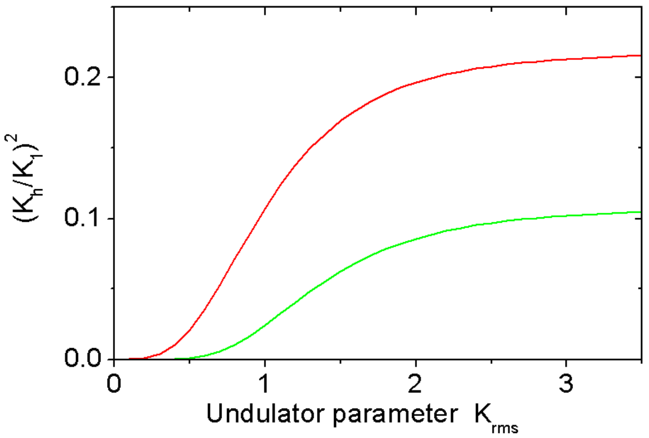


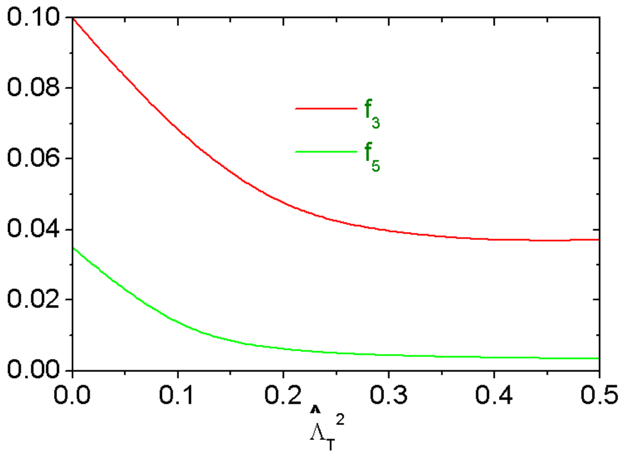
R. Brinkmann, E. Schneidmiller, M. Yurkov, NIMA 616(2010)81

A. Lutman et al., Nature Photonics 10(2016)745

Multiple colors: odd harmonics, NHG mechanism

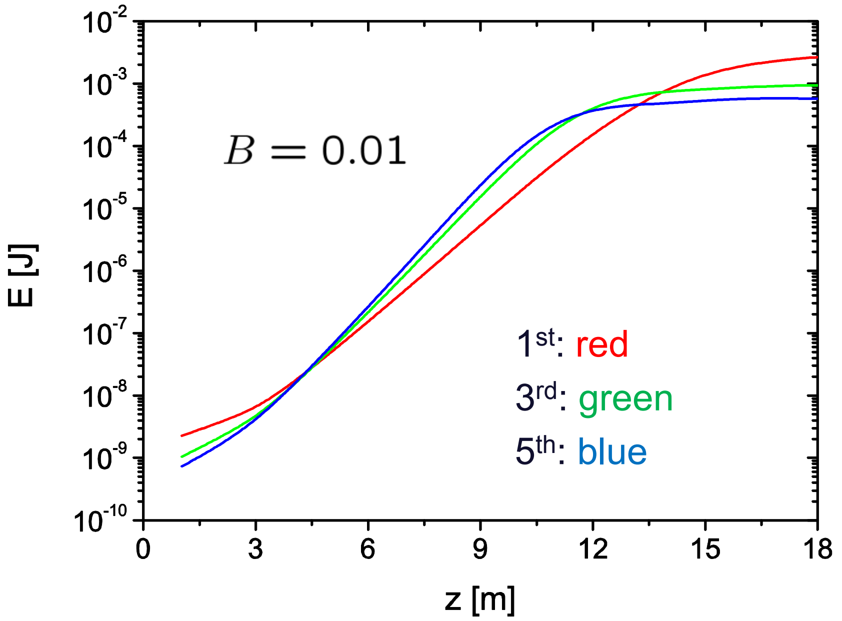


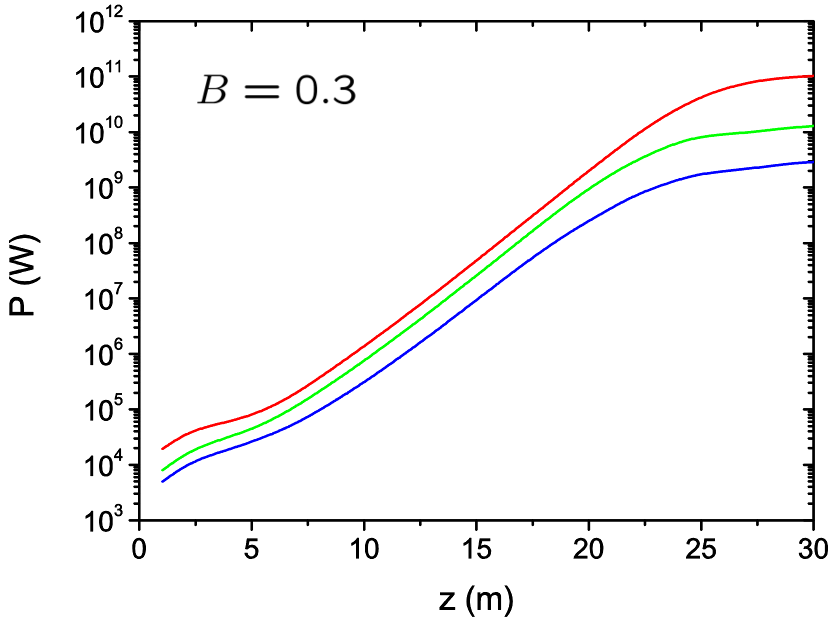




E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST Accel. Beams 9(2006)030702

Multiple colors: Anomalous harmonic lasing for thin electron beam





XFEL.EU: fundamental at 4.5 nm, beam energy 10.5 GeV, bunch charge 100 pC

- Odd harmonics exhibit anomalous high gain for the case of thin electron beam.
- This feature can be used in pump-probe experiments, or for multi-user operation.
- Necessity for selective suppression of harmonics with phase shifters requires relatively short undulator sections, present EXFEL standard of 5 meters is too long.
- Q: Do we need special undulator design with embedded phase shifters like E.S. & M.Y., Nucl. Inst. and Meth. A 717 (2013)37-43 ?

E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST Accel. Beams 9(2010)030702

Multiple colors: 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 2nd harmonic.
- Frequency doubler allows operation in a two-color mode and operation at shorter wavelengths with respect to standard SASE scheme.

Multiple colors: frequency doubler

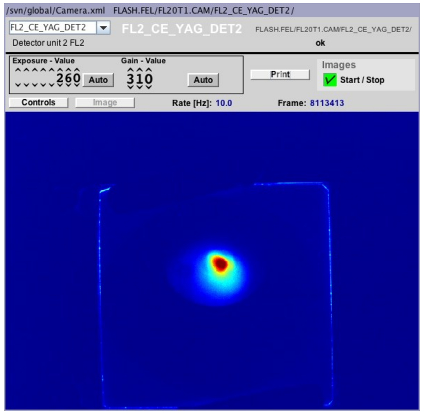
14.09.2016 22:59 Schneidmiller/Yurkov/

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.


/svn/global/Camera.xml FLASH.FEL/FL20T1.CAM/FL2_CE_YAG_DET2/

FL2_CE_YAG_DET2 FLASH.FEL/FL20T1.CAM/FL2_CE_YAG_DET2/

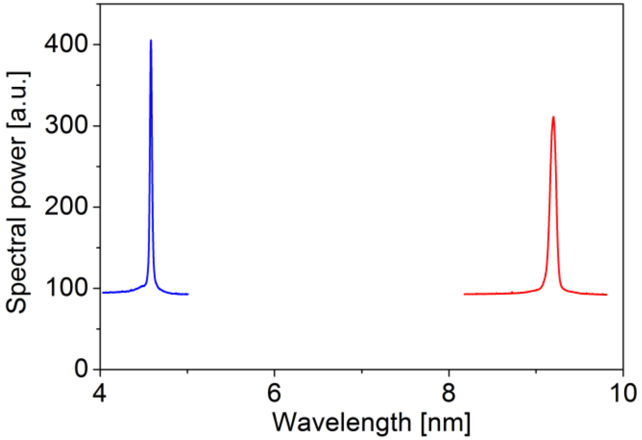
Detector unit 2 FL2 ok

Exposure - Value 260

Gain - Value 310

Rate [Hz]: 10.0

Frame: 8113413

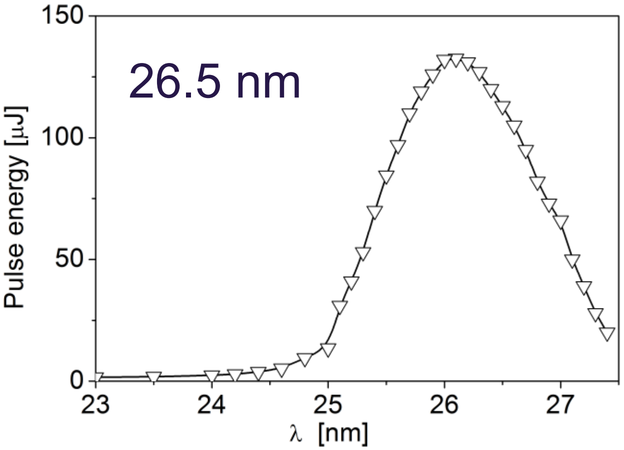


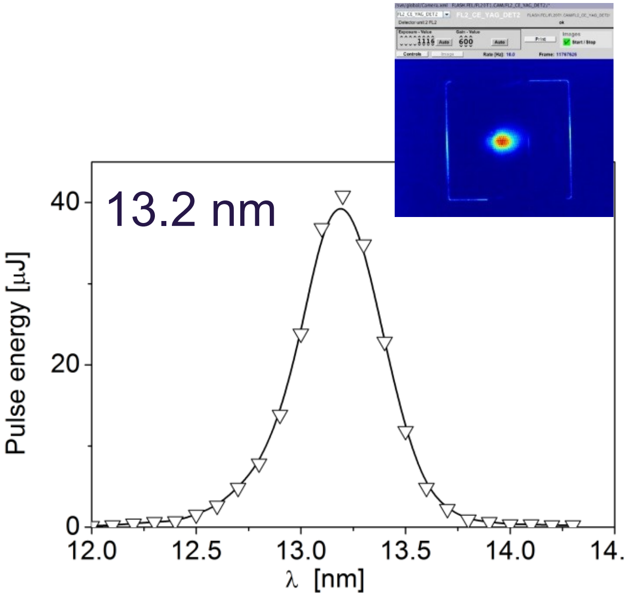
Courtesy to
Marion Kuhlmann

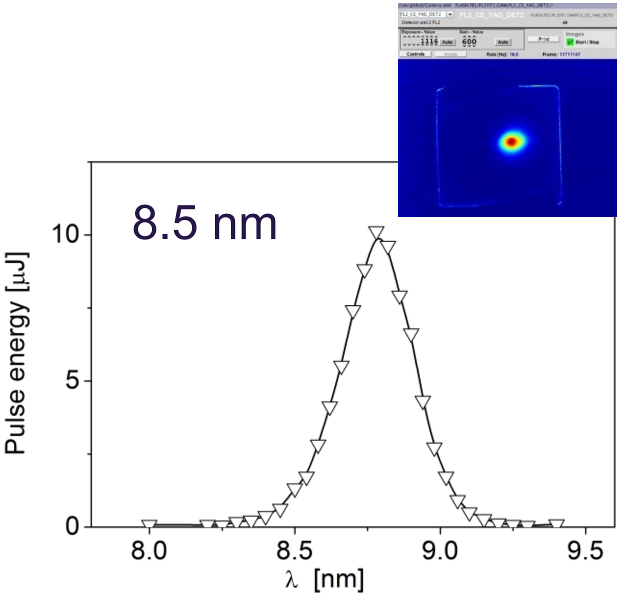
Multiple colors: Reverse tapering scheme + afterburner for harmonics

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, 8.5 nm

Yesterday talk by Evgeny







- High contrast of the afterburner radiation with reverse undulator tapering scheme at the fundamental harmonic frequency and harmonics (150 for fundamental).
- Effective operation of an afterburner at the 2nd and the 3rd harmonic with intensities which are much higher (orders of magnitude) than harmonic content of SASE radiation.

Multiple colors: independent colors

To generate independent colors with single bunch, undulator sections are tuned to desired frequencies one after another in an alternate manner. For instance, for generation of two independent colors ω_1 and ω_2, odd sections are tuned to ω_1, and even sections to ω_2. In the linear regime amplification process at different frequencies develops independently up to almost complete bunching, and radiation powers at sub-saturation level are produced in the nonlinear regime.

Realization of the lasing scheme with independent colors requires roughly one saturation length for every color, and can be realized in a long undulator only.

Present EXFEL standard of 5 meters for undulator sections is too long for flexible generation of independent colors.

Multiple colors: independent colors at FLASH

22.10.2018 22:58 Schneidmiller/Yurkov/Faatz

Summary on generation of two independent colors in FLASH2

Electron energy 675 MeV, bunch charge 0.25 nC.

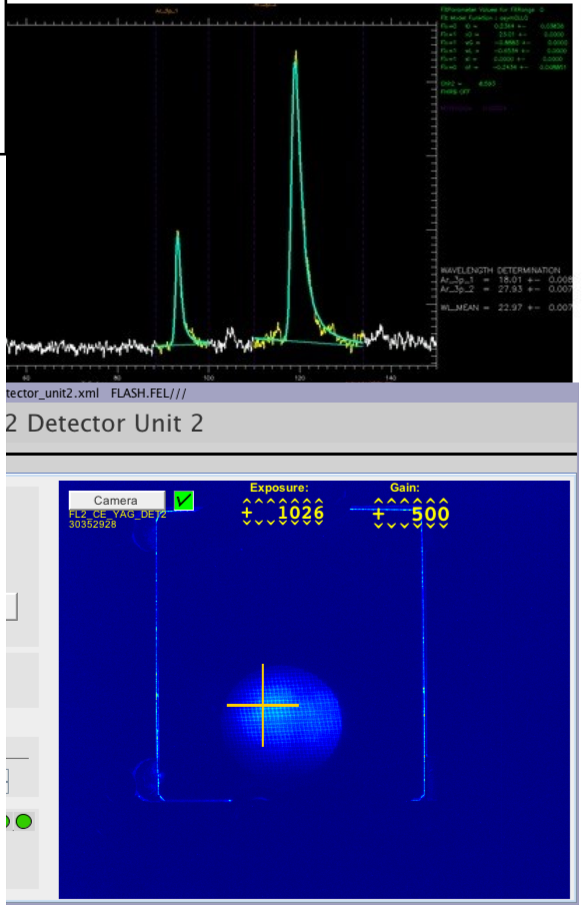
Configuration of the undulator:

Modules 1-3-5-7-9-11 are tuned to 18 nm.
Modules 2-4-6-8-19-12 are tuned to 28 nm.

Two colors can be distinguished visually in the photon beam image: brighter spot from 18 nm fraction on a wider spot from 28 nm fraction.

Spectral measurements with OPIS shows two spectral lines corresponding to 18 nm and 28 nm.

Estimate for the radiation pulse energy is of the order of 10 by 10 uJ, need to be confirmed later with more detailed analysis of data.



```
WAVELENGTH DETERMINATION
Ar_3p_1  =  18.01 +-  0.008
Ar_3p_2  =  27.93 +-  0.007

WL_MEAN  =  22.97 +-  0.007
```

Pump-probe capabilities

- Tunability range.
- Control of the radiation pulse duration.
- Coherence control: temporal and spatial.
- Polarization control: linear, circular, elliptical.
- Generation of multiple colors simultaneously: harmonics and independent colors.
- Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources, THz undulator in the main tunnel.
- Control of the photon flux up to ultimate level.

- ✓ Optical pump probe lasers are in use at all facilities.
- ✓ THz undulator and dedicated infrared beamline are installed at FLASH. THz undulator (high field SC) in the main tunnel of EXFEL is under discussion. Unwanted features: kW level of SR power, high critical energy of photons, up to 2 MeV.
- ✓ Accelerator based radiation sources are under discussion (talk by Mikhail).

Ultimate level of photon flux

- Tunability range.
- Control of the radiation pulse duration.
- Coherence control: temporal and spatial.
- Polarization control: linear, circular, elliptical.
- Generation of multiple colors simultaneously: harmonics and independent colors.
- Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources, THz undulator in the main tunnel.
- Control of the photon flux up to ultimate level.

✓ Operation with high charges (talk by Mikhail).
✓ Application of optimum undulator tapering.

Motivation

- Both, FEL radiation power and radiation pulse energy constitute only a small fraction (between per mille and per cent level) of the electron beam power and kinetic energy of electrons.
- Kinetic energy of electron beam and its peak power are limited by maximum attainable electron energy E, bunch charge Q, and peak current I.
- European XFEL is driven by the most powerful electron beams with E = 17.5 GeV, Q = 1 nC, I = 5 kA and providing:
- Kinetic energy of electron bunch: E x Q = 17.5 J;
- Peak power of electron beam: E x I = 87.5 TW.
- Thus, we deal with evident limitations on attainable radiation pulse energy and power.
- Experience from low energy facilities (like FLASH with E = 1.25 GeV) shows that there are many “photon hungry” experiments which will benefit from higher photon flux (radiation pulse energies). It is evident that similar problem will face EXFEL users as well.
- Keeping in mind this problem, during design stage of the project we did foreseen several options which would allow to extend users capabilities in terms of increasing photon flux (E.A. Schneidmiller and M.V. Yurkov, DESY 11-152).

FEL physics: Amplification process in SASE FEL

- Operation of the FEL amplifier is described by the diffraction parameter B, the energy spread parameter $\hat{\Lambda}_{\mathrm{T}}^2$, and the betatron motion parameter $\hat{k}_\beta$:

$$B = 2\Gamma\sigma^2\omega/c \,, \qquad \hat{k}_\beta = 1/(\beta\Gamma) \,, \qquad \hat{\Lambda}_{\mathrm{T}}^2 = (\sigma_{\mathrm{E}}/\mathcal{E})^2/\rho^2 \,,$$

with the gain parameter Γ and 3D FEL parameter $\bar{\rho}$:

$$\Gamma = \left[\frac{I}{I_{\mathrm{A}}}\frac{8\pi^2K^2A_{\mathrm{JJ}}^2}{\lambda\lambda_{\mathrm{w}}\gamma^3}\right]^{1/2} \,, \qquad \bar{\rho} = \frac{\lambda_{\mathrm{w}}\Gamma}{4\pi} \,.$$

- When effects of betatron oscillations and energy spread are small, efficiency of FEL amplifier in saturation is universal function of the only diffraction parameter B:

$$\eta \simeq \bar{\rho} \qquad \text{for} \quad B < 1 \,,$$

$$\eta \simeq \bar{\rho}/B^{1/3} \quad \text{for} \quad B > 1 \,.$$

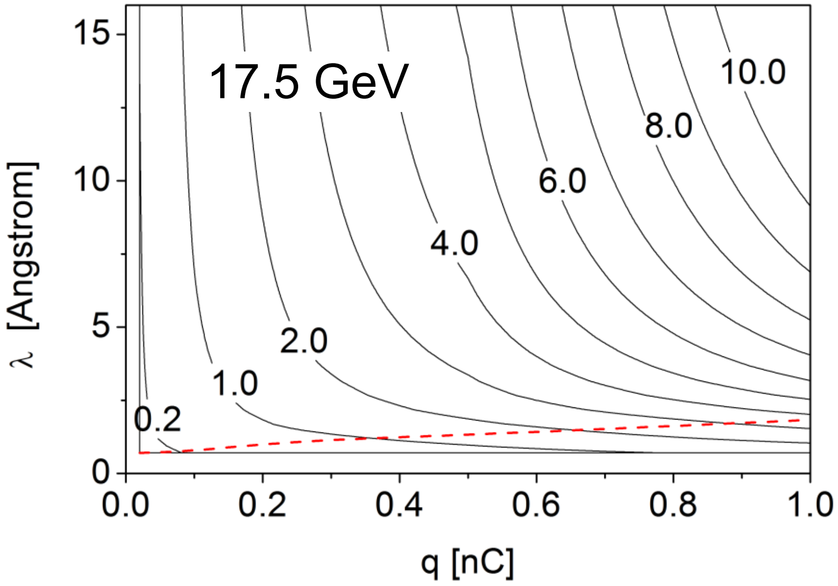
- Maximum radiation energy is reached for diffraction limited beam, $B < 1$:

$$E_{\mathrm{rad}} \simeq \bar{\rho} \times N_e \times \gamma \times m_e c^2 \propto N_e \times \gamma^{1/2} \times I^{1/2}.$$

- Roadmap to increase radiation pulse energy is straightforward:
  - Operate with diffraction limited beams, $B < 1$.
  - Increase FEL efficiency parameter $\bar{\rho}$: higher peak current.
  - Increase kinetic energy of electron beam: number of electrons (bunch charge) and electron beam energy.
  - Apply undulator tapering.

Baseline parameters of the European XFEL
Radiation pulse energy @ saturation

SASE3: Radiation pulse energy @ saturation, mJ



$$E_{\rm rad} \simeq \bar{\rho} \times N_e \times \gamma \times m_e c^2 \propto N_e \times \gamma^{1/2} \times I^{1/2}.$$

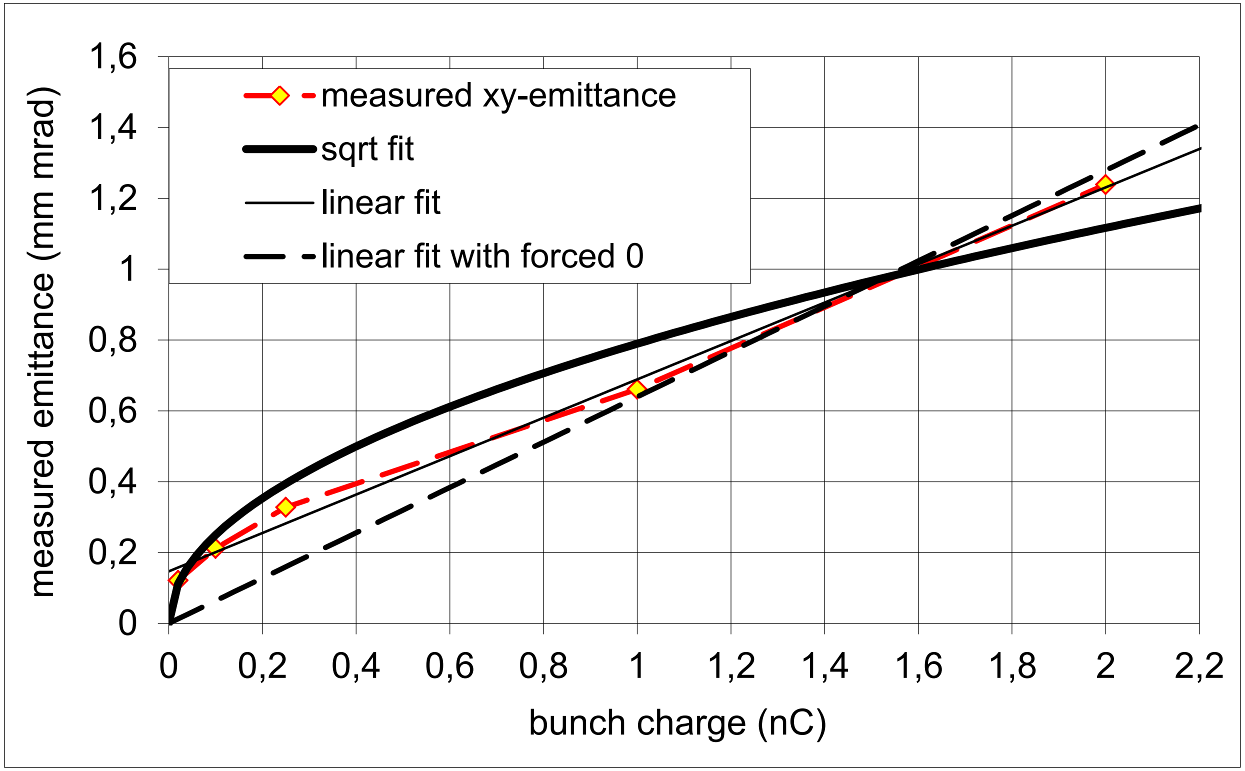
Unique features of the European XFEL:

(i) Electron gun is capable to generate low emittance bunches with charge up to 5 nC (talk by Mikhail);

(ii) Electron beams with high charge can be successfully accelerated in superconducting accelerator with large aperture.

E.A. Schneidmiller and M.V. Yurkov, DESY 11-152

PITZ: An option of high charges



Measured normalized projected emittance as a function of the bunch charge. Square root and two linear fits (with and without offset at zero charge) are plotted as well.

M KRASILNIKOV ET AL., AN OPTION OF HIGH CHARGE OPERATION FOR THE EUROPEAN XFEL, PROC. FEL2011 CONFRERENCE, THPA08.

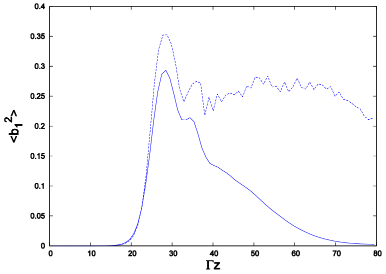
Post saturation undulator tapering for efficiency increase

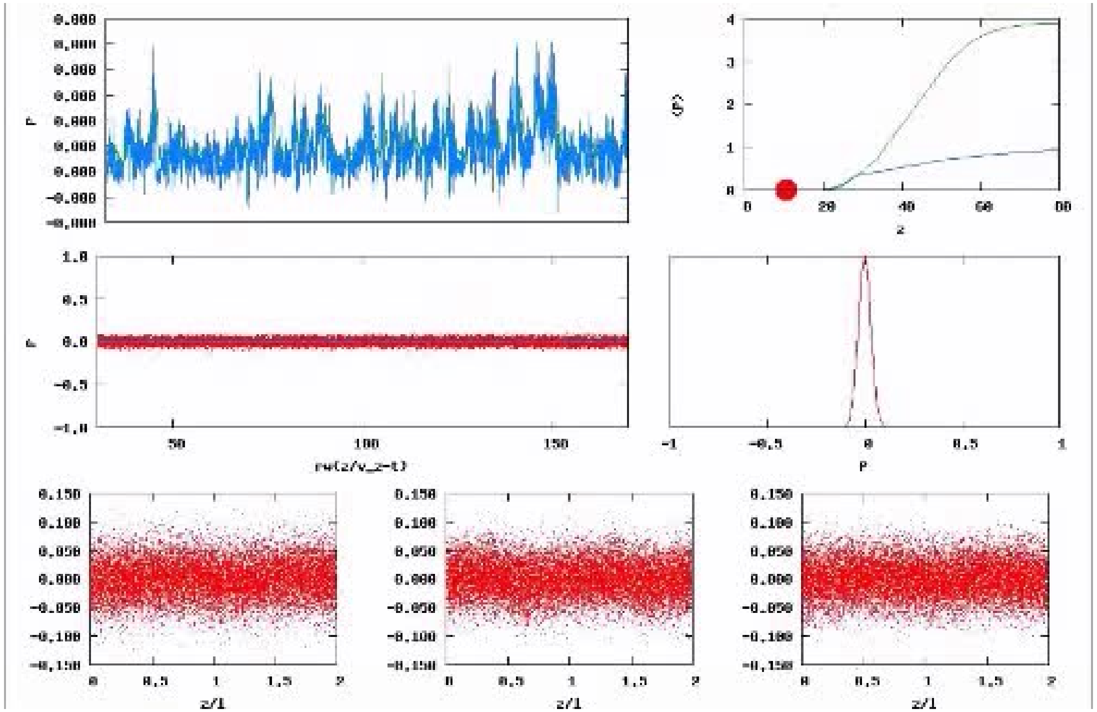
- The next step is application of post saturation undulator tapering to preserve resonance interaction of electrons and radiation and increase FEL efficiency [originally proposed by N.M. Kroll, P.L. Morton, and M.N. Rosenbluth, IEEE J. Quantum Electronics, QE-17, 1436 (1981)]:

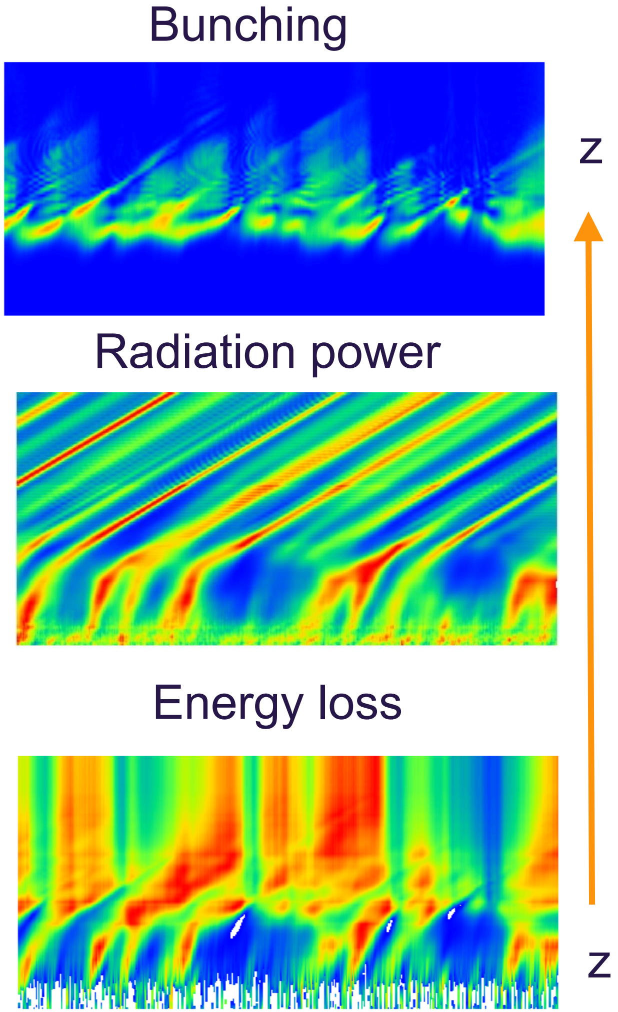
$$\lambda \simeq \lambda_{\mathrm{w}}(z) \frac{1 + K^2(z)}{2\gamma^2(z)} .$$

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

[redacted]

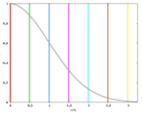
$$\hat{C} = \alpha_{tap}(\hat{z} - \hat{z}_0)\left[\arctan\left(\frac{1}{2N}\right) + N\ln\left(\frac{4N^2}{4N^2+1}\right)\right] , \qquad N = \frac{\beta_{tap}}{(\hat{z} - \hat{z}_0)}$$

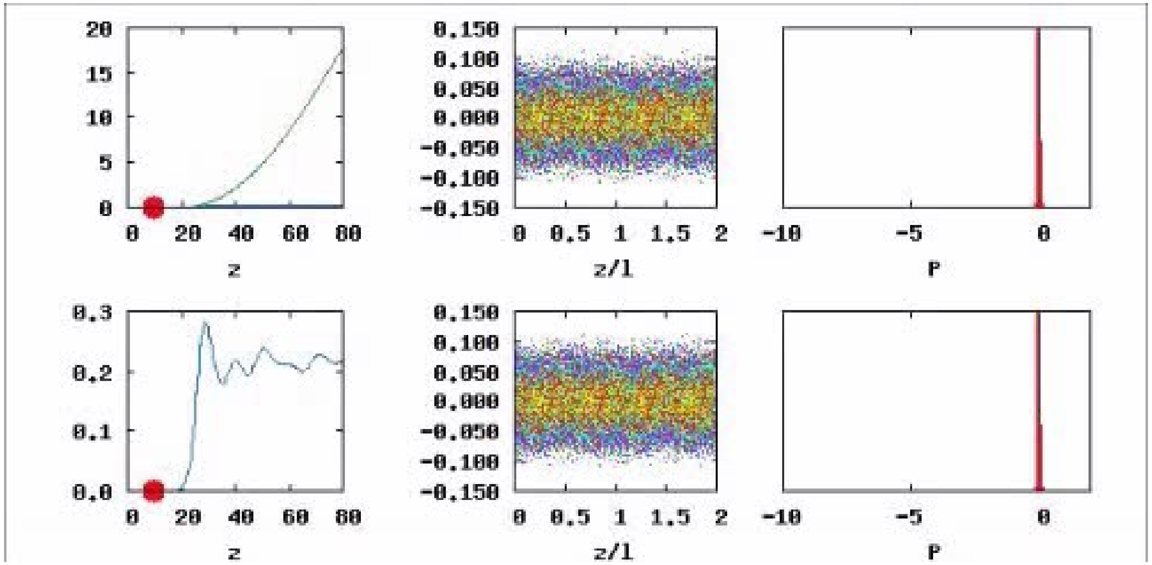
E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST AB 18 (2015) 030705

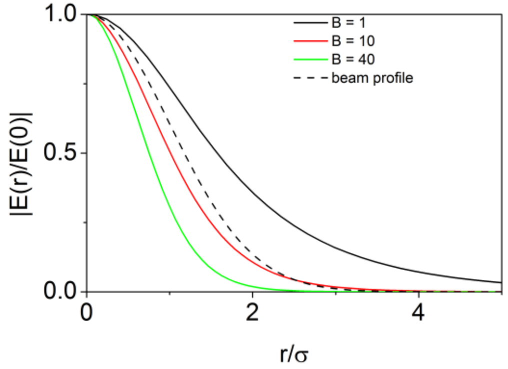
Seeded FEL, optimum tapering: how it works

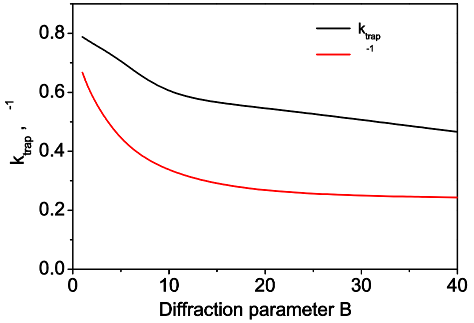
Top: tapered

Bottom: untapered







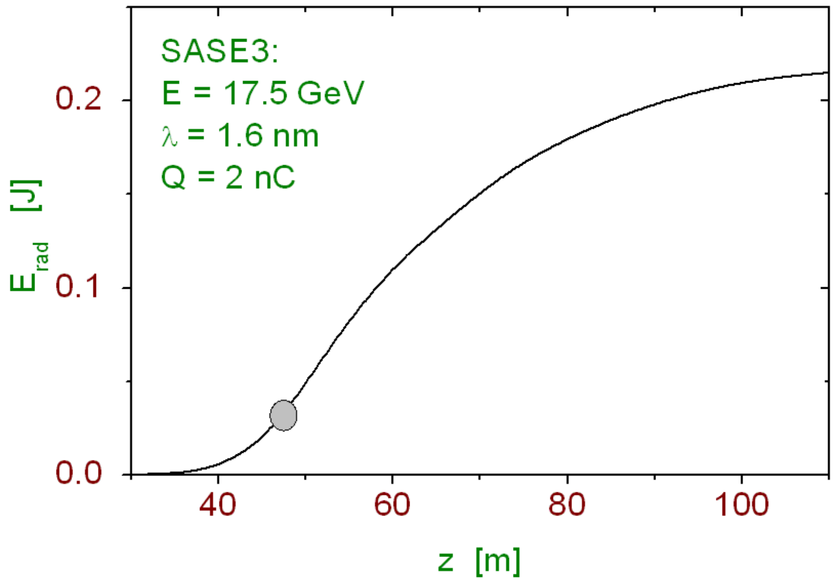


$$\hat{C} = \alpha_{tap}(\hat{z}-\hat{z}_0)\left[\arctan\left(\frac{1}{2N}\right) + N\ln\left(\frac{4N^2}{4N^2+1}\right)\right], \qquad N = \frac{\beta_{tap}}{(\hat{z}-\hat{z}_0)}$$

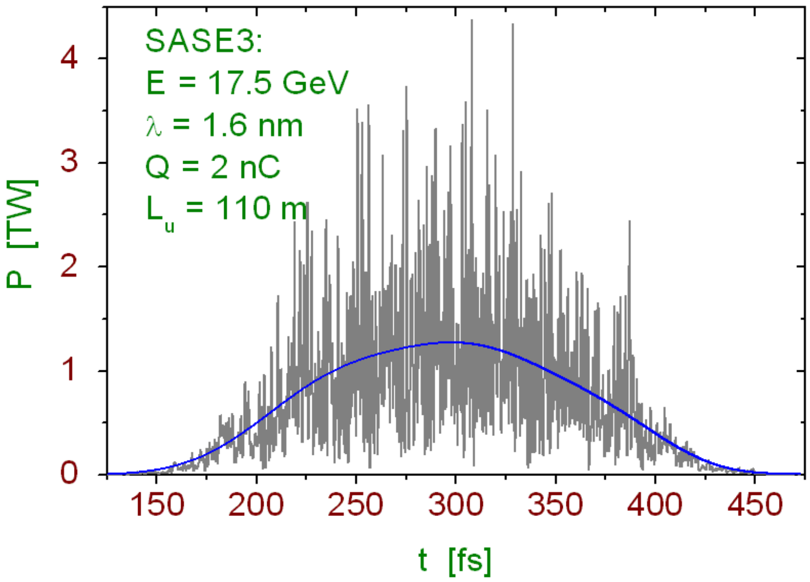
- The particles in the core of the beam (red, green, blue color) are trapped most effectively. Nearly all particles located at the edge of the electron beam (braun, yellow color) leave the stability region very soon. The trapping process lasts for a several field gain lengths when the trapped particles 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

High charge mode of SASE3 operation



Energy in the radiation pulse for SASE3 with tapered undulator. Circle shows saturation point.

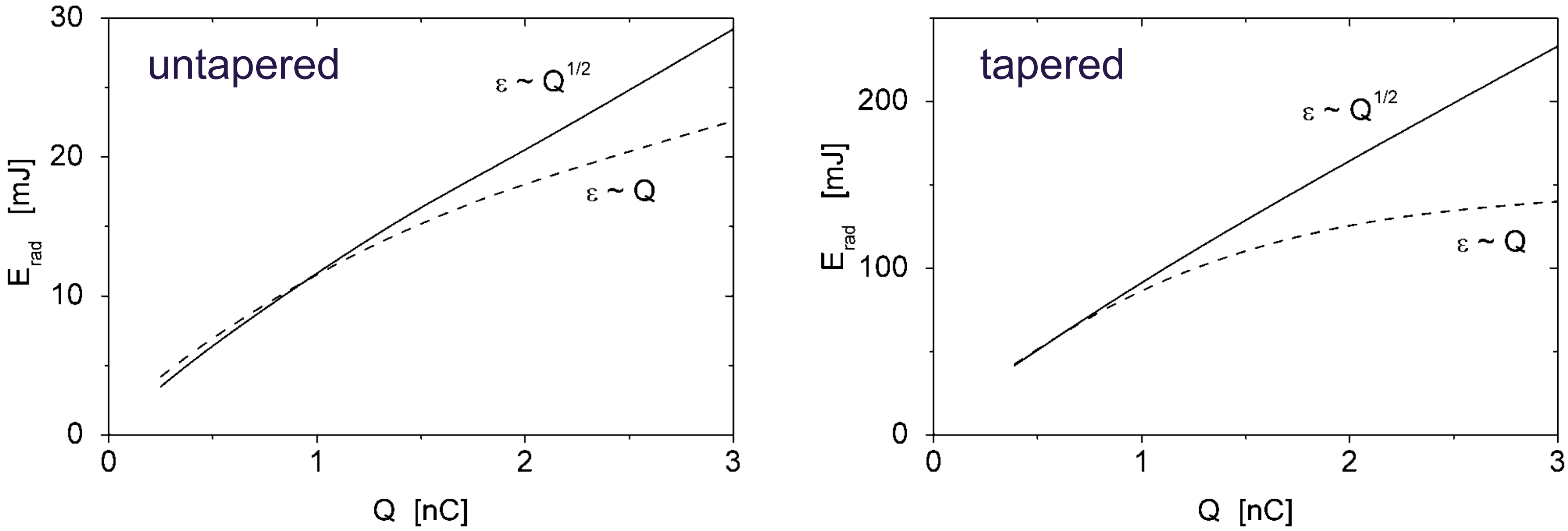


Temporal structure of the radiation pulse from SASE3 with tapered undulator at the undulator length 100 m.

Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm, bunch charge is 2 nC, normalized rms emittance is 1.4 mm-mrad, peak beam current is 5 kA.

E.A. Schneidmiller and M.V. Yurkov, DESY 11-152
M KRASILNIKOV ET AL., AN OPTION OF HIGH CHARGE OPERATION FOR THE EUROPEAN XFEL, PROC. FEL2011 CONFRERENCE, THPA08.

High charge mode of SASE3 operation



Energy in the radiation pulse versus bunch charge for SASE3 at the European XFEL. Left plot: FEL operates in the saturation regime. Right plot: operation with tapered parameters for the undulator length of 100 meters. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm. Solid and dashed lines correspond to the emittance scaling as $Q^{1/2}$, and Q, respectively.

E.A. Schneidmiller and M.V. Yurkov, DESY 11-152
M KRASILNIKOV ET AL., AN OPTION OF HIGH CHARGE OPERATION FOR THE EUROPEAN XFEL, PROC. FEL2011 CONFRERENCE, THPA08.

Summary

Infrustructure of SASE5 tunnel allows to design low photon energy FEL beamline with extended user capabilities:

- Tunability range.
- Control of the radiation pulse duration.
- Coherence control: temporal and spatial.
- Polarization control: linear, circular, elliptical.
- Generation of multiple colors simultaneously: harmonics and independent colors.
- Wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources.
- Control of the photon flux up to ultimate level.

We believe that the results presented here will stimulate experts from the user community for formulation of advanced user requirements which, in turn, will seed further design process.

Thank you very much for attention!

Selected references relates to this talk

Harmonics and harmonic lasing self-seeded FEL :

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, A possible upgrade of FLASH for harmonic lasing down to 1.3 nm, Nucl. Instrum. and Methods A 717 (2013)37-43.
E.A. Schneidmiller, and M.V. Yurkov, Studies of harmonic lasing self-seeded FEL at FLASH2, Proc. IPAC2016, MOPOW009.
E.A. Schneidmiller et al., First operation of a harmonic lasing self-seeded free electron laser, Phys. Rev. Accel. Beams 20, 020705.

Reverse undulator tapering:

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

Post-saturation undulator tapering:

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).

Frequency doubler:

J. Feldhaus et al., Efficient frequency doubler for the soft X-ray SASE FEL at the TESLA Test Facility, Nucl. Instrum. and Methods A 528 (2004) 471-475.
M. Kuhlmann, E.A. Schneidmiller, M.V. Yurkov, Frequency doubler and two-color mode of operation at free electron laser FLASH2, Proc. SPIE 10237, 1023710 (2017); doi: 10.1117/12.2265584.

Accelerator based THz source and THz source in the tunnel:

M. Gensch et al., New infrared undulator beamline at FLASH, Infrared Physics & Technology, 51 (2008) 423-425.
E.A. Schneidmiller and M.V. Yurkov, M. Krasilnikov, F. Stephan, Tunable THz Source for Pump Probe Experiments at the European XFEL, Proc. FEL2012 Conference, Nara, Japan, 2012, WEPD55.
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov , Optical afterburner for an x-ray free electron laser as a tool for pump-probe experiments, Phys. Rev. ST Accel. Beams 13 (2010) 030701.
M. Foerst et al, Optical Afterburner for a SASE FEL: First Results from FLASH, Proceedings of IPAC2011, San Sebastian, Spain, 2011, THPC084, pp. 3089-3091.

Extended spectral range of the European XFEL

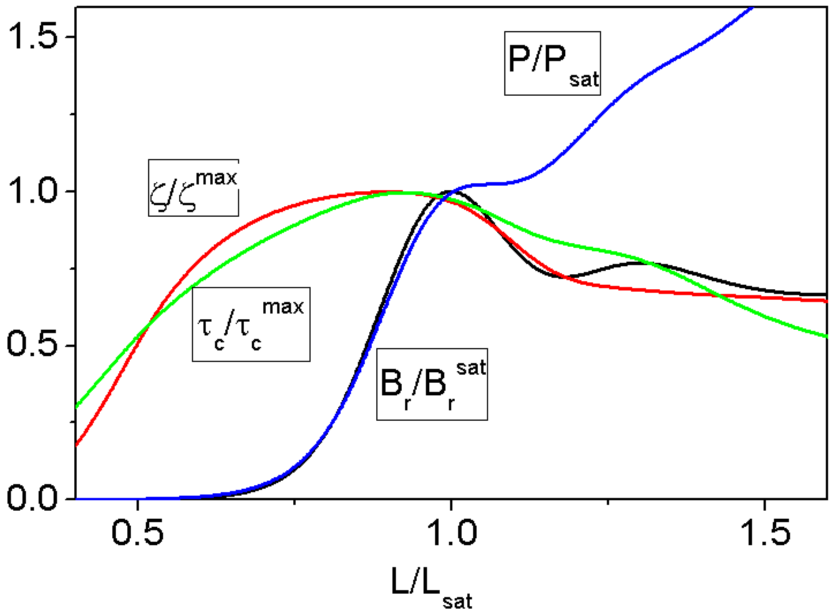
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov , The Potential for Extending the Spectral Range Accessible to the European X-ray Free Electron Laser in the Direction of Longer Wavelengths, TTF FEL 2004-05.
R. Brinkmann, E.A. Schneidmiller, and M.V. Yurkov, Possible Operation of the European XFEL with Ultra-Low Emittance Beams, Nucl. Instrum. and Methods A616 (2010) 81-87.

Baseline parameters of the European XFEL and high pulse energy mode of operation:

E.A. Schneidmiller and M.V. Yurkov, Photon Beam Properties at the European XFEL (December 2010 Revision), Preprint DESY 11-152, TESLA-FEL 2011-01.
M. Krasilnikov et al., An Option of High Charge Operation for the European XFEL, Proc. FEL2011 Conference, Shanghai, China, 2011, THPA08.

Backup slides

FEL physics:
Amplification process in SASE FEL



Radiation power
Brilliance
Degree of transverse coherence
Coherence time

- Amplification process in SASE FEL starts from the shot noise in the electron beam, passes stage of the exponential gain, reaches saturation, and then evolves in the post-saturation regime.
- Radiation power continues to grow along the undulator length.
- Degree of transverse coherence and coherence time reach their maximum values in the end of exponential regime.
- **Brilliance reaches maximum value at the saturation point.**

E.A. Schneidmiller and M.V. Yurkov, DESY 11-152