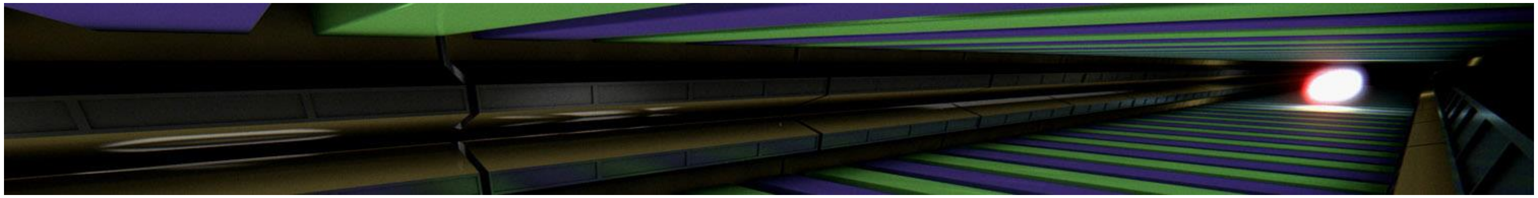


Reverse taper experiment at FLASH

E. Schneidmiller and M. Yurkov

8th Hard X-ray FEL Collaboration Meeting

Pohang, Korea

October 26, 2016

Mainstream for 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 (saturation)

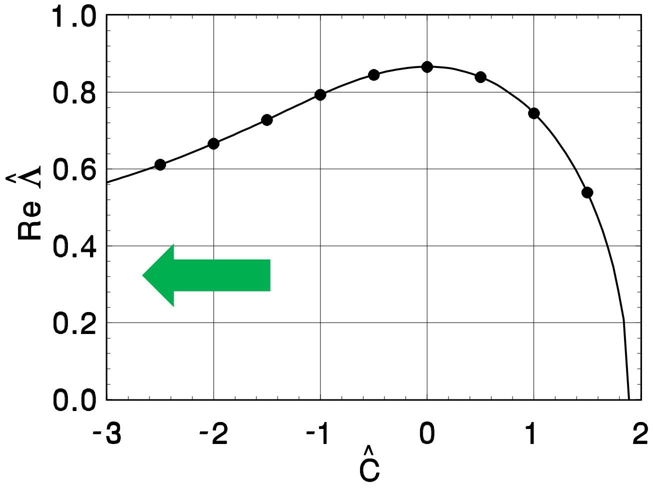
helical afterburner

- 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

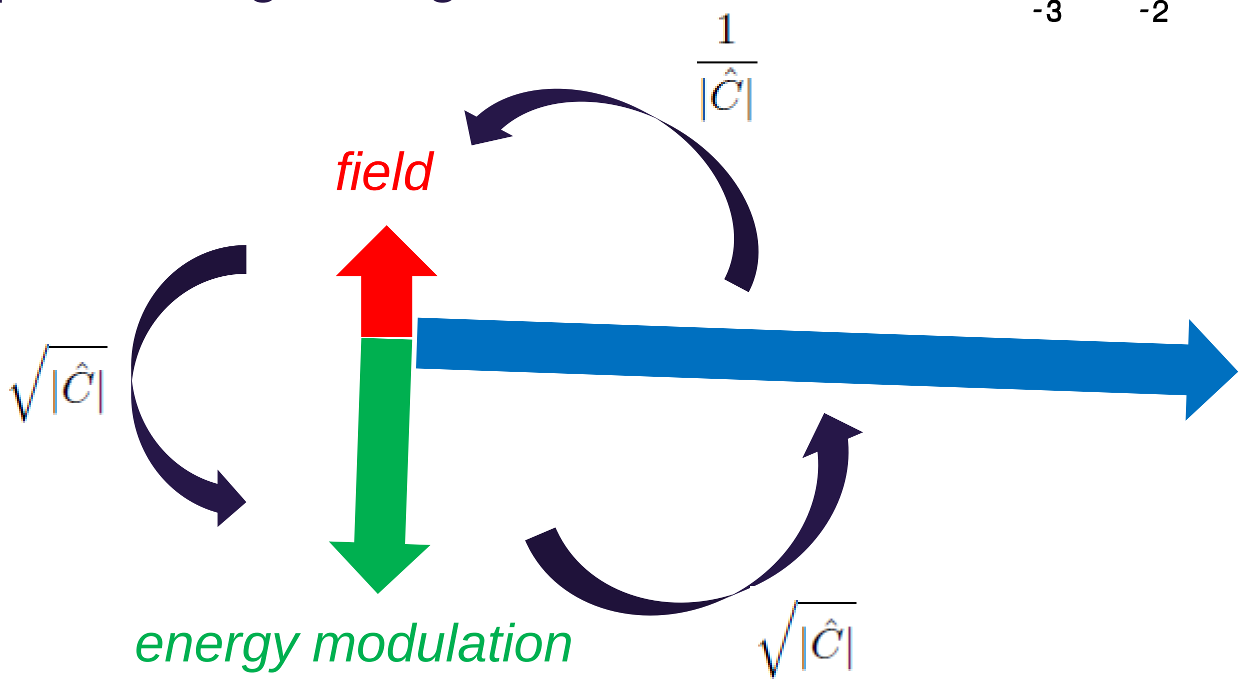
Steady-state, exponential gain regime

Consider monochromatic seed, no taper but large negative detuning: $\hat{C} < 0$, $|\hat{C}| \gg 1$.



Scaled gain length is now $L_g\Gamma \approx \sqrt{|\hat{C}|}$.

One can solve initial-value problem and find for the exponential gain regime:

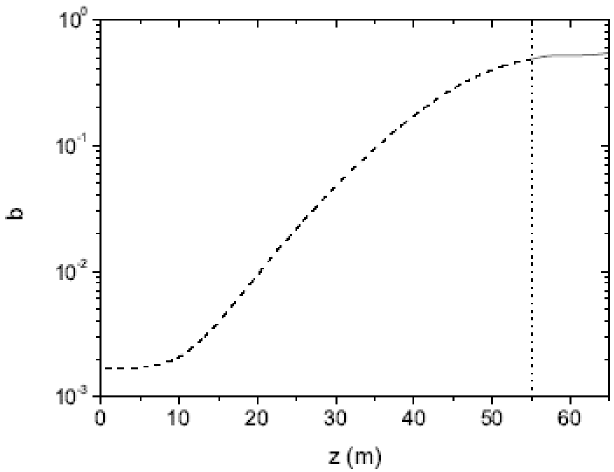


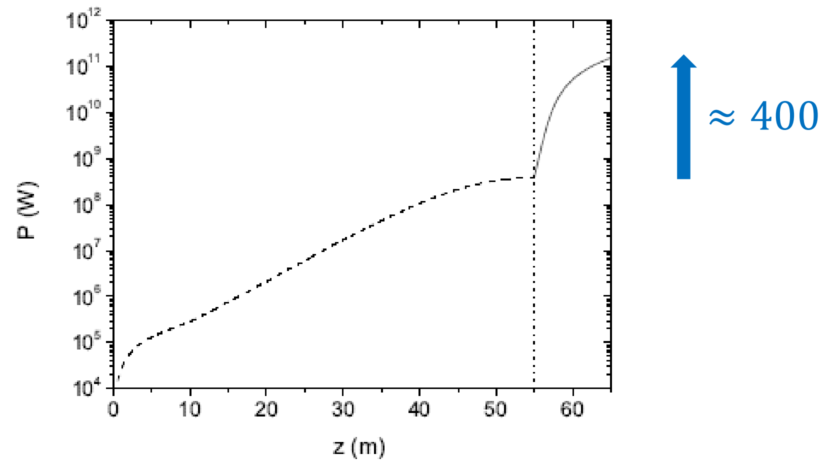
$$|b|^2 \simeq |\hat{C}|^2\hat{\eta}$$

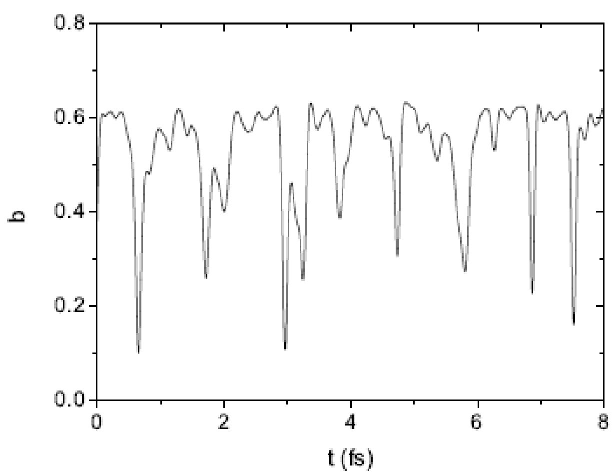
Parameters for 3D simulations of SASE3

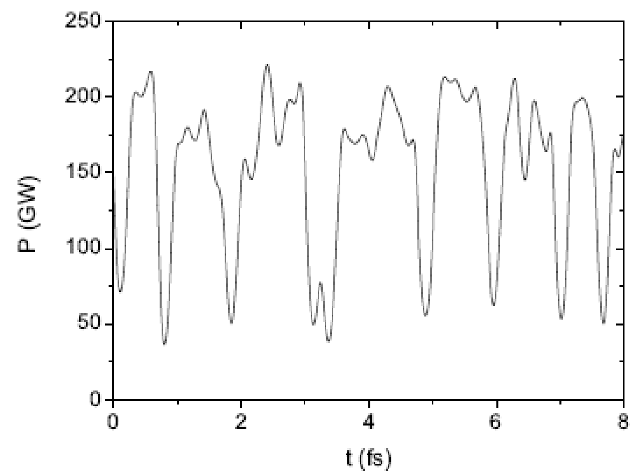
Electron beam	
Energy	14 GeV
Charge	0.5 nC
Peak current	5 kA
Rms normalized slice emittance	0.7 μm
Rms slice energy spread	2.2 MeV
Planar undulator	
Period	6.8 cm
K_{rms}	5.7
Beta-function	15 m
Active magnetic length	55 m
Taper $\Delta K_{\mathrm{rms}}/K_{\mathrm{rms}}(0)$	2.1 %
Helical afterburner	
Period	16 cm
K	3.6
Beta-function	15 m
Magnetic length	10 m
Radiation	
Wavelength	1.5 nm

Simulations for European XFEL (SASE3)









bunching

power

Reverse taper at LCLS

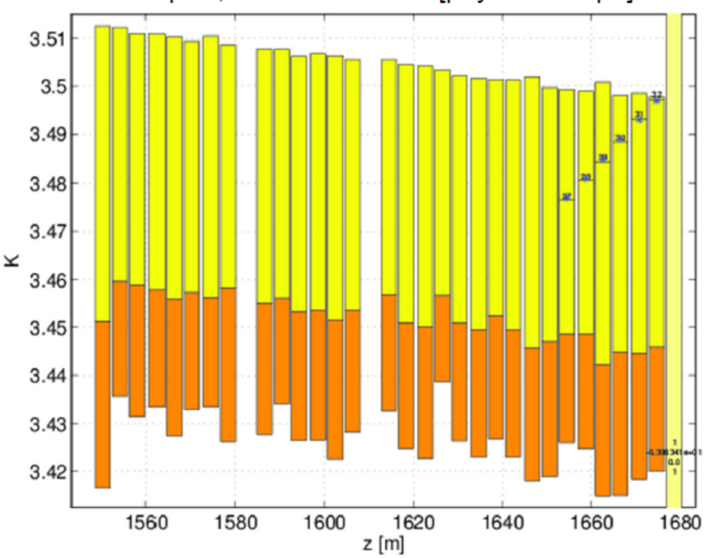
FEL2015 Daejeon Korea, 23rd – 28th August 2015 Heinz-Dieter Nuhn

Delta in Enhanced Afterburner Configuration at 710 eV

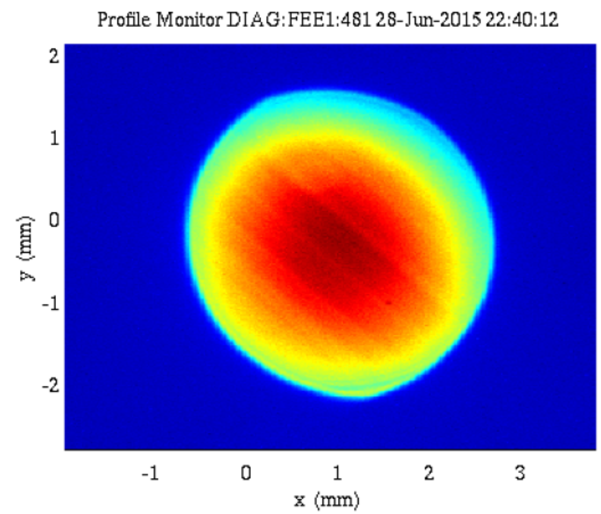
SLAC

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

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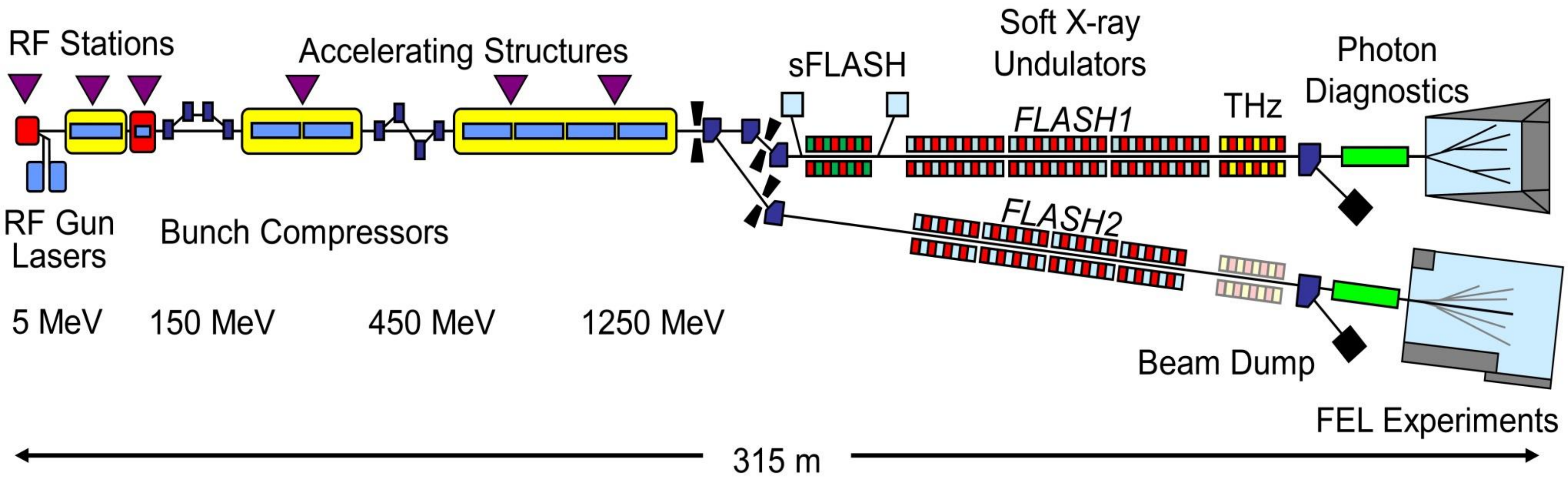
Courtesy H.-D. Nuhn

FLASH layout

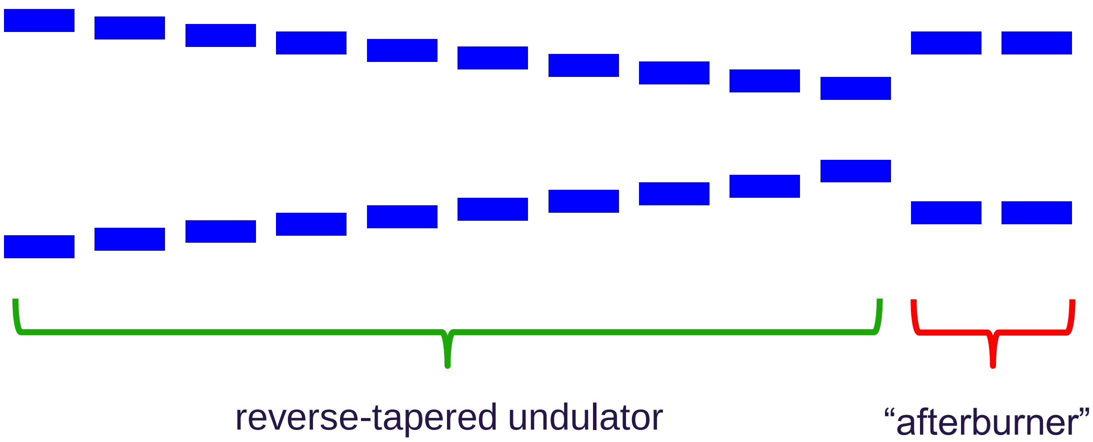


Undulators

	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

Reverse taper experiment at FLASH2

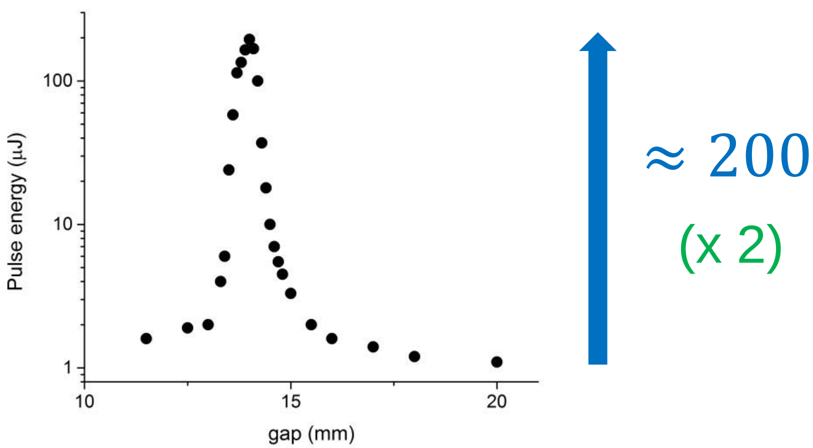
23.01.2016



Beam energy 720 MeV, wavelength 17 nm.

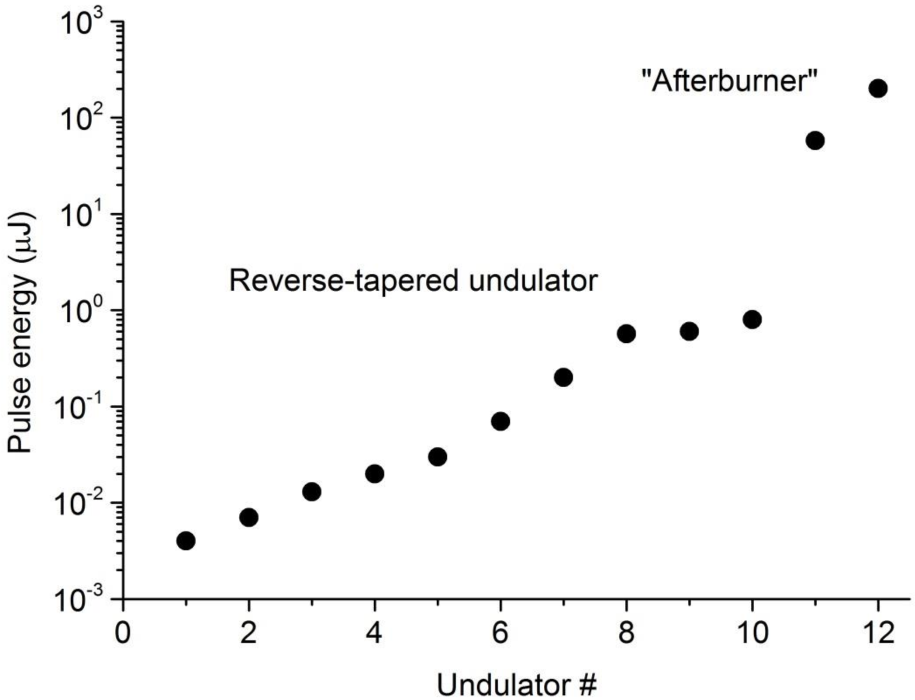
Reverse taper (10%) was applied to the 10 undulator segments;

the gap of the 11th and 12th segments was scanned.



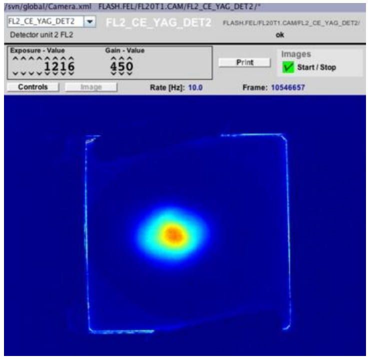
Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.

Reverse taper experiment at FLASH2 (cont'd)



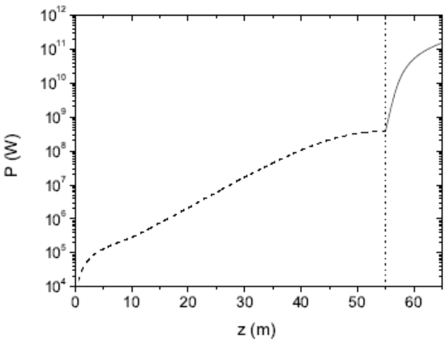
≈ 200

(x 2)



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

Simulations for SASE3



≈ 400

Reverse taper plus harmonic afterburner

Experiment at FLASH2 on Oct. 10, 2016:

Main undulator: 9 modules, 26.5 nm, -5% taper.

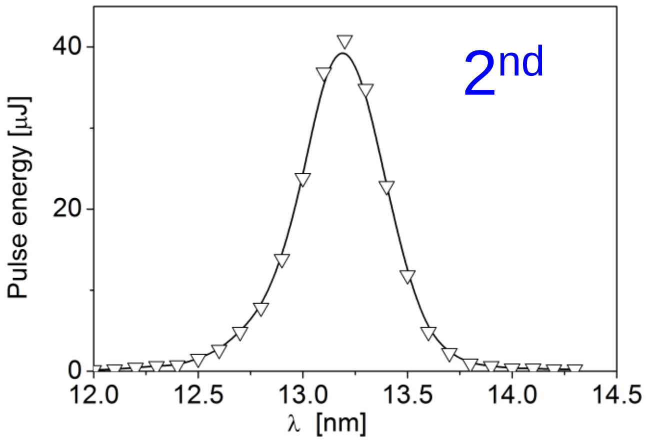
Afterburner: 2 modules, 26.5 nm, 13.2 nm, 8.8 nm

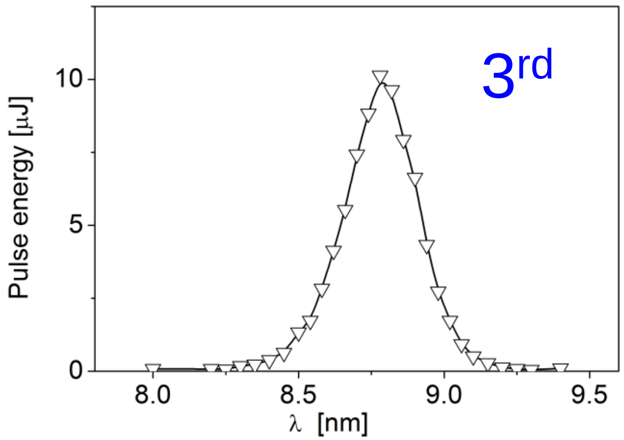
Pulse energy after tapered part: < 1 microjoule

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

Conclusion

- Reverse taper is a simple and elegant method for suppression of linearly polarized background and obtaining high degree of circular polarization
- The method is free and easy to implement
- It is routinely used at LCLS and shown to work nicely at FLASH2
- The method will be used for SASE3 undulator of the European XFEL, it can also be used for FLASH2 with harmonic afterburner

Backup slides

1D parameters

$$\hat{C} = \left(k_\mathrm{w} - \frac{\omega(1+K^2)}{2c\gamma^2} \right) \Gamma^{-1}$$ Detuning parameter

$$\hat{z} = \Gamma z$$ Normalized longitudinal coordinate

$$\Gamma = 4\pi\rho/\lambda_\mathrm{w}$$ Gain parameter (≈inverse gain length at resonance)

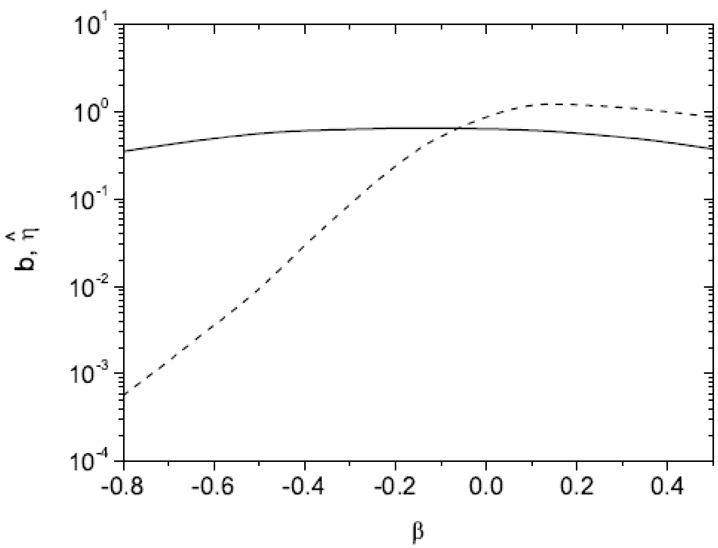
Now let K be linear function of z:

$$\hat{C}(\hat{z}) = \beta \hat{z}$$

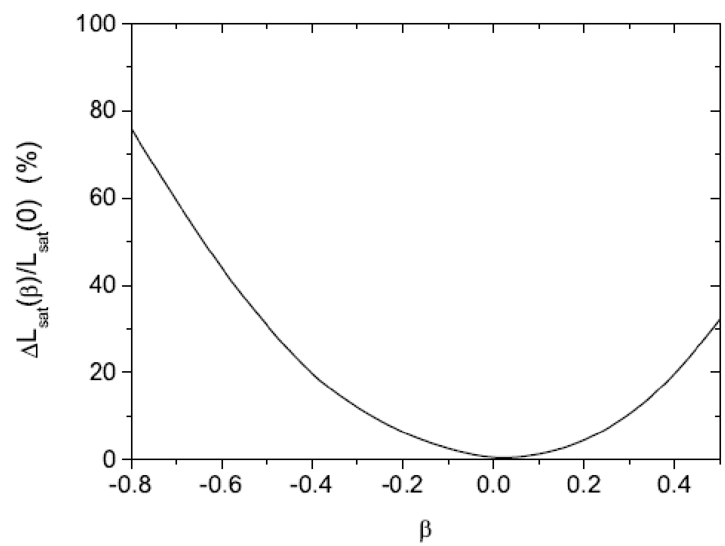
$$\beta = -\frac{\lambda_\mathrm{w}}{4\pi\rho^2} \frac{K(0)}{1+K(0)^2} \frac{dK}{dz}$$

SASE FEL: 1D simulations

b	bunching (0<b<1)
$\hat{\eta} = P/(\rho P_{\mathrm{beam}})$	normalized power (efficiency)
$\hat{\Lambda}_{\mathrm{T}} = \sigma_{\gamma}/(\gamma\rho) = 0.2$	energy spread parameter



Bunching and power at saturation

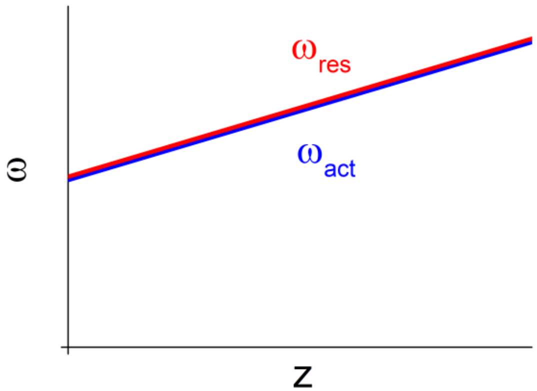


Relative increase of the saturation length

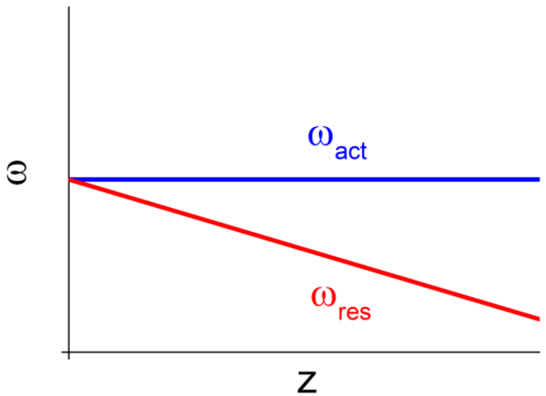
Frequency shift

In a SASE FEL the evolution of the amplified frequency band depends on tapering. Consider the asymptote of a large parameter $|\beta|$.

$\beta > 0$



$\beta < 0$



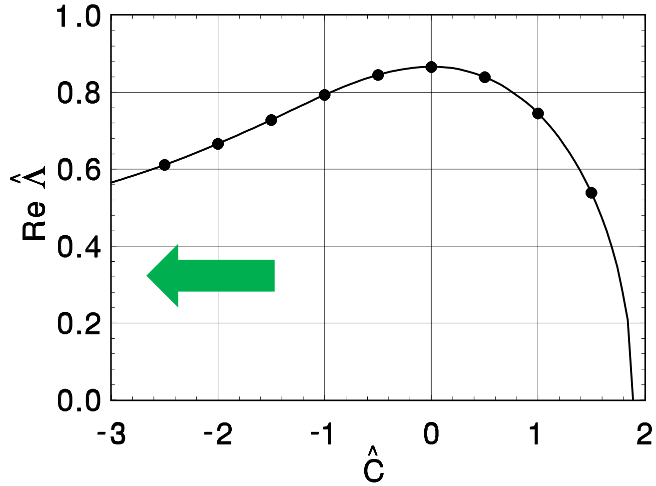
For positive parameter, the frequency follows the change of resonance completely. For negative parameter, it doesn't follow current resonance at all; it stays at the resonance with undulator parameters at its entrance.

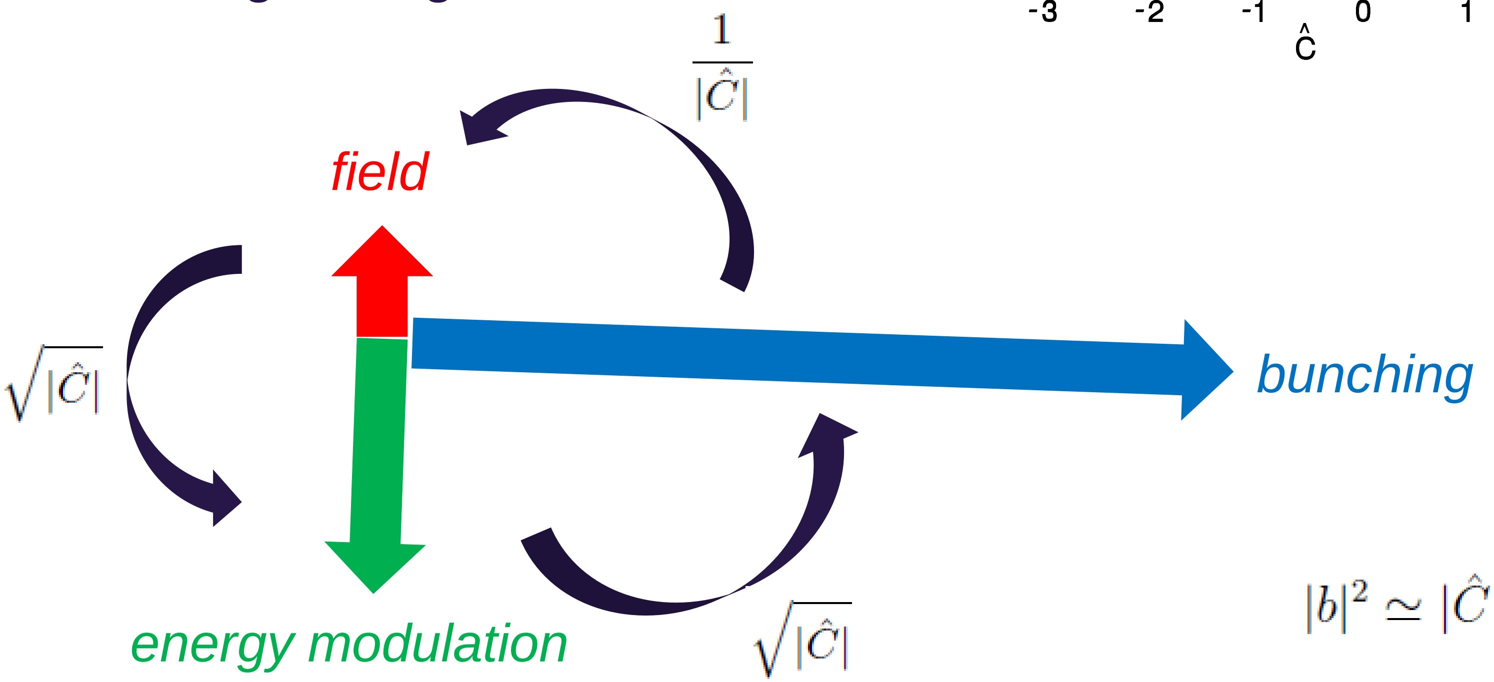
Steady-state, exponential gain regime

Consider monochromatic seed, no taper but large negative detuning: $\hat{C} < 0$, $|\hat{C}| \gg 1$.

Scaled gain length is now $L_g \Gamma \approx \sqrt{|\hat{C}|}$.

One can solve initial-value problem and find for the exponential gain regime:





$$|b|^2 \simeq |\hat{C}|^2 \hat{\eta}$$

SASE FEL, large reverse paper

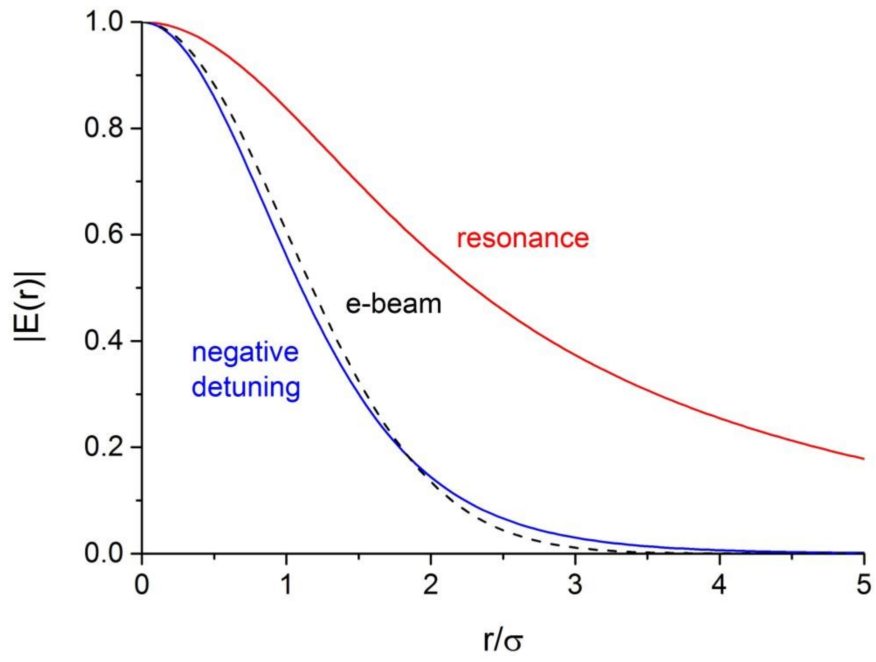
Now SASE and large reverse taper. The FEL frequency band stays close to resonance at the undulator entrance (and not at the present position), i.e. detuning increases as the beam propagates through the undulator. Gain length also increases and the ratio is

$$< |b|^2 > \simeq |\beta|^2 \hat{z}^2 < \hat{\eta} >$$

Since gain length increases along the undulator length, an increase in saturation length is smaller than an increase in last gain length(s).

3D bonus

Transverse mode gets more narrow for negative detuning. Thus, the field acting on particles is stronger for the same power.



B = 0.1

C = 0

C=-20

Energy spread constraints

Proceedings of FEL2015, Daejeon, Korea - Pre-Release Snapshot 30-Sep-2015 00:00 WEP004

ENERGY SPREAD CONSTRAINTS ON FIELD SUPPRESSION IN A REVERSE TAPERED UNDULATOR*

J. MacArthur, A. Marinelli, A. Lutman, H.-D. Nuhn, Z. Huang
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

$$\left|\frac{b_\nu}{a_\nu}\right| \leq \frac{1}{\zeta^2} = \frac{\rho^2\gamma_0^2}{\sigma_\gamma^2},$$

$$P_C/P_L \sim (\rho\gamma_0/\sigma_\gamma)^4$$

Table 2: Genesis Simulation Parameters

Qauntity	Value	Units
energy ($\gamma_0 m_e c^2$)	3.969	GeV
energy spread ($\sigma_\gamma m_e c^2$)	3.5, 7.0	MeV
transverse emittance	0.6	µm
photon energy (nominal)	700	eV
undulator period	3.0	cm
starting K value	3.50	
ending K value	3.52	
undulator gap K value	0.0	
undulator modules	6	
peak current	5.5	kA
phase space	ideal Gaussian beam	
Pierce Parameter (ρ)	2.2×10^{-3}	

Energy spread constraints (cont'd)

$P_C/P_L \sim (\rho\gamma_0/\sigma_\gamma)^4$ $\rho \sim 2 \times 10^{-3}$ SASE3 in fresh bunch mode

	Energy, GeV	En. spread, MeV	Maximal contrast	Comment
LCLS	4	5	$\simeq 10$	measured
XFEL (design)	14	2.2	$\simeq 10^4$	realistic
XFEL (pessimistic)	14	5	$\simeq 10^3$	possible but not likely
XFEL (impossible)	14	18	$\simeq 10$	desaster for SASE1&2

SASE3 will be the best place for implementation of the method because we will generate soft X-rays using very high electron energy.

Can we improve the contrast for SASE3?