European XFEL

Harmonic Lasing in X-ray FELs

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DESY

HELMHOLTZ | ASSOCIATION

Harmonics in FELs

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

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

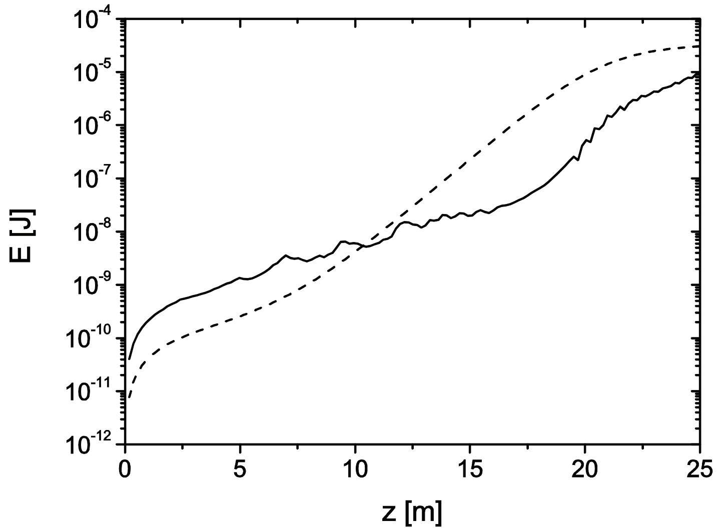
- There are two basic mechanisms in FELs:

-Nonlinear harmonic generation
-Harmonic lasing

We consider SASE process in a baseline XFEL undulator

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
- Several successful experiments with FEL oscillators
- High-gain FELs: only few theoretical papers



1^{st}: solid
3^{rd}: dash

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 (or even larger than) that of the fundamental!

Why don't we consider this option?

Harmonic lasing: the history

- First theoretical consideration for low-gain FELs more than 30 years ago (Colson, 1981)
- Several successful experiments with FEL oscillators in infrared range (1988-2010)

- High-gain FELs:

  1D theory of harmonic lasing

  Murphy, Pellegrini, Bonifacio, 1985

  Bonifacio, De Salvo, Pierini, 1990

  3D theory (everything included)

  Z. Huang and K.-J. Kim, 2000

  Disruption of the fundamental (phase shifters):

  McNeil et al., 2005

  Parisi et al., 2005

3D theory by Z. Huang and K.-J. Kim (2000)

- Eigenvalue equation for calculation of gain length of harmonic lasing including all important effects: emittance, betatron motion, diffraction of radiation, energy spread etc.
- Numerical example for LCLS: NO harmonic lasing, only nonlinear harmonic generation possible. Reason: too large emittance and energy spread anticipated at that time.

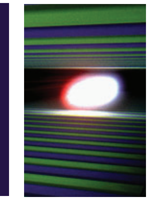
$$\bar{\Phi}_{nm}(p) = -\frac{h^2 A_{JJh}^2}{A_{JJ1}^2 (2\,\mathrm{i}\,hB\hat{\Lambda} - p^2)} \int\limits_0^\infty \mathrm{d}\,p' p' \bar{\Phi}_{nm}(p')$$
$$\times \int\limits_0^\infty \mathrm{d}\,\zeta \frac{\zeta}{(1 - \mathrm{i}\,hB\hat{k}_\beta^2 \zeta/2)^2} \exp\left[-\frac{h^2 \hat{\Lambda}_\mathrm{T}^2 \zeta^2}{2} - (\hat{\Lambda} + \mathrm{i}\,\hat{C})\zeta\right]$$
$$\times \exp\left[-\frac{p^2 + p'^2}{4(1 - \mathrm{i}\,hB\hat{k}_\beta^2 \zeta/2)}\right] I_n\left[\frac{pp' \cos(\hat{k}_\beta \zeta)}{2(1 - \mathrm{i}\,hB\hat{k}_\beta^2 \zeta/2)}\right] .$$

Our recent revision

- Found simple parametrization of the gain length
- Could then analyze parameter space (with optimistic conclusions)
- Proposed new methods for suppression of the fundamental
- Suggested method for improvement of spectral brightness
- Discovered qualitatively new effect of anomalously strong harmonic lasing for thin electron beams
- Considered practical applications to different facilities (XFEL.EU, LCLS, FLASH etc.)

Our conclusion: the option must be seriously considered!

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



Gain length of harmonic lasing

Generalization of formulas from Saldin, Schneidmiller and Yurkov, Opt. Commun. 235(2004)415

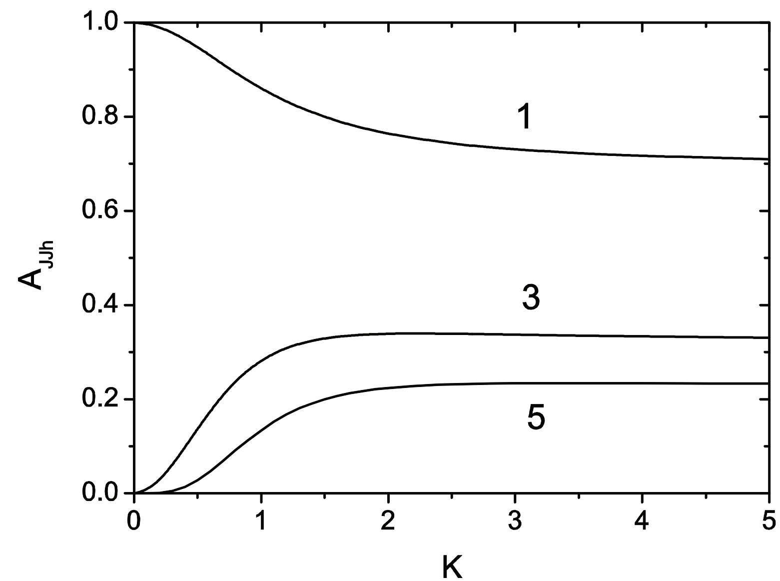
$$L_g \simeq L_{g0}\ (1+\delta)$$ field gain length

$$A_{JJh}(K) = J_{(h-1)/2}\left(\frac{hK^2}{2(1+K^2)}\right) - J_{(h+1)/2}\left(\frac{hK^2}{2(1+K^2)}\right)$$

$$L_{g0} = 1.67\left(\frac{I_A}{I}\right)^{1/2}\frac{(\epsilon_n\lambda_{\mathrm{w}})^{5/6}}{\lambda_h^{2/3}}\ \frac{(1+K^2)^{1/3}}{h^{5/6}KA_{JJh}}$$

$$\delta = 131\ \frac{I_A}{I}\ \frac{\epsilon_n^{5/4}}{\lambda_h^{1/8}\lambda_{\mathrm{w}}^{9/8}}\ \frac{h^{9/8}\sigma_\gamma^2}{(KA_{JJh})^2(1+K^2)^{1/8}}$$

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



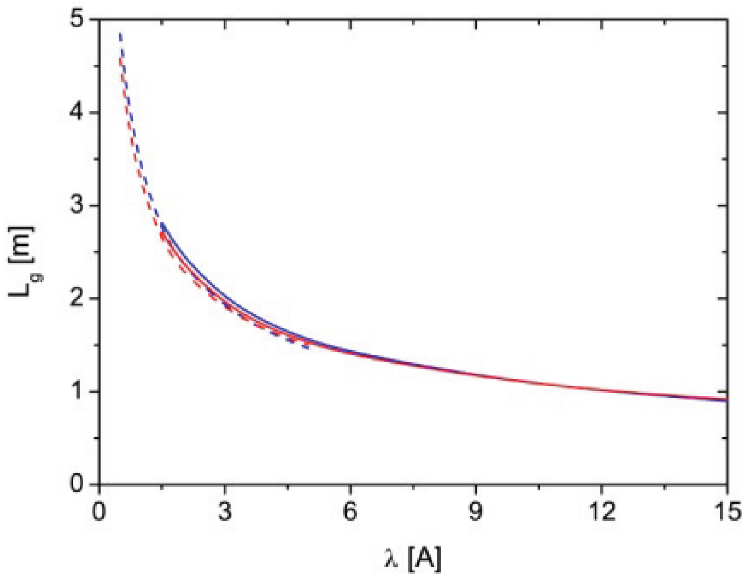
$$L_g(\beta) \simeq L_g(\beta_{\mathrm{opt}})\left[1 + \frac{(\beta-\beta_{\mathrm{opt}})^2(1+8\delta)}{4\beta_{\mathrm{opt}}^2}\right]^{1/6}$$ for $\beta > \beta_{\mathrm{opt}}$ new also for the fundamental

$2\pi\epsilon/\lambda \sim 1$ or $2\pi\epsilon/\lambda >> 1$

Practical example: LCLS

We also generalized Ming Xie formulas to the case of harmonic lasing

Power gain length versus wavelength:



Beam parameters: peak current 3 kA, normalized emittance 0.4 mm mrad, energy spread 1.4 MeV. Beta-function scales with energy: $\beta[m] = 30\,\frac{E[GeV]}{13.6}$

Blue: our formulas
Red: generalized Ming Xie formulas
Solid: the fundamental
Dash: the 3rd harmonic

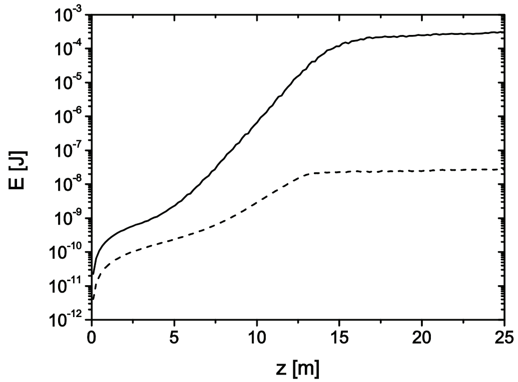
Saturation length is about 20 power gain lengths; saturation is possible at 0.5 A with 13.6 GeV.
But: one has to suppress the fundamental

Disruption of the fundamental: phase shifters

The method is proposed by McNeil et al., 2005
Parisi et al., 2005

If phase shifters are tuned such that the phase delay is $2\pi/3$ (or $4\pi/3$) for the fundamental, then its amplification is disrupted. At the same time the phase shift is equal to 2π for the third harmonic, i.e. it continues to get amplified without being affected by phase shifters.

Consecutive use of the same phase shifters, as proposed in McNeil et al., 2005 works well for a monochromatic seed but not for SASE. There is a frequency shift depending on number and magnitude of phase shifts.

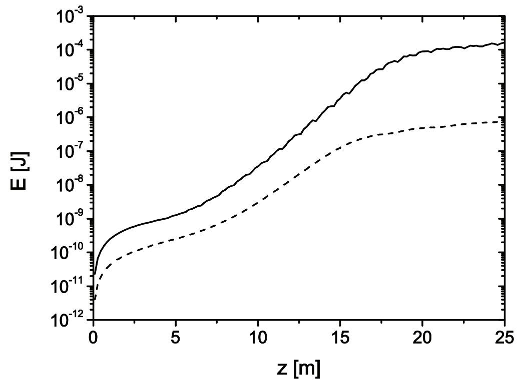


1st: solid
3rd: dash

49 phase shifters!

A more efficient method (alternation of phase shifts $2\pi/3$ and $4\pi/3$) is proposed in Parisi et al., 2005

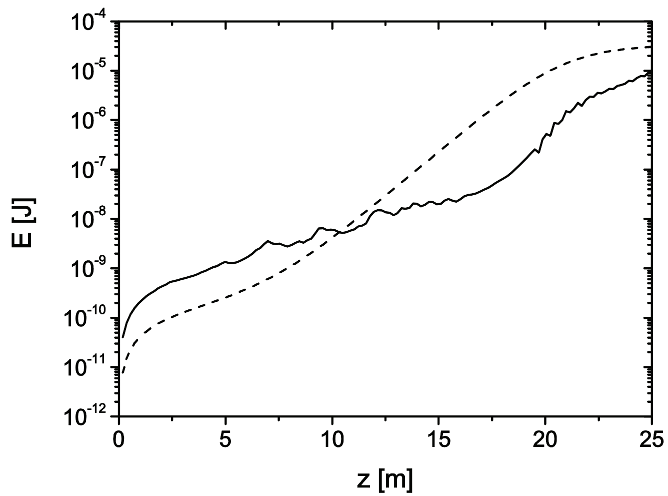
Still not efficient enough!



Our modification of phase shifters method

Our method for disruption of the fundamental mode can be defined as a piecewise use of phase shifters with the strength $2\pi/3$ and $4\pi/3$.

Works much better!



1st: solid
3rd: dash

Proposal for FLASH: 1.3 nm at 1.25 GeV

Poster WEPSO53

Example for XFEL.EU

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.

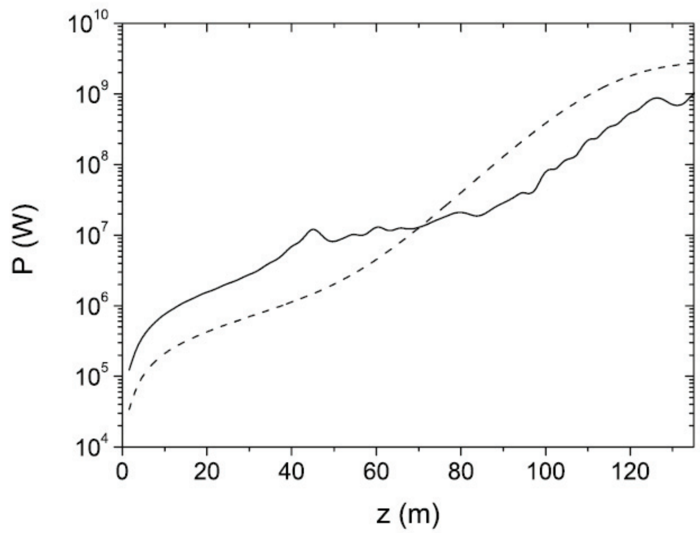


Fig. 8. An example for the European XFEL. Averaged peak power for the fundamental harmonic (solid) and the third harmonic (dash) versus magnetic length of SASE1 undulator. The wavelength of the third harmonic is 0.2 Å (photon energy 62 keV). The fundamental is disrupted with the help of phase shifters installed after 5 m long undulator segments. The phase shifts are $4\pi/3$ after segments 1-8 and 21-26, and $2\pi/3$ after segments 9-16. Simulations were performed with the code FAST.

3D simulations, modified FAST

1st: solid
3rd: dash

bandwidth is 2×10^{-4} (FWHM)

Intraundulator spectral filtering

In the middle of the undulator the electron beam trajectory deviates from a straight line (chicane or closed bump), and a filter is inserted.

Transmitted intensity scales as $\exp(-\mu d)$, where d is the thikness, and the coefficient μ depends on frequency as $a \exp(-b\omega)$. Very efficient high-pass filter due to the double exponential suppression.

Beam modulations are smeared through the chicane due to R56.

Entrance of the second part of the undulator: no modulations, and only 3rd harmonic radiation.

Can be combined with a self-seeding setup: just add the filter!

If one filter is not sufficient: use two filters or a combination with phase shifters.

Proposal for LCLS

3rd harmonic lasing at 25 keV; filter in HXRSS chicane: 600 um of Si + phase shifters

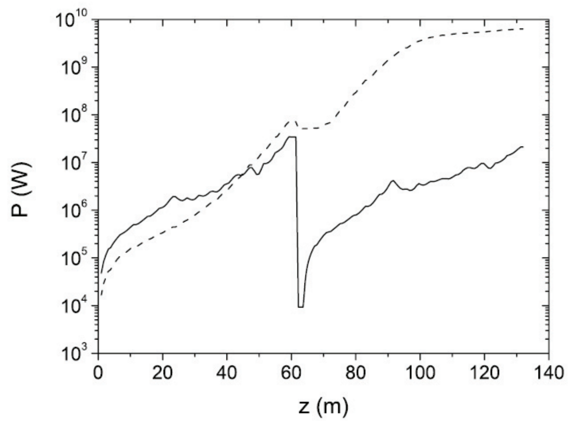
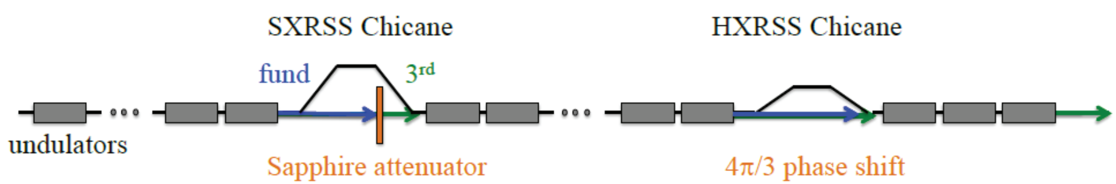


Fig. 7. Averaged peak power for the fundamental harmonic (solid) and the third harmonic (dash) versus geometrical length of the LCLS undulator (including breaks). The wavelength of the third harmonic is 0.5 Å (photon energy 25 keV). Beam and undulator parameters are in the text. The fundamental is disrupted with the help of the spectral filter (see the text) and of the phase shifters. The phase shifts are $4\pi/3$ after segments 1-5 and 17-22, and $2\pi/3$ after segments 6-10 and 23-28. Simulations were performed with the code FAST.

6 GW at 25 keV

BW is 3 x 10^{-4} (FWHM)

Test experiment (w/o phase shifters) is planned: Poster WEPSO53 by D. Ratner

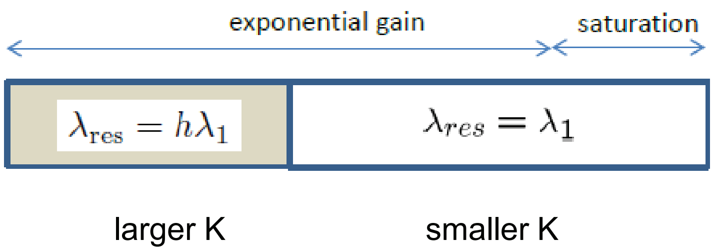


18-24 keV

HLSS FEL (Harmonic Lasing Self-Seeded FEL)

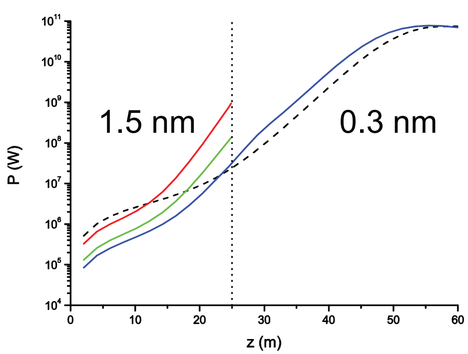
We proposed a simple trick for improvement of spectral brightness in a gap-tunable undulator: harmonic lasing in linear regime (with narrow bandwidth) in the first part of the undulator, then reducing K and reaching saturation at the fundamental. Then we have high power and narrow BW.

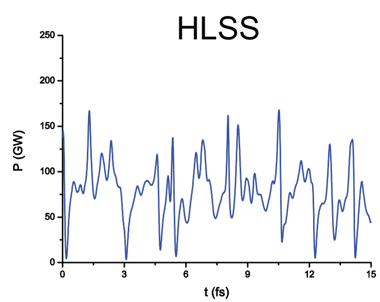
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702

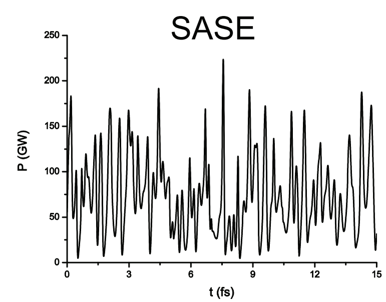


More efficient post-saturation taper possible

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.



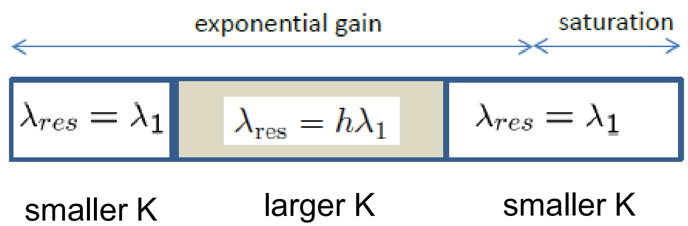




Poster WEPSO53

HLSS vs pSASE

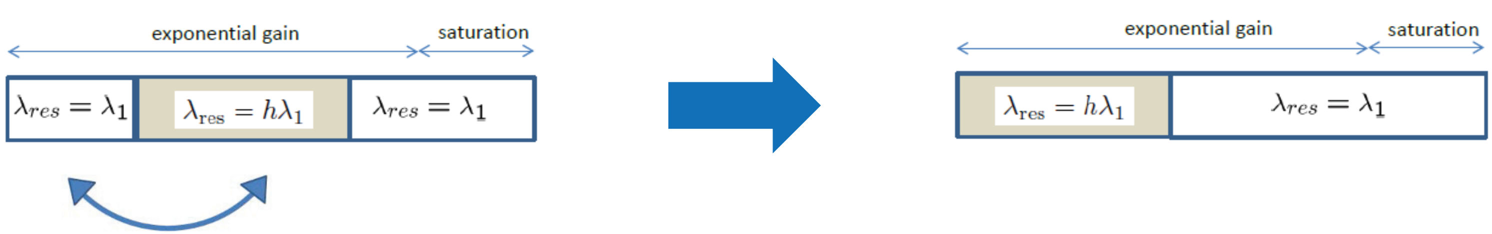
A similar concept (pSASE) was proposed recently: D. Xiang et al., PRST-AB 16(2013)010703



First two sections are linear amplifiers (with large BW and small BW). One can swap them and keep the same properties of radiation in the end (small BW and high power):

pSASE FEL

HLSS FEL



Anomalous harmonic lasing of a thin beam

The case $2\pi\epsilon/\lambda \sim 1$ is typical for hard X-ray beamlines

If the same beam is used to drive a soft X-ray undulator (like SASE3 of XFEL.EU), the case $2\pi\epsilon/\lambda << 1$ is automatically achieved

For a reasonable beta-function one deals then with a small diffraction parameter $B = 4\pi\epsilon\beta\Gamma/\lambda$ ($L_g \propto 1/\Gamma$)

If the diffraction parameter is sufficiently small and K is sufficiently large, harmonics can grow faster than the fundamental!

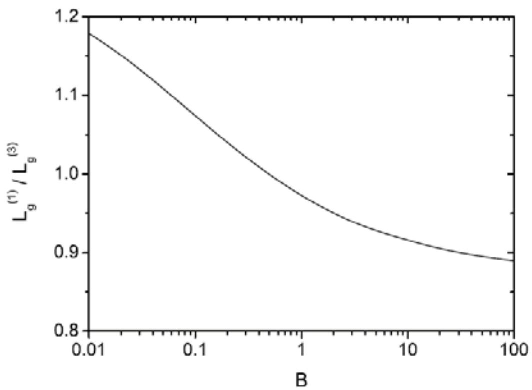
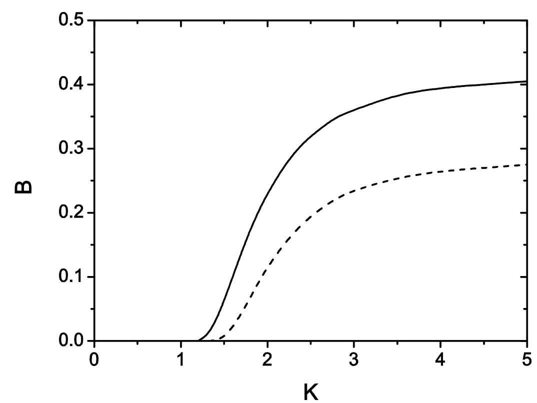


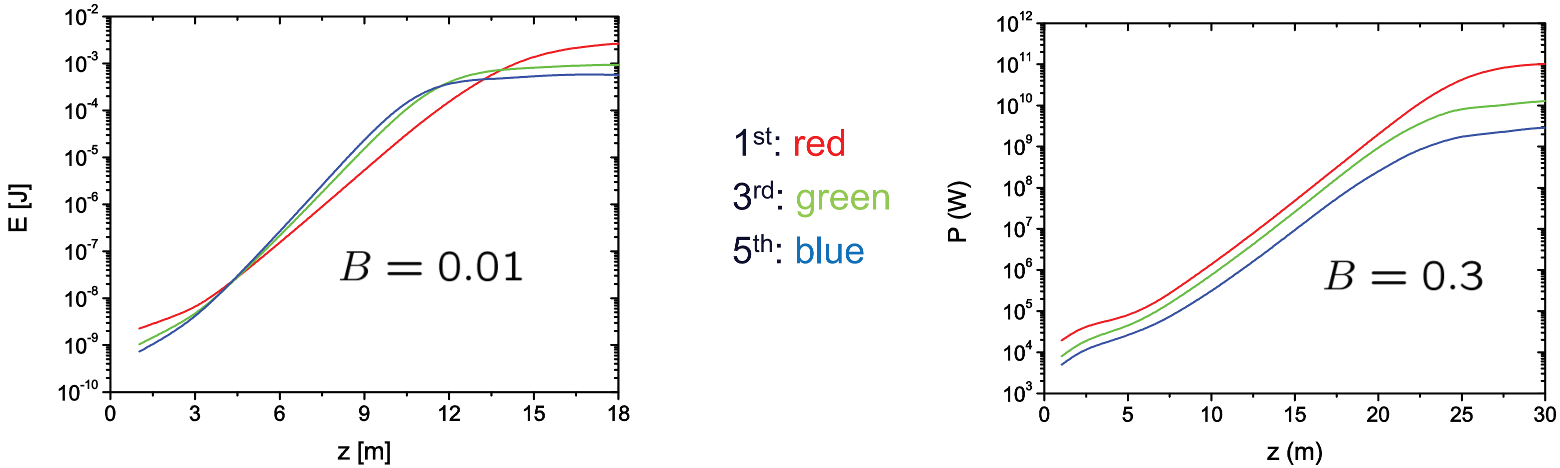
Fig. 4. Ratio of gain lengths for lasing at the fundamental wavelength and at the third harmonic versus diffraction parameter of the fundamental wavelength for large values of the undulator parameter K.

3D: $\Gamma \propto (A_{JJ}^2 \omega^2)^{1/2}$

1D: $\Gamma_{1D} \propto (A_{JJ}^2 \omega)^{1/3}$



Anomalous harmonic lasing (cont'd)



XFEL.EU: fundamental at 4.5 nm, beam energy 10.5 GeV, slice parameters for 100 pC from s2e, energy spread is 1 MeV

One can use this effect (in pump-probe experiments or for multi-user operation) or find ways to suppress it (if disturbs).

Possible applications in XFELs

- Extension of wavelength range;
- XFELs driven by low-energy beams:

 - CW upgrade of XFEL.EU (7.5 -10 GeV, lasing below 1 A in the same undulators)

 - standard undulator technology instead of small-gap in-vacuum undulators (can be done at the Swiss FEL, for example)

- More flexible operation of multi-undulator facilities at different electron energies;
- Bandwidth reduction and brilliance increase (HLSS);
- High-power (TW) option;
- Jitter-free two-color operation for pump-probe experiments;
- …