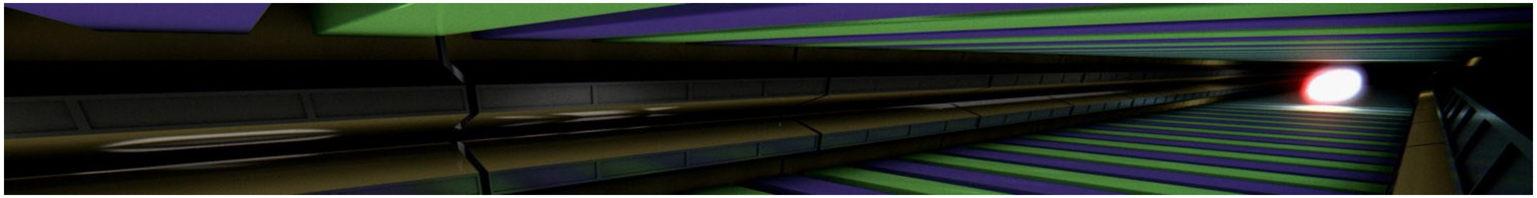


A hard (7 keV - 25 keV) and ultrahard (25 keV - 100 keV) X-ray source for the European XFEL

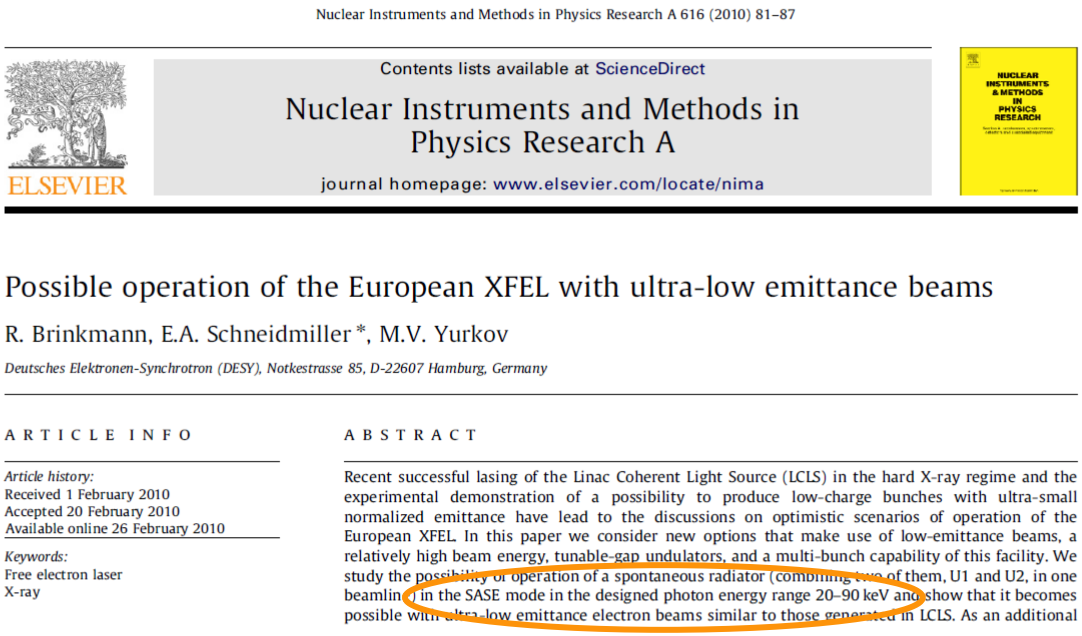
V. Balandin, W. Decking, M. Dohlus, N. Golubeva, D. Nölle,
E. Schneidmiller, M. Yurkov, I. Zagorodnov
DESY
Y. Li, J. Pflüger, S.Tomin
European XFEL GmbH

Workshop “Shaping the Future of the European XFEL: Options for the SASE4/5 Tunnels”
December 6-7, 2018, Schenefeld

Outline

- Possible SASE4/5 layout and parameters
- Is 100 keV lasing possible at all?
- Lasing scenarios in different undulators
- Advanced operation modes for UHXR
- Other advanced concepts
- Discussion and summary

Proposal for 90 keV lasing of the European XFEL (2010)



Nuclear Instruments and Methods in Physics Research A 616 (2010) 81–87

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Possible operation of the European XFEL with ultra-low emittance beams

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ABSTRACT

Recent successful lasing of the Linac Coherent Light Source (LCLS) in the hard X-ray regime and the experimental demonstration of a possibility to produce low-charge bunches with ultra-small normalized emittance have lead to the discussions on optimistic scenarios of operation of the European XFEL. In this paper we consider new options that make use of low-emittance beams, a relatively high beam energy, tunable-gap undulators, and a multi-bunch capability of this facility. We study the possibility of operation of a spontaneous radiator (combining two of them, U1 and U2, in one beamline) in the SASE mode in the designed photon energy range 20–90 keV and show that it becomes possible with ultra-low emittance electron beams similar to those generated in LCLS. As an additional

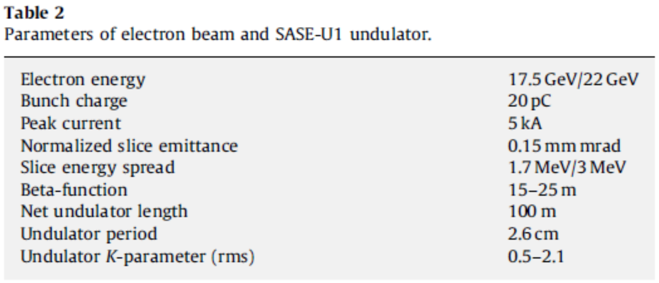
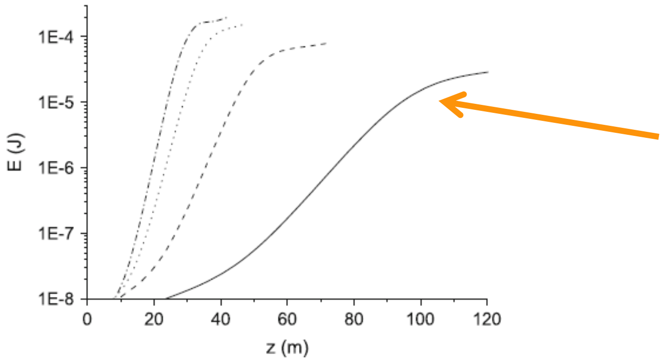


Table 2
Parameters of electron beam and SASE-U1 undulator.

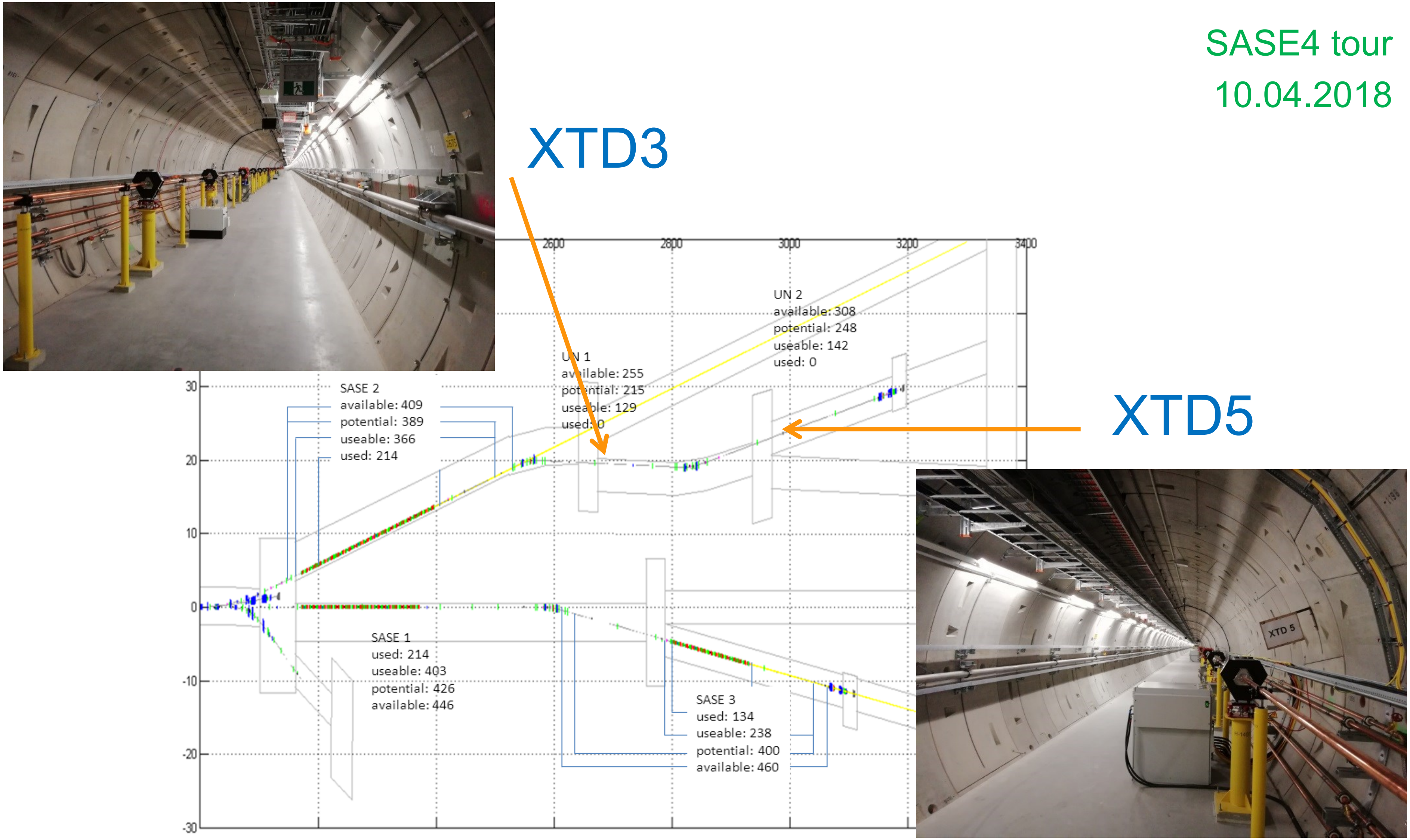
Electron energy	17.5 GeV/22 GeV
Bunch charge	20 pC
Peak current	5 kA
Normalized slice emittance	0.15 mm mrad
Slice energy spread	1.7 MeV/3 MeV
Beta-function	15–25 m
Net undulator length	100 m
Undulator period	2.6 cm
Undulator K-parameter (rms)	0.5–2.1



90 keV

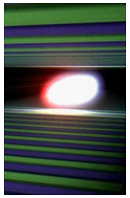
Undulator tunnels

SASE4 tour
10.04.2018

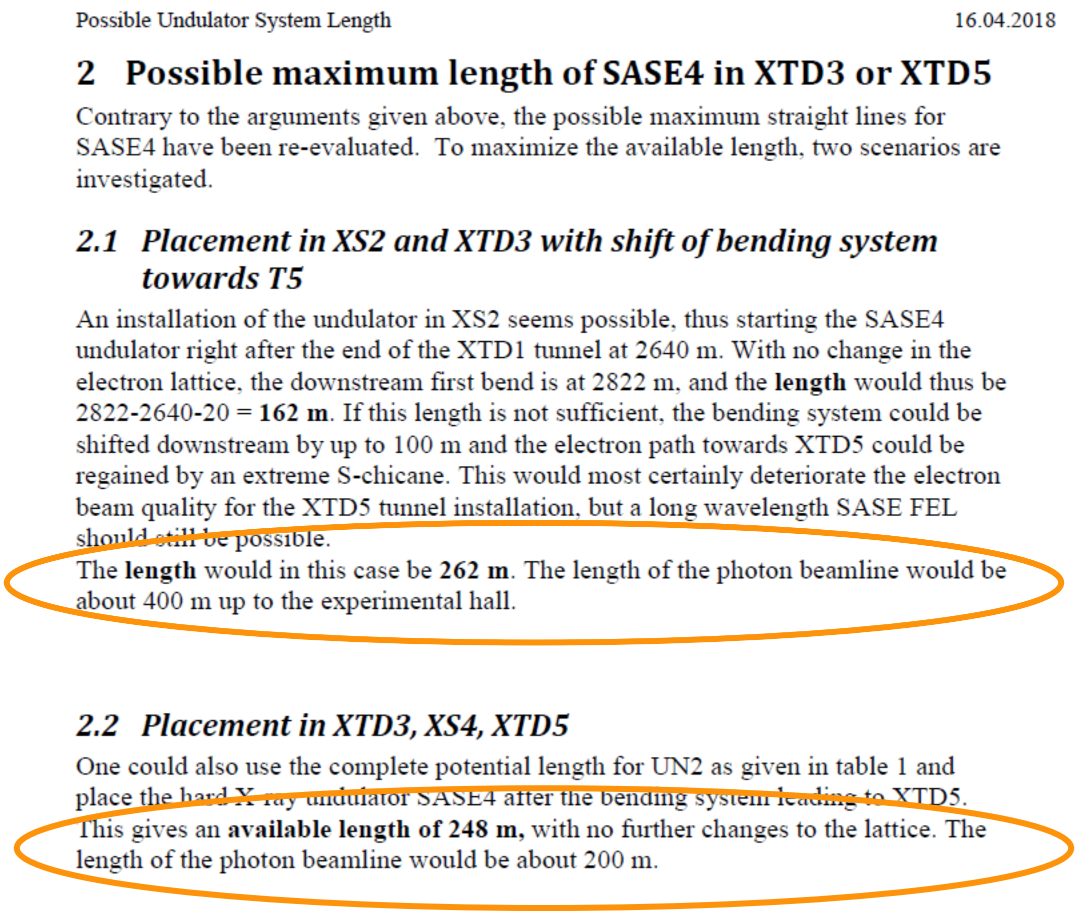


XTD3

XTD5



Two scenarios for a new undulator line



Possible Undulator System Length 16.04.2018

2 Possible maximum length of SASE4 in XTD3 or XTD5

Contrary to the arguments given above, the possible maximum straight lines for SASE4 have been re-evaluated. To maximize the available length, two scenarios are investigated.

2.1 Placement in XS2 and XTD3 with shift of bending system towards T5

An installation of the undulator in XS2 seems possible, thus starting the SASE4 undulator right after the end of the XTD1 tunnel at 2640 m. With no change in the electron lattice, the downstream first bend is at 2822 m, and the **length** would thus be 2822-2640-20 = **162 m**. If this length is not sufficient, the bending system could be shifted downstream by up to 100 m and the electron path towards XTD5 could be regained by an extreme S-chicane. This would most certainly deteriorate the electron beam quality for the XTD5 tunnel installation, but a long wavelength SASE FEL should still be possible.
The **length** would in this case be **262 m**. The length of the photon beamline would be about 400 m up to the experimental hall.

2.2 Placement in XTD3, XS4, XTD5

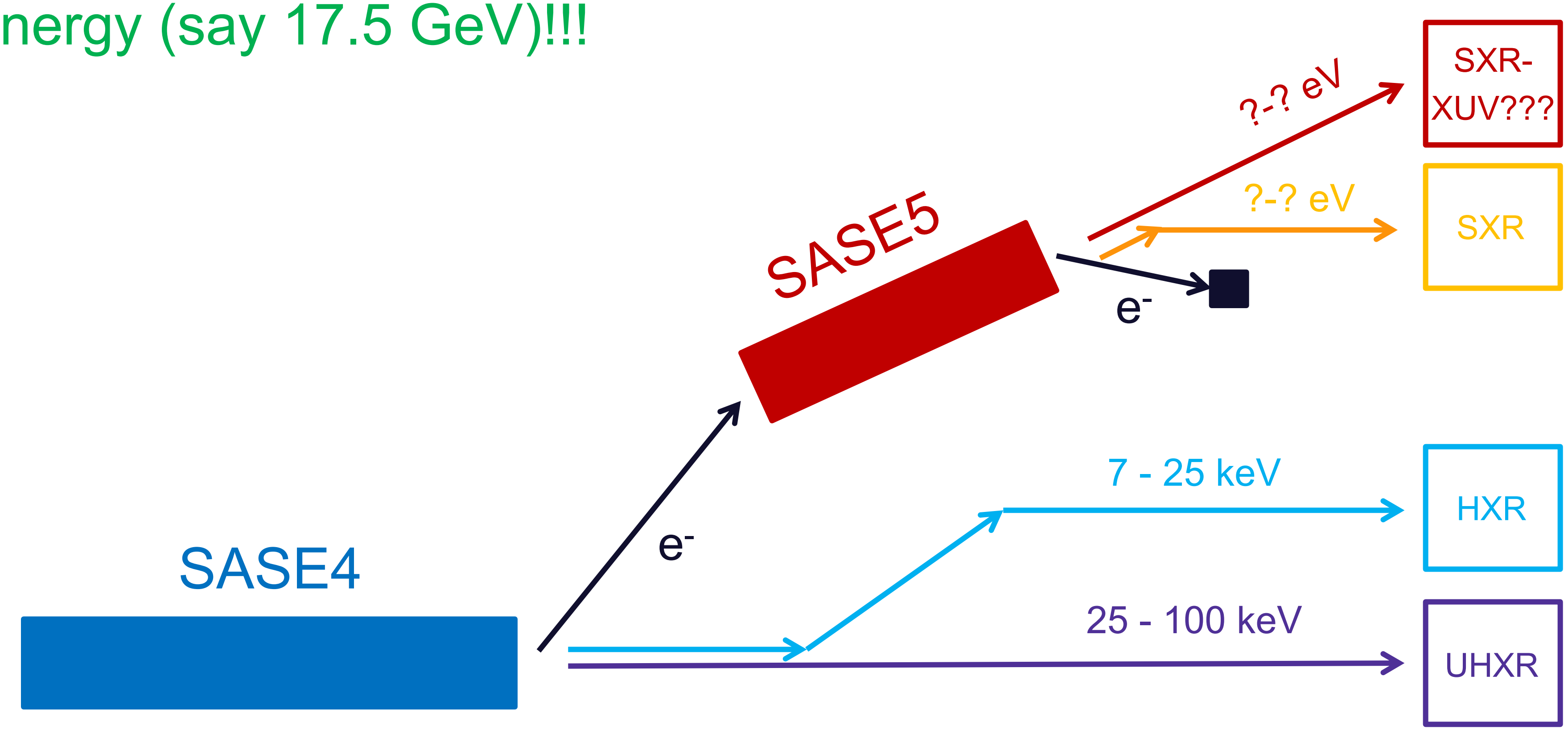
One could also use the complete potential length for UN2 as given in table 1 and place the hard X-ray undulator SASE4 after the bending system leading to XTD5. This gives an **available length of 248 m,** with no further changes to the lattice. The length of the photon beamline would be about 200 m.

Note of W. Decking

Possible SASE4/5 layout

Operation at a FIXED electron energy (say 17.5 GeV)!!!

Mikhail's talk tomorrow



SASE4 and SASE5 positions can be swapped with some complications for photon transport

Outline

- Possible SASE4/5 layout and parameters
- Is 100 keV lasing possible at all?
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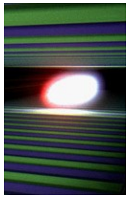
Wavelength limit: early studies



- In the mid-1990s we started design of XFEL as a part of linear collider project
- It was realized that wavelength (WL) limit is determined by energy diffusion in the undulator (due to quantum fluctuations of undulator radiation), an estimate for the shortest WL was published in

J. Rossbach, E. Saldin, E. Schneidmiller , M. Yurkov, NIMA 374(1996)401

- Then we obtained the expression for energy diffusion

E. Saldin, E. Schneidmiller , M. Yurkov, NIMA 381(1996)545

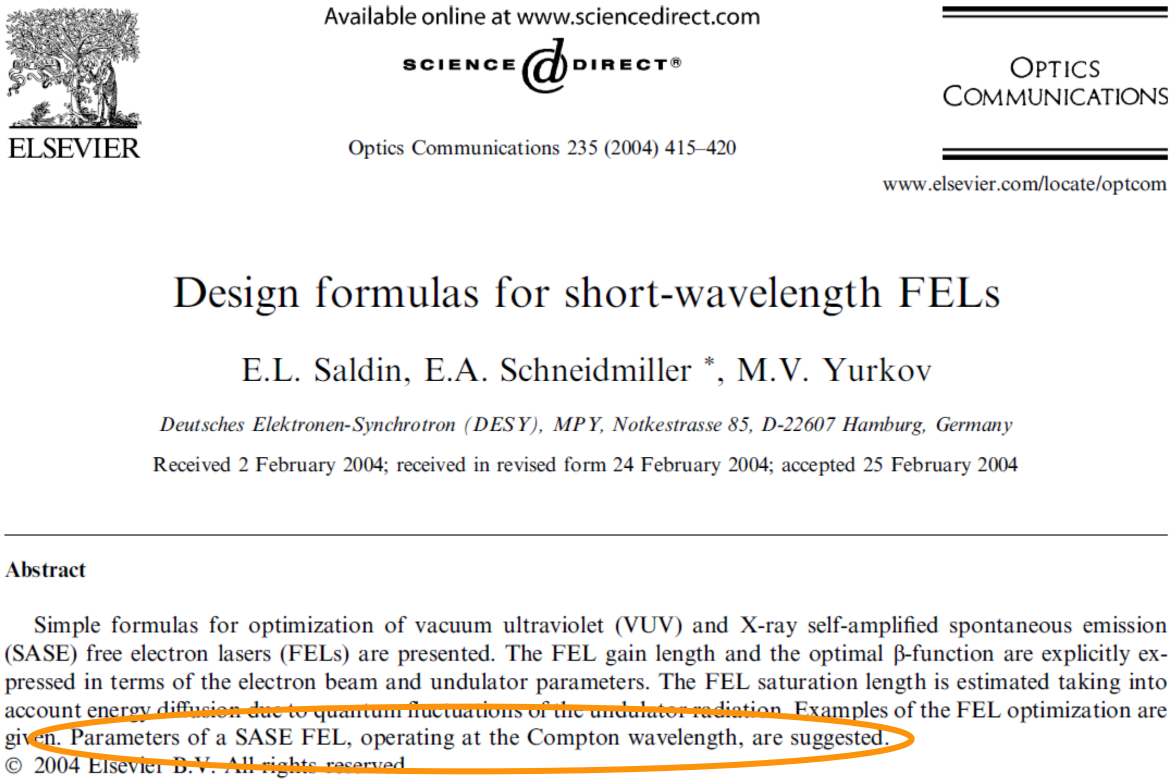
$$\frac{d\sigma_\gamma^2}{dz} = \frac{14}{15} \bar{\lambda}_c r_e \gamma^4 \kappa_w^3 K^2 F(K) \, ,$$

where $\bar{\lambda}_c = 3.86 \times 10^{-11}$ cm, $r_e = 2.82 \times 10^{-13}$ cm, $\kappa_w = 2\pi/\lambda_w$, and

Planar undulator, rms K here

$$F(K) = 1.70K + (1 + 1.88K + 0.80K^2)^{-1}$$

Wavelength limit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Optics Communications 235 (2004) 415–420

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Design formulas for short-wavelength FELs

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Received 2 February 2004; received in revised form 24 February 2004; accepted 25 February 2004

Abstract

Simple formulas for optimization of vacuum ultraviolet (VUV) and X-ray self-amplified spontaneous emission (SASE) free electron lasers (FELs) are presented. The FEL gain length and the optimal β-function are explicitly expressed in terms of the electron beam and undulator parameters. The FEL saturation length is estimated taking into account energy diffusion due to quantum fluctuations of the undulator radiation. Examples of the FEL optimization are given. Parameters of a SASE FEL, operating at the Compton wavelength, are suggested.

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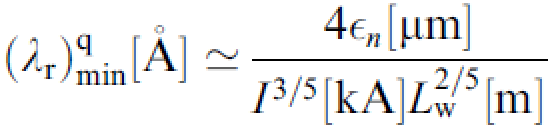
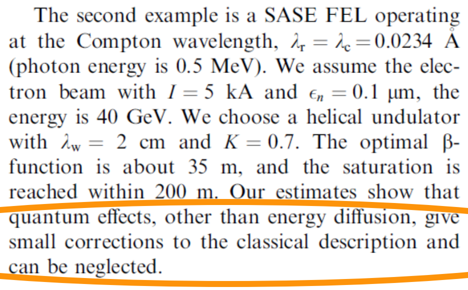

$$(\lambda_{\mathrm{r}})^{\mathrm{q}}_{\min}[\text{Å}] \simeq \frac{4\epsilon_n[\mu\mathrm{m}]}{I^{3/5}[\mathrm{kA}]L_{\mathrm{w}}^{2/5}[\mathrm{m}]}$$


The second example is a SASE FEL operating at the Compton wavelength, $\lambda_{\mathrm{r}} = \lambda_{\mathrm{c}} = 0.0234$ Å (photon energy is 0.5 MeV). We assume the electron beam with $I = 5$ kA and $\epsilon_n = 0.1$ µm, the energy is 40 GeV. We choose a helical undulator with $\lambda_{\mathrm{w}} = 2$ cm and $K = 0.7$. The optimal β-function is about 35 m, and the saturation is reached within 200 m. Our estimates show that quantum effects, other than energy diffusion, give small corrections to the classical description and can be neglected.

Design formulas

$$\left.\begin{aligned}
L_g &\simeq L_{g0}\,(1+\delta)\,, \\[2em]
L_{g0} &= 1.67\left(\frac{I_A}{I}\right)^{1/2}\frac{(\epsilon_n\lambda_{\mathrm{w}})^{5/6}}{\lambda_h^{2/3}}\,\frac{(1+K^2)^{1/3}}{h^{5/6}KA_{JJh}}\,, \\[2em]
\delta &= 131\,\frac{I_A}{I}\,\frac{\epsilon_n^{5/4}}{\lambda_h^{1/8}\lambda_{\mathrm{w}}^{9/8}}\,\frac{h^{9/8}\sigma_\gamma^2}{(KA_{JJh})^2(1+K^2)^{1/8}}\,.
\end{aligned}\right\}$$

Field gain length

$$\beta_{\mathrm{opt}} \simeq 11.2\left(\frac{I_A}{I}\right)^{1/2}\frac{\epsilon_n^{3/2}\lambda_{\mathrm{w}}^{1/2}}{\lambda_h h^{1/2}KA_{JJh}}\,(1+8\delta)^{-1/3}$$

Optimal beta-function

$$L_{\mathrm{sat}} \simeq (9\pm 0.5)\times L_g\,.$$

Saturation length

Design formulas (cont’d)

$$L_{\mathrm{sat}} \simeq 9\, L_{g0}\, \frac{1+\delta}{1-\delta_q}\,,$$

$$\delta_q = 5.5 \times 10^4 \left(\frac{I_A}{I}\right)^{3/2} \frac{\bar{\lambda}_{\mathrm{c}} r_{\mathrm{e}} \epsilon_n^2}{\lambda_h^{11/4} \lambda_{\mathrm{w}}^{5/4}} \frac{(1+K^2)^{9/4} F(K)}{K A_{JJh}^3 h^{5/3}}$$

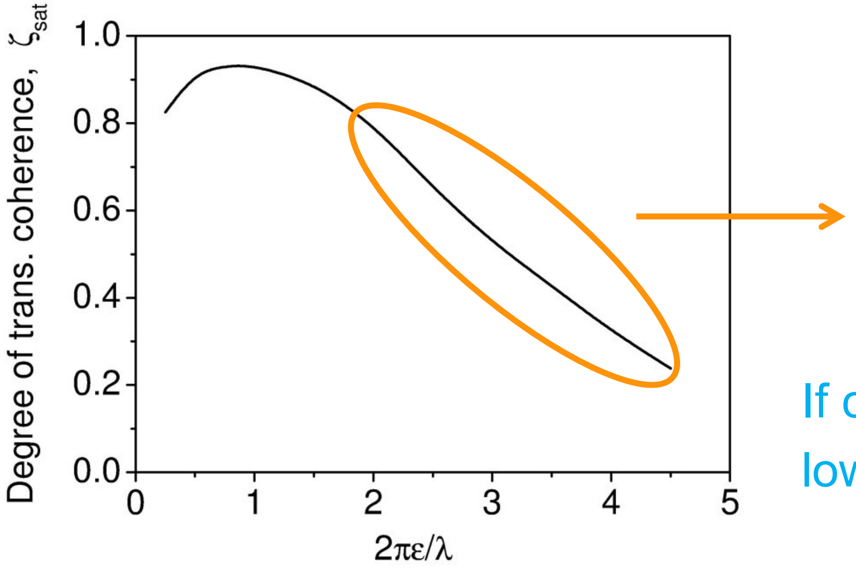
Saturation length modified, quantum diffusion included

E. Saldin, E. Schneidmiller , M. Yurkov, Opt. Commun. 235(2004)415

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

Formulas were used to obtain most of the plots of this presentation

Transverse coherence



For high photon energies ~ 50-100 keV

If coherence is important, we have to use low-charge, low-emittance beams!

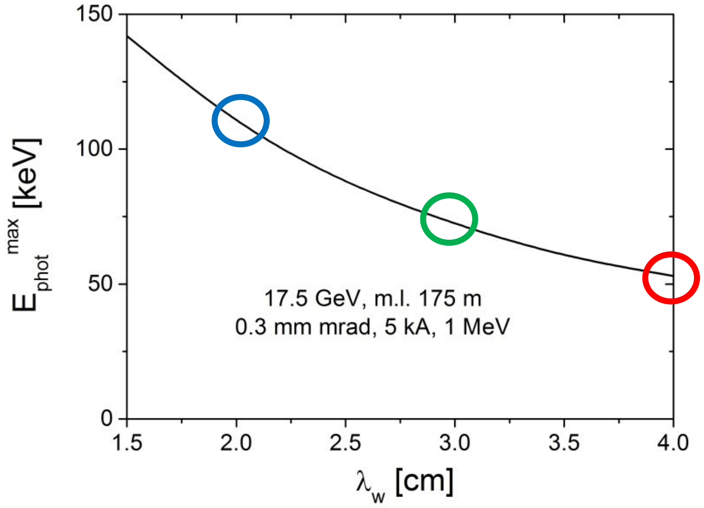
Plot from: E. Saldin, E. Schneidmiller , M. Yurkov,
Opt. Commun. 281(2008)1179

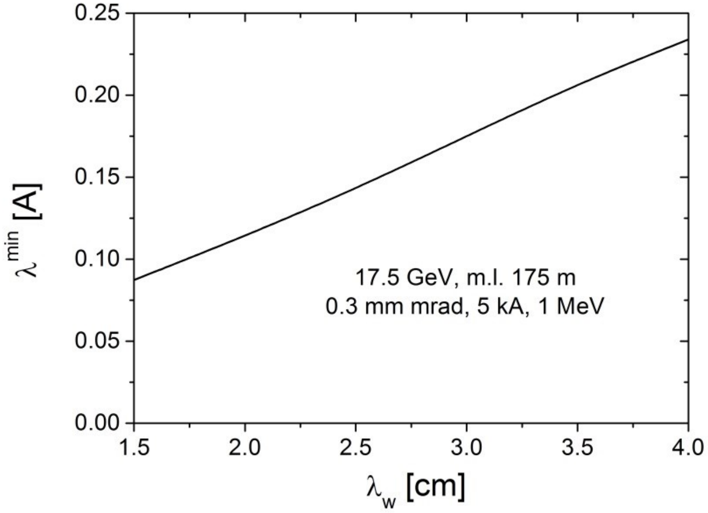
For optimized beta-function and small energy spread, the degree of transverse coherence only depends on (geometrical)emittance-to-wavelength ratio.

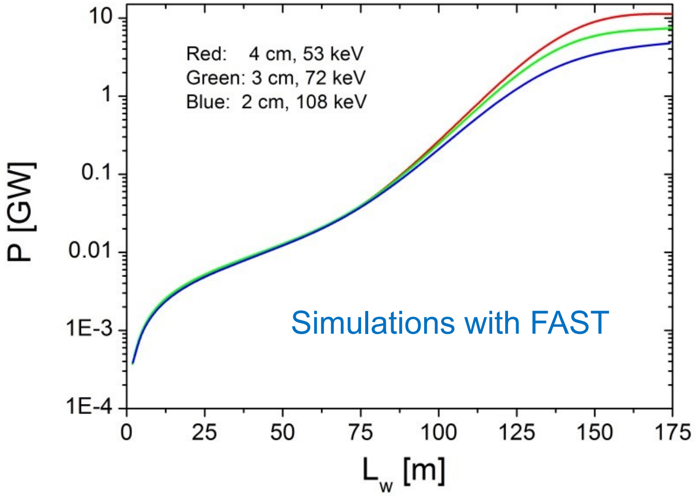
Intermediate conclusions

- The only quantum effect to be considered is the energy diffusion due to quantum fluctuations of the undulator radiation. It is included in our calculations
- To design 100 keV FEL we can use the same formulas, tools, simulation codes that were used to design the European XFEL in its present form
- At 100 keV it would be difficult to reach the same good level of transverse coherence that we have now

Highest photon energy vs undulator period





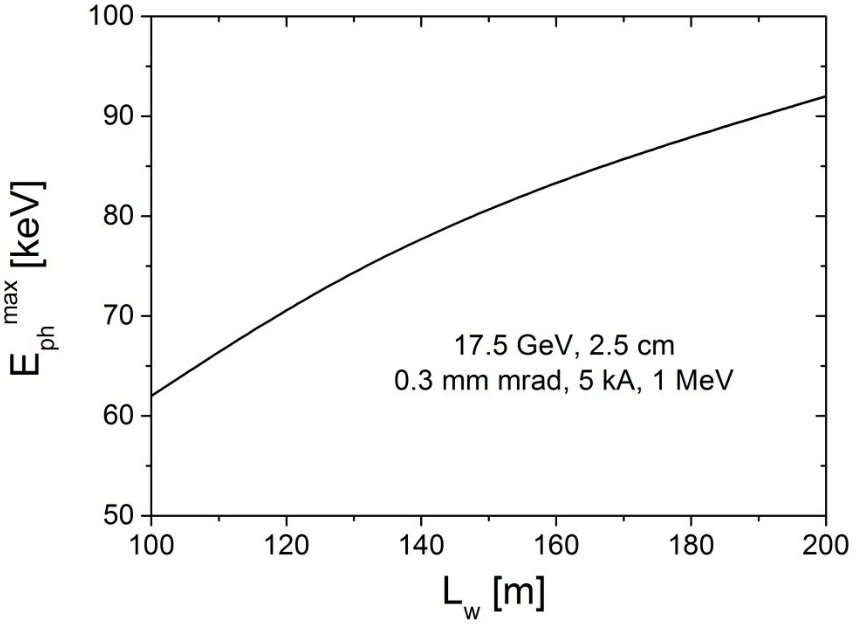


Simulations with FAST

$$\lambda_{min} \propto \lambda_w$$

The shortest wavelength is proportional to undulator period

Highest photon energy vs undulator length



Outline

- Possible SASE4/5 layout and parameters
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- Other advanced concepts
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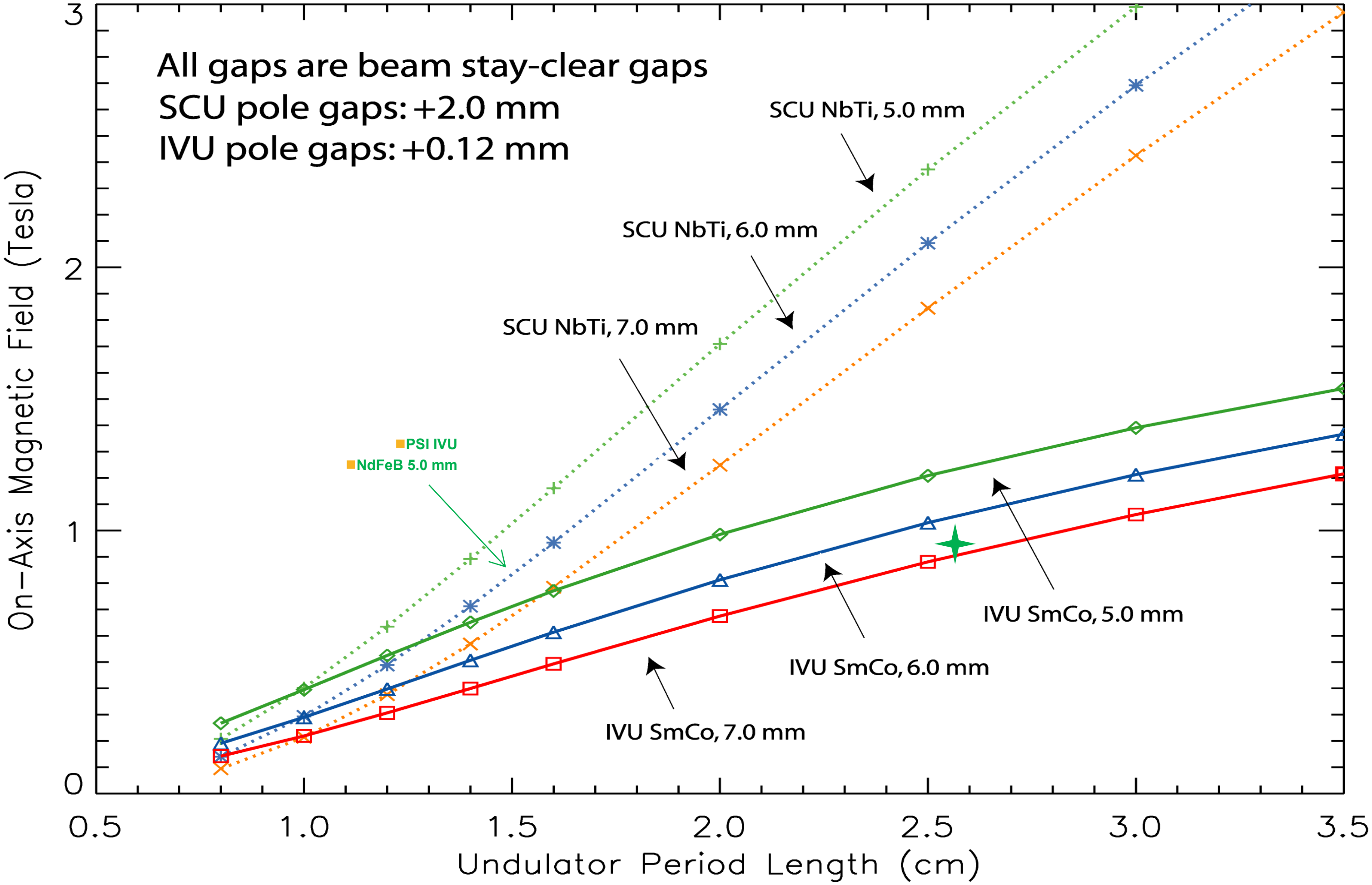
Comparison PM - EM - SC



Courtesy: Efim Gluskin APS Aug 2012

Three possible solutions

- A. Short-period (2-2.5 cm) undulator with a relatively small tunability range for a fixed elecron energy:

  in-vacuum or standard out-of-vacuum (small gap)

- B. Short-period (~2.5 cm) undulator with a large tunability range for a fixed elecron energy:

  superconducting

- C. Long-period (3-4 cm) undulator, with advanced lasing concepts (harmonic lasing, different schemes for nonlinear harmonics), with a large tunability range for a fixed electron energy:

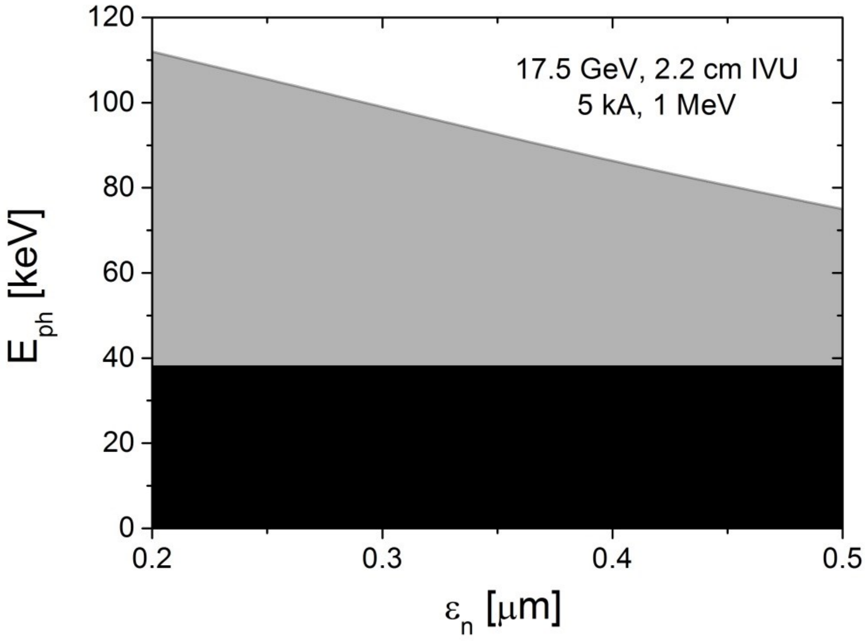
  standard out-of-vacuum (present or somewhat reduced gap)

Example A: In-vacuum undulator

U22IV

U22IV: period 2.2 cm, g= 5 mm, Krms = 1.3, m.l.= 175 m

beam stay-clear gap



Grey: operating range at 17.5 GeV

Black: can be reached for lower electron energies

White: can be reached for higher peak current

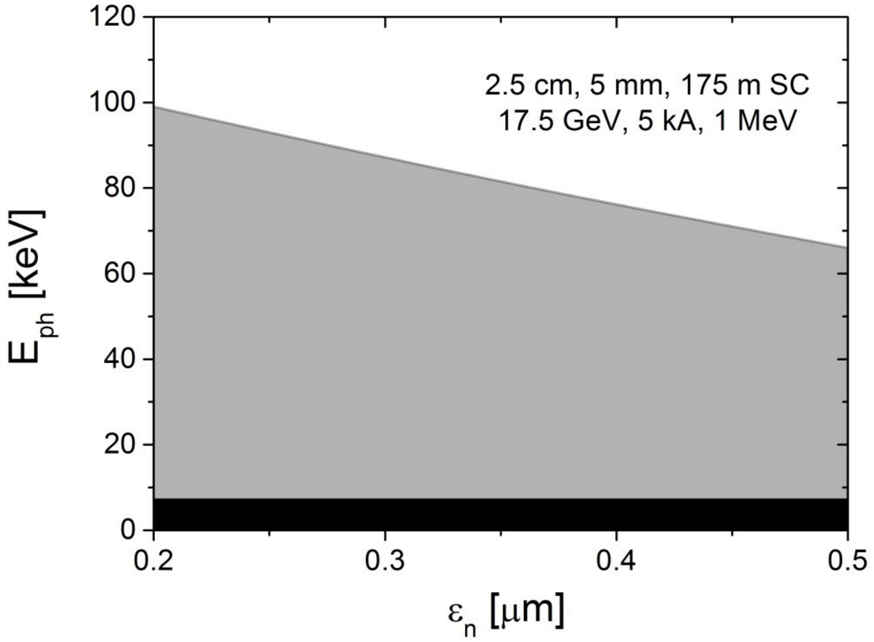
- High photon energies (~ 100 keV) are achieved
- Relatively small tunability range, factor 2-3

Example B: superconducting undulator

U25SC

U25SC: period 2.5 cm, g= 5 mm, Krms = 3.93, m.l.= 175 m

beam stay-clear gap



Grey: operating range at 17.5 GeV

Black: can be reached for lower electron energies

White: can be reached for higher peak current

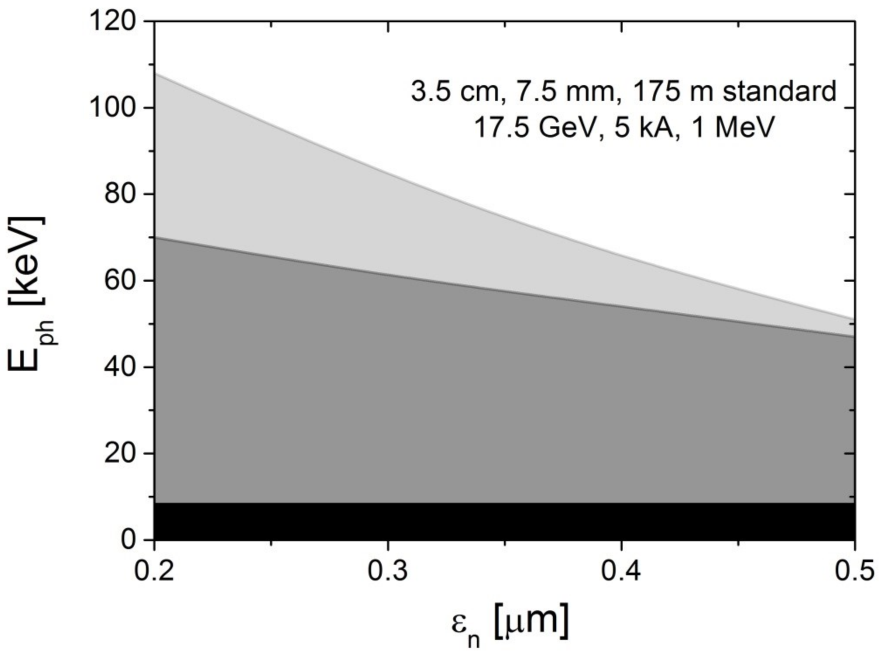
- High photon energies are achieved
- Lalge tunability range, factor 10-15

Example C1: standard undulator

U35

U35: period 3.5 cm, g= 7.5 mm , Krms = 3, m.l.= 175 m

pole gap (compare with 7.2 mm for LCLS-II)



Grey: operating range at 17.5 GeV (fund.)

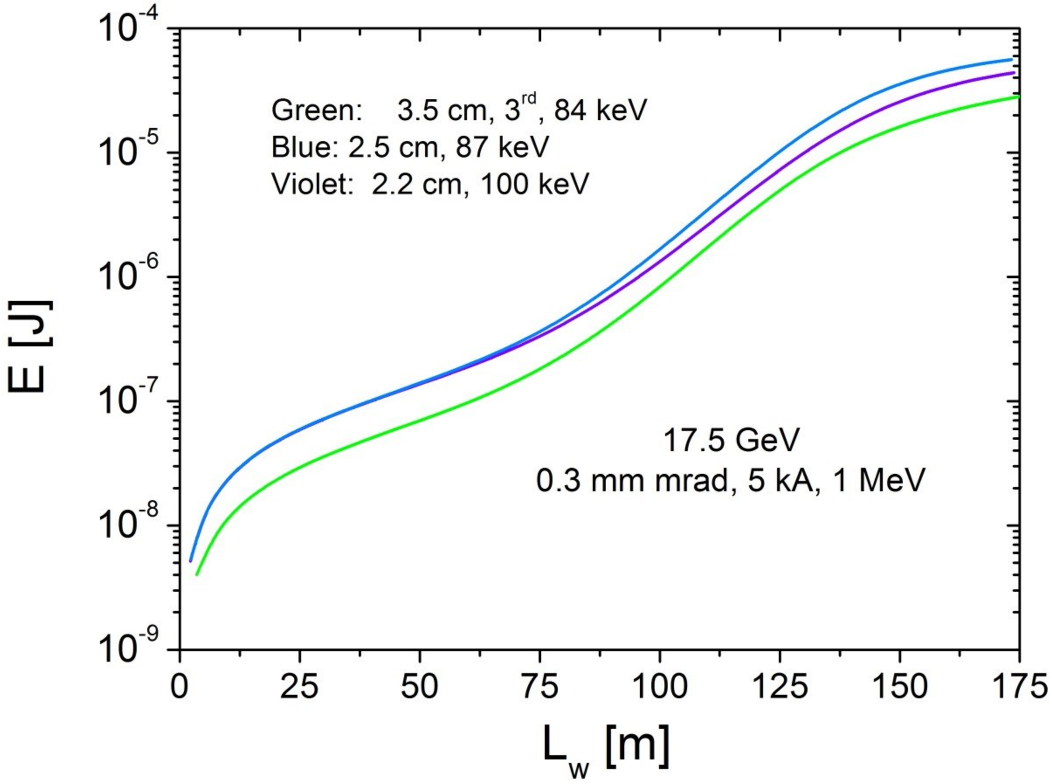
Light grey: with harmonic lasing

Black: can be reached for lower electron energies

White: can be reached for higher peak current

- 50-70 keV are achieved on the fund.; up to ~100 keV with harmonic lasing
- Lalge tunability range, factor 6-10 on the fund., up to ~15 with harm. lasing

Performance at highest photon energies



Pulse energies between 30 uJ and 60 uJ.

Spectral power is the same in all cases.

Bandwidth is 10^(-4) for harmonic lasing (FWHM).

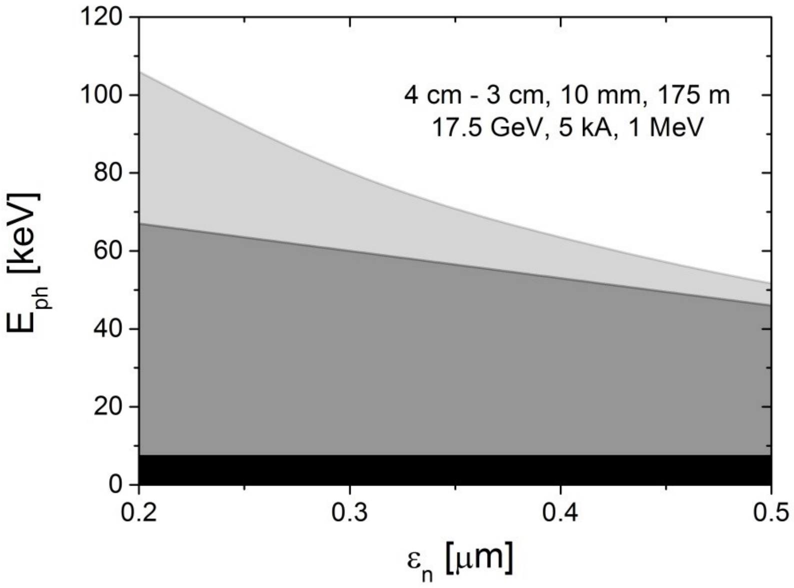
Simulations with FAST for 100 pC bunch

Example C2: standard undulator, two periods

U40: period 4 cm, g = 10 mm, Krms = 3, m.l.= 100 m

U30: period 3 cm, g = 10 mm, Krms = 1.65, m.l.= 75 m

pole gap, most conservative



Grey: operating range at 17.5 GeV (fund.)

Light grey: with harmonic lasing

Black: can be reached for lower electron energies

White: can be reached for higher peak current

- ~50-70 keV are achieved on the fund.; up to ~100 keV with harmonic lasing
- Lalge tunability range, factor 6-10 on the fund., up to ~15 with harm. lasing

Hybrid solutions?

- For g = 7 mm, standard U35 + U27 undulators give the same lower photon energy as U40 + U30 with 10 mm gap (~7 keV), but increase higher photon energies
- U20SC is initially short (maybe ~10 m); it starts with 25 keV (as U27) but works better at high photon energies; allows to get higher FEL power
- If it works well, we can later upgrade the system: exchange (maybe in steps?) U27 by U20SC, then U35 by U25SC
- This keeps the same lower photon energies available but greatly improves operation at high photon energies; risk is minimized

Outline

- Possible SASE4/5 layout and parameters
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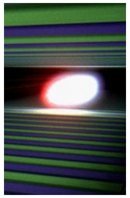
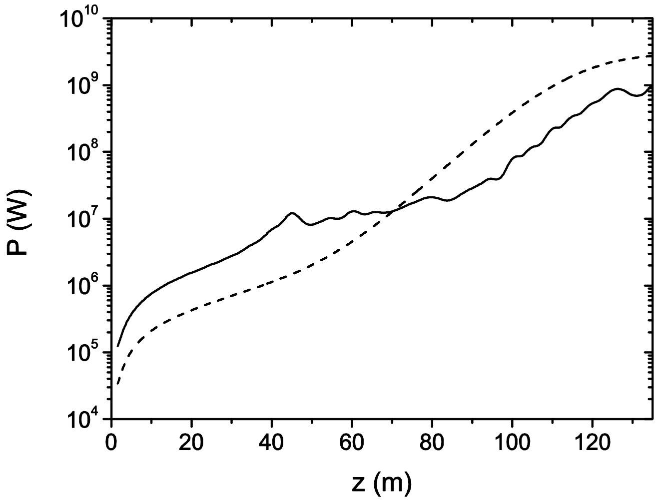
Options to reach higher photon energies (than SASE on the fundamental)



- Nonlinear harmonics generation (always there)
- Harmonic lasing and HLSS (the most brilliant solution)
- Reverse tapering plus harmonic afterburner
- Cascaded frequency multiplication
- Multi-stage optical klystron (chicanes required)
- Two last items combined
- …

Harmonic lasing

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



1st: solid

3rd: dash

the fundamental is disrupted by phase shifters (McNeil et al., PRL96(2006) 084801)

3rd harmonic lasing of SASE2 at 62 keV (0.2 A). Beam parameters for 100 pC from s2e (quantum diffusion in the undulator added), energy 17.5 GeV.

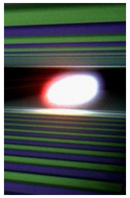
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702

Properties of harmonic lasing

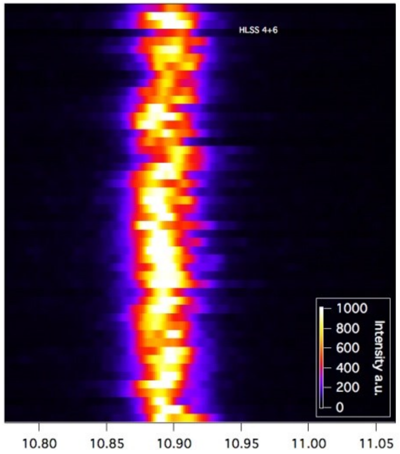
- Saturation efficiency of h-th harmonic scales as ~ $\lambda_w/(hL_{sat})$
- Relative rms bandwidth scales as ~ $\lambda_w/(hL_{sat})$
- Shot-to-shot intensity fluctuations are comparable (the same statistics)

Brilliance is comparable to that of the fundamental!

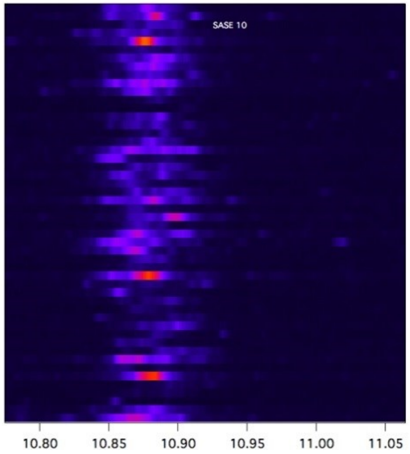
Harmonic lasing at FLASH2 (2016)

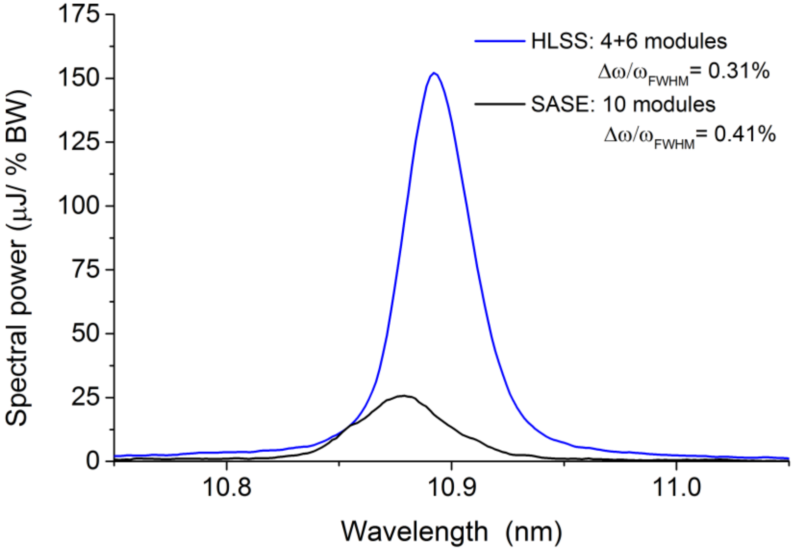


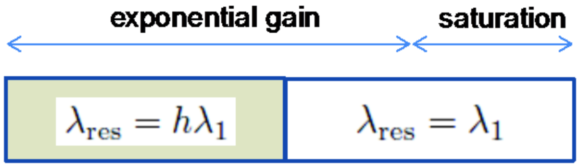
HLSS (4+6)



SASE (10)







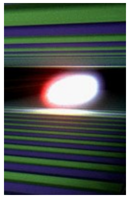
exponential gain **saturation** (actually, no saturation)

$\lambda_{\mathrm{res}} = h\lambda_1$ $\lambda_{\mathrm{res}} = \lambda_1$

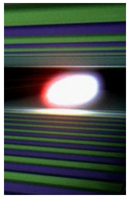
4 und. at 33 nm 6 und. at 11 nm

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

Harmonic lasing: status



- Known theoretically since 1980s (Colson 1981)
- Experiments with infrared FEL oscillators
- Theoretical studies for high-gain FELs (Murphy et al. 1985, Z. Huang and K.-J. Kim 2000, McNeil et al. 2006)
- No prospects for XFEL facilities
- This was changed recently (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; first users
- PAL XFEL down to 1nm (2017)
- Interest at LCLS, SACLA and Swiss FEL
- Experiments at the European XFEL just started



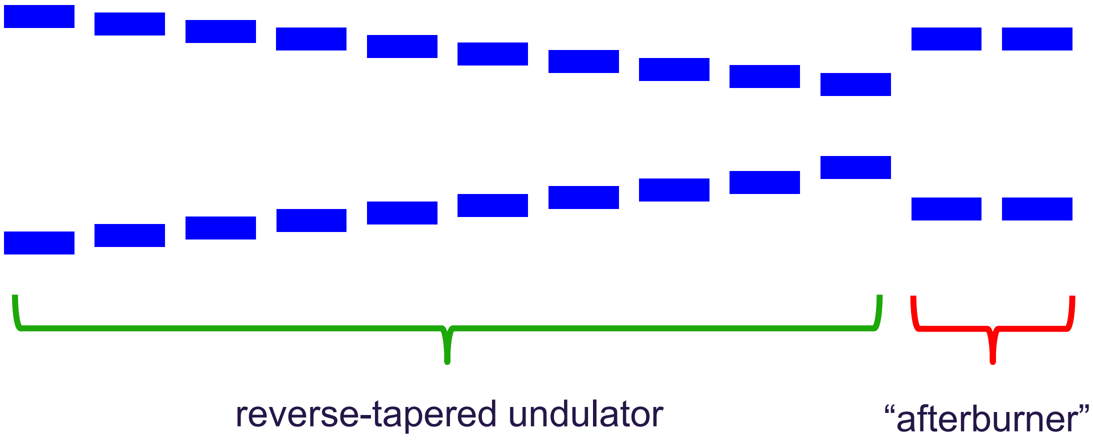
Reverse tapering plus harmonic afterburner

- 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 afterburner tuned to the resonance
- The afterburner can be tuned to a harmonic; then a background-free production of harmonics is possible

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

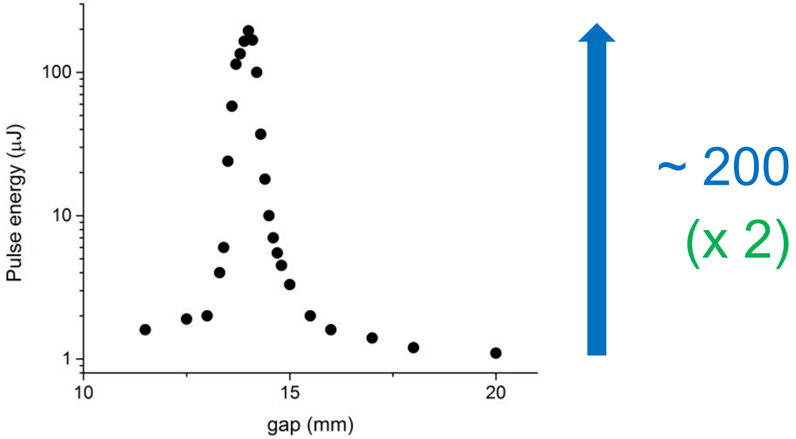
Reverse taper experiment at FLASH2

23.01.2016



Beam energy 720 MeV, wavelength 17 nm.

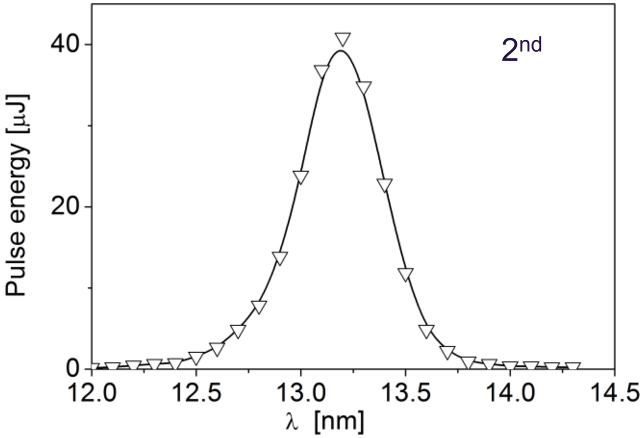
Reverse taper was applied to the 10 undulator segments; the gap of the 11th and 12th segments was scanned.

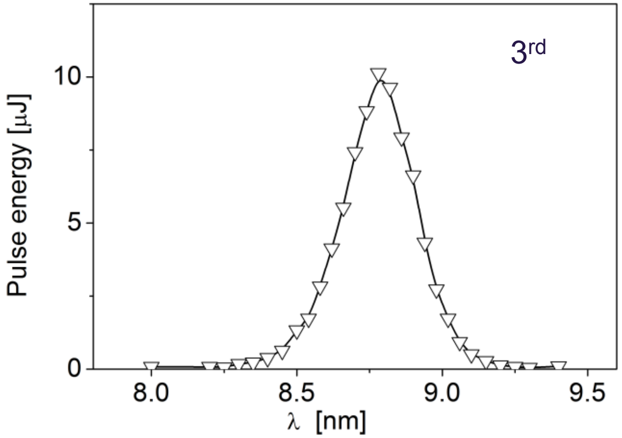


Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.

Reverse taper plus harmonic afterburner: experiment at FLASH2

- 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

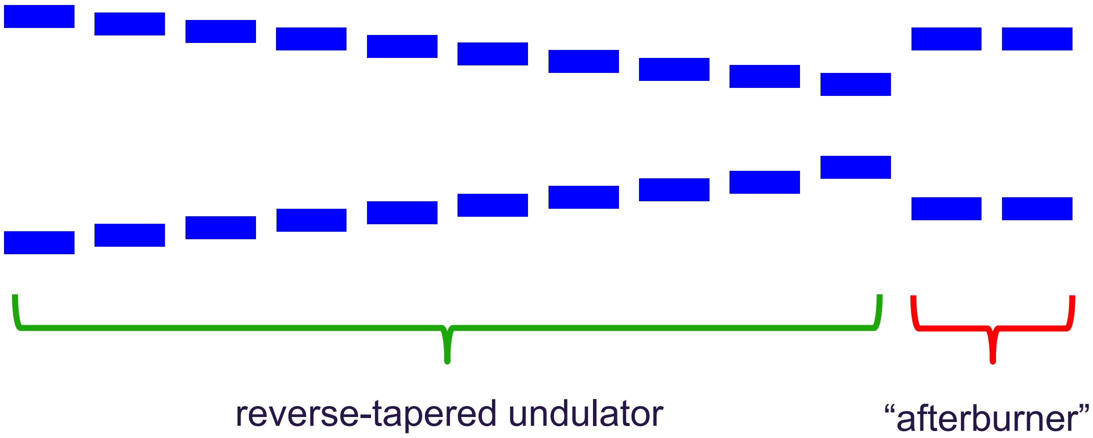




Reverse taper can be used for efficient background-free generation of harmonics in an afterburner

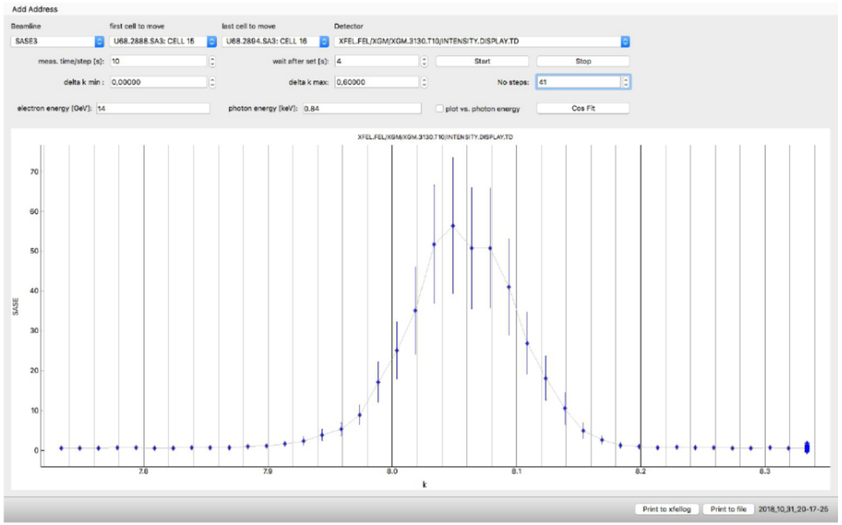
Reverse taper experiment at SASE3

31.10.2018



reverse-tapered undulator

“afterburner”



Add Address

Beamline: SASE3
first cell to move: U68.2888.SA3: CELL 15
last cell to move: U68.2894.SA3: CELL 16
Detector: XFEL.FEL/XGM/XGM.3130.T10/INTENSITY.DISPLAY.TD
meas. time/step [s]: 10
wait after set [s]: 4
delta k min : 0,00000
delta k max: 0,60000
No steps: 41
electron energy [GeV]: 14
photon energy [keV]: 0.84
☐ plot vs. photon energy

Beam energy 14 GeV, wavelength 1.5 nm.

Reverse taper (2.4%) was applied to the 12 undulator segments;

the gap of the 13th and 14th segments was scanned.

Power ratio on the order of 100 was obtained.

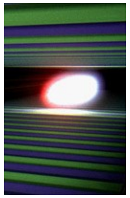
Cascaded frequency multiplication, optical klystron etc.

- Large tunability of an undulator with a large K supports cascaded frequency multiplication, for example:

  10 keV → 20 keV → 40 keV → 80 keV

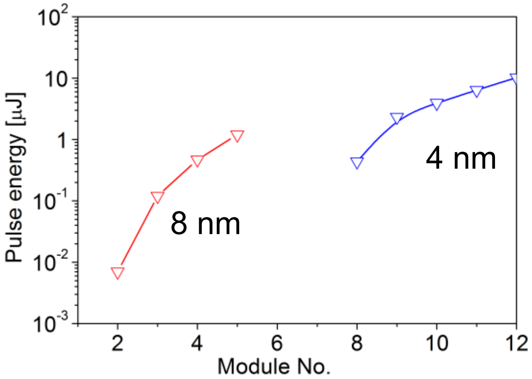
- Optionally, compact chicanes (R56 ~ 100 nm) can be installed. Then one can operate optical klystron on the fundamental (thus reducing saturation length) and/or on harmonics

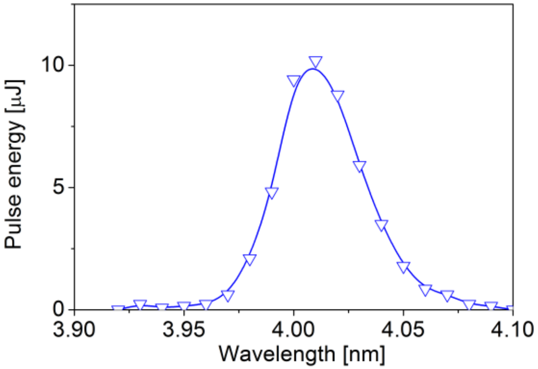
Frequency doubler at FLASH2



(Bonifacio et al.,1990; Fawley, 1996; Feldhaus et al., 2004; H.-D. Nuhn et al., 2010)

- Undulator is divided into 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.





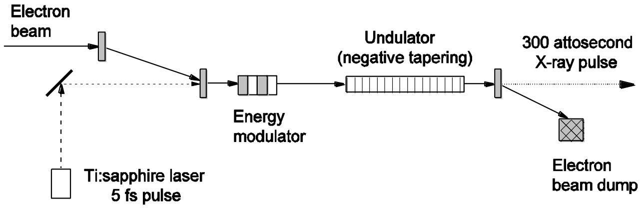
Kuhlmann, Schneidmiller , Yurkov, IPAC'17

Outline

- Possible SASE4/5 layout and parameters
- Is 100 keV lasing possible at all?
- Lasing scenarios in different undulators
- Advanced options for UHXR
- Other advanced concepts
- Discussion and summary

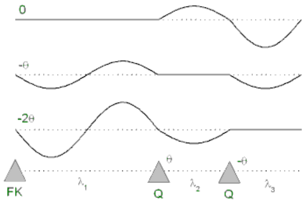
Additional options

- Attosecond pulses: there is space upstream (end of XTD1 tunnel and the XS2 hall) to install hardware (laser transport, short wiggler, chicane)



E. Saldin, E. Schneidmiller , M. Yurkov, PRST-AB 9(2006)050702

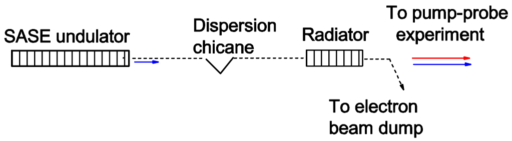
- Multi-color operation: use betatron switcher principle



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

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

- XUV (and optical) afterburner: convert energy modulations on the scale of FEL coherence length into density modulations, need a chicane and a short radiator undulator (10s nm – 1000s nm range possible);



E. Saldin, E. Schneidmiller, M. Yurkov, Phys. Rev. ST-AB 13, 030701 (2010)

Eight decades of e.m. spectrum

- SASE1-5 might be able to cover the range from UHXR to SXR (and maybe XUV)
- SASE afterburners can work from XUV to NIR
- THz facility (talk by M. Krasilnikov) and/or a wiggler (talk by T. Tanikawa): MIR to FIR
- Together with optional XUV and optical afterburners, and accelerator-based THz facillty, the European XFEL would cover continuously eight decades of e.m. spectrum (from 1 meV to 100 keV)

Outline

- Possible SASE4/5 layout and parameters
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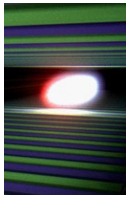
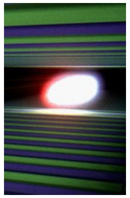
Why large tunability for fixed energy?



- Ideal multi-user XFEL facility: runs with constant electron energy, and photon energies are changed by undularors only
- This will not work by us (although we can think of possible upgrade of SASE1-3), but the tendency would be to operate most of the time at a nominal high energy
- Reducing energy from time to time is necessary but it might be painful (performance is reduced), also logistics is complicated
- The problem at SASE4 with a weakly tunable undulator is that (for nominal electron energy) photon energies are always in UHXR regime. Will we have enough users? What if there is no lasing there?
- In a widely tunable undulator one can always change to a standard range (7-25 keV) and work for users or fix problems with lasing; smooth commissioning and operation should be possible; day-night switching between two ranges (HXR and UHXR) should be possible



Summary

- Lasing up to ~100 keV should be feasible.
- Concept of the SASE4 undulator allows for a wide tunability range (from 7 keV to 100 keV) at a fixed electron energy of 17.5 GeV by making use of either SC undulator or standard undulator technology plus advanced lasing options. Two instruments for a “standard” HXR range (7-25 keV) and for UHXR (25-100 keV) can then be operated.
- After implementation of some additional options, the European XFEL would cover continuously eight decades of e.m. spectrum (1 meV to 100 keV) being unique.

Backup slides