European XFEL

Reverse undulator tapering for polarization control at X-ray FELs

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DESY

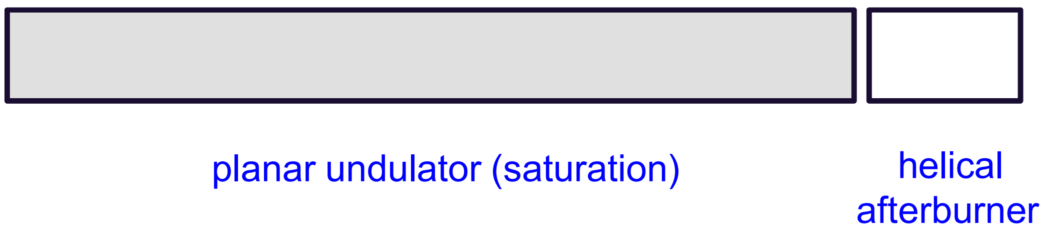
HELMHOLTZ ASSOCIATION

Circular polarization for X-ray FEL facilities

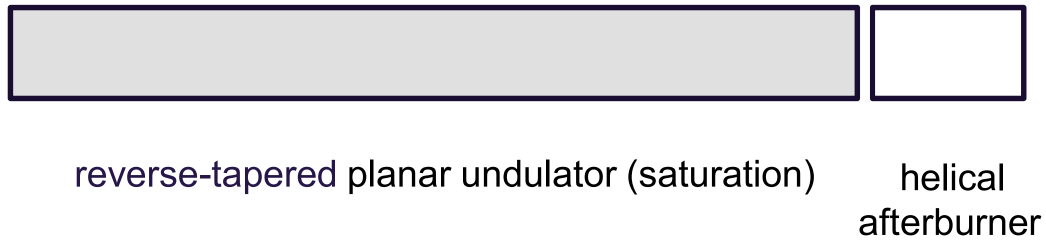
- Strongly requested by the user community
- Especially interesting is soft X-ray regime
- Undulators are planar
- There are many ideas for circular polarization production (following K.-J. Kim's cross-planar configuration)

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



- 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

Standard (positive) taper

- Undulator K decreases along the undulator length;
- Positive taper is used to
  - compensate beam energy loss due to spontaneous undulator radiation and wakefields;
  - increase power of a high-gain FEL after saturation (post-saturation taper)

Reverse (negative) taper

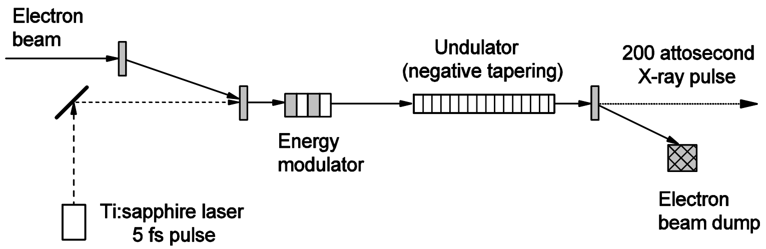
- Undulator K increases along the undulator length;
- Two applications were proposed for FELs:

  - to increase efficiency of FEL oscillators

    Saldin, Schneidmiller, Yurkov, Opt. Commun. 103(1993)297

  - to use in an attosecond scheme for X-ray FELs combining taper and energy chirp in a short slice

    Saldin, Schneidmiller, Yurkov, Phys. Rev. ST-AB 9(2006)050702



Now we discover another useful feature of the reverse taper: a possibility to produce strong microbunching at a very much reduced radiation power

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)

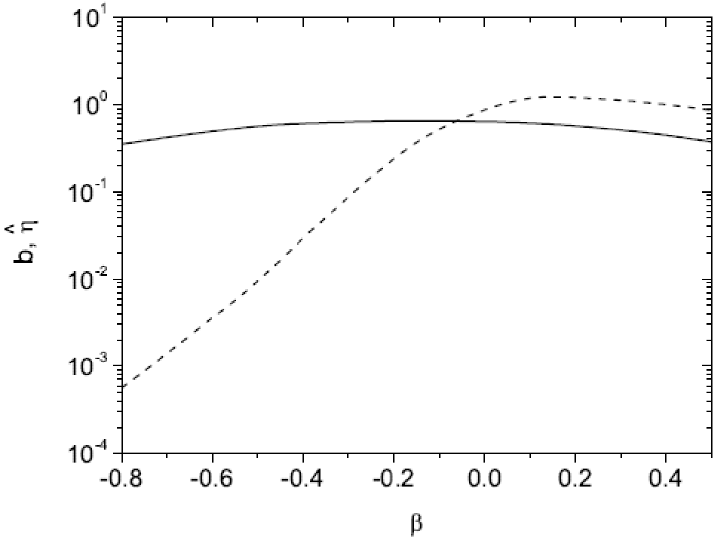
Now let K be linear function of z:

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

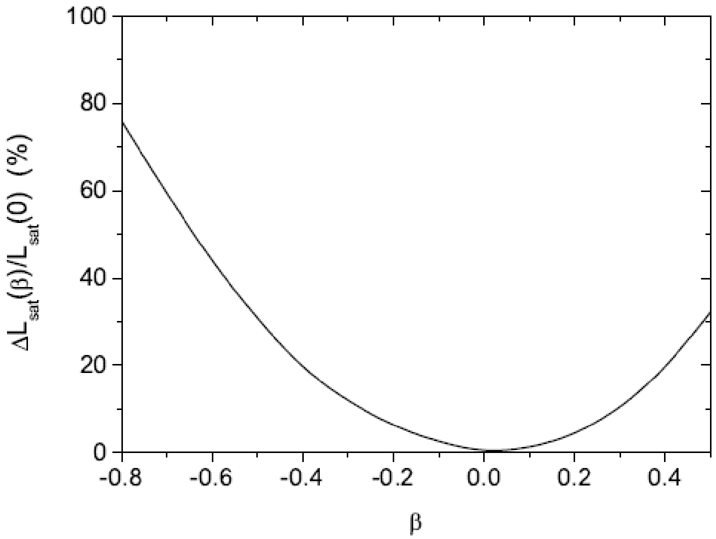
$$\beta = -\frac{\lambda_{\mathrm{w}}}{4\pi\rho^2} \frac{K(0)}{1+K(0)^2} \frac{dK}{dz}$$

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

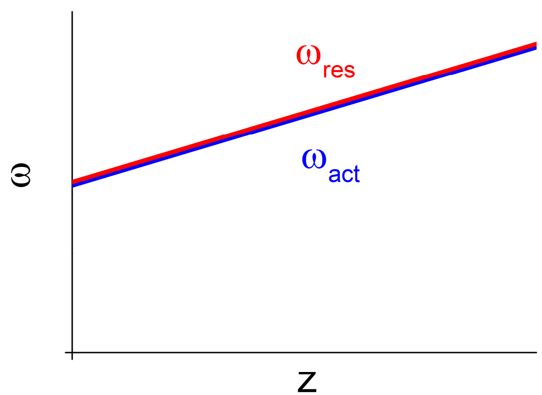


Relative increase of the saturation length

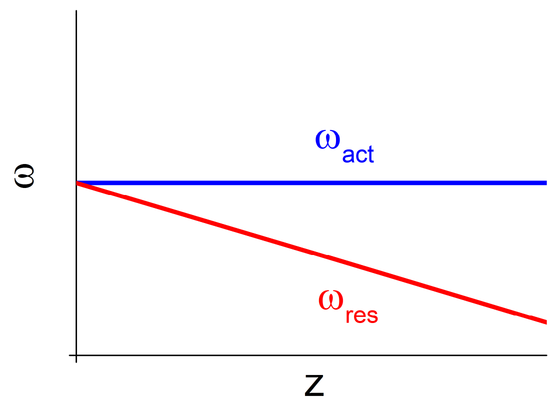
Frequency shift

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

$\beta > 0$



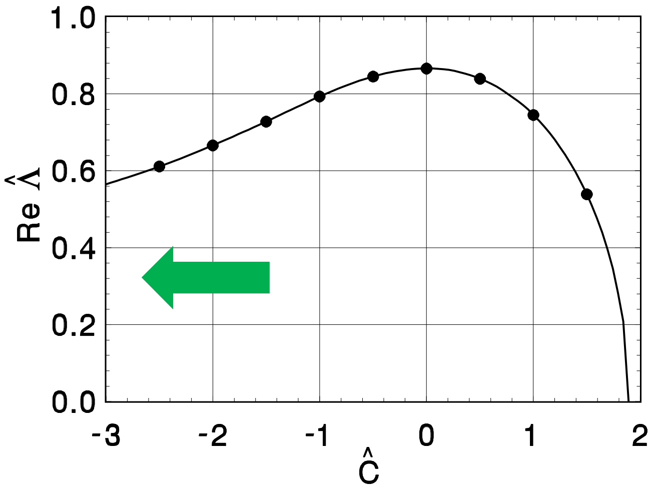
$\beta < 0$



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.

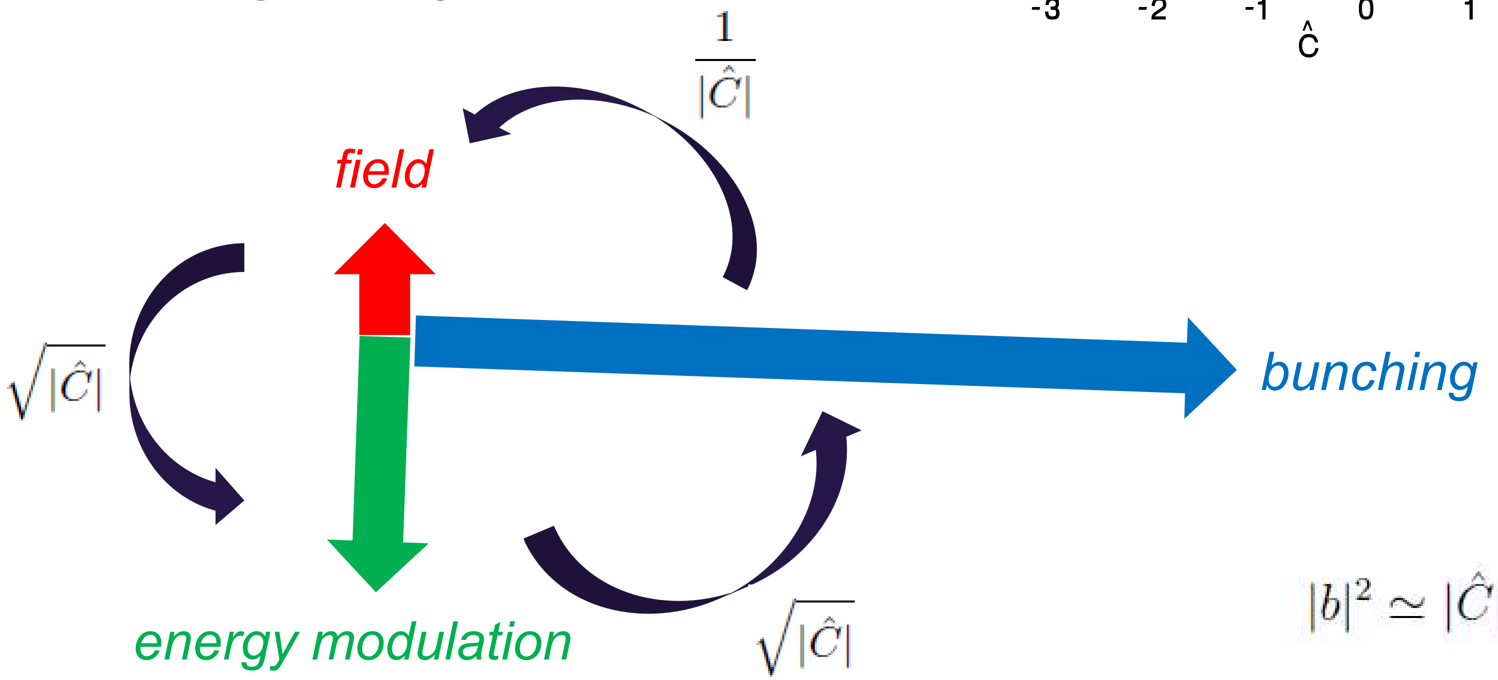
Steady-state, exponential gain regime

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



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

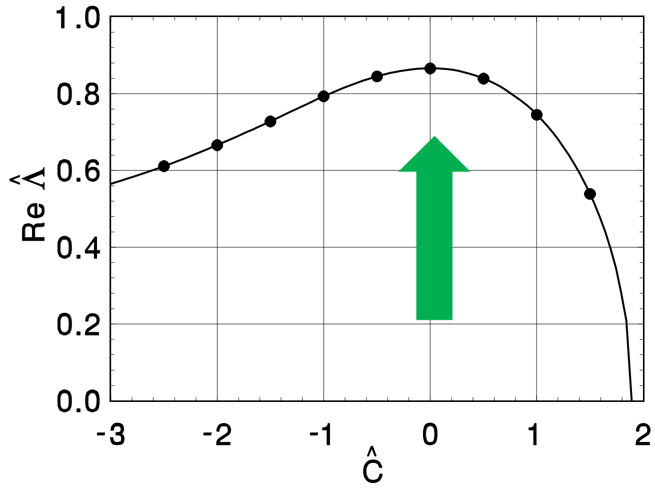
One can solve initial-value problem and find for the exponential gain regime:

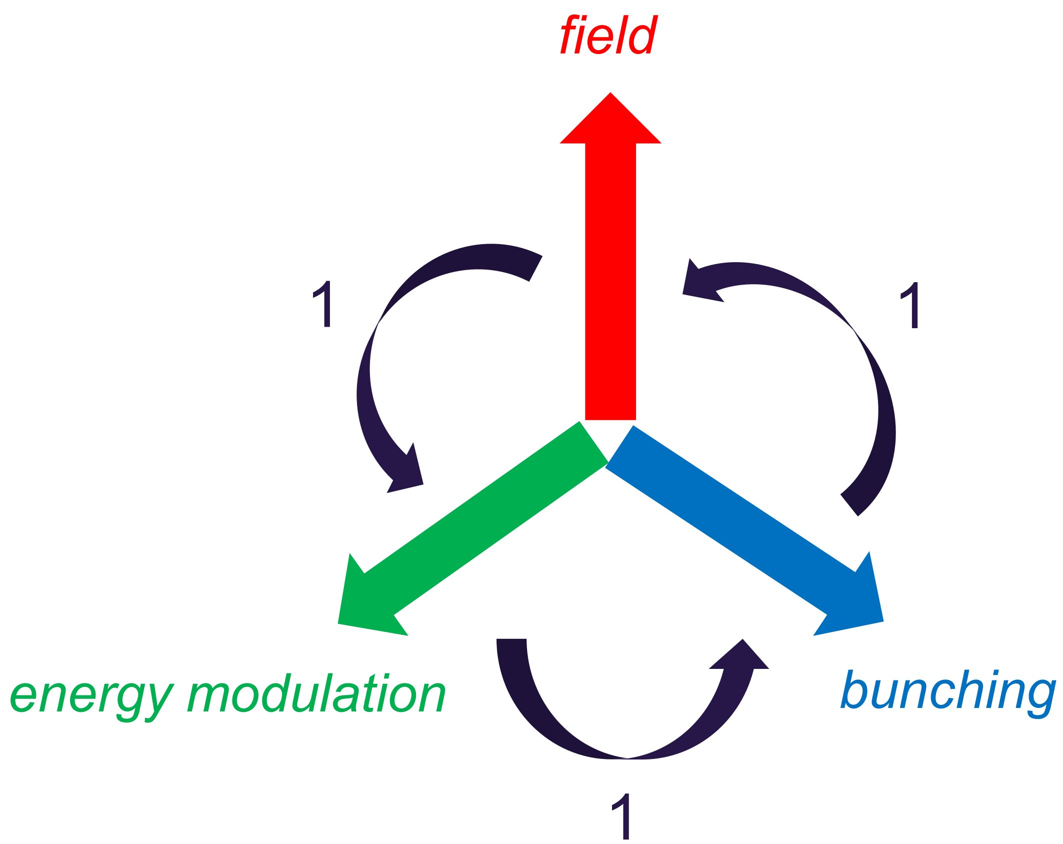


$$|b|^2 \simeq |\hat{C}|^2 \hat{\eta}$$

Steady-state, exponential gain regime: resonance

Scaled gain length is now $L_g\Gamma \approx 1$





SASE FEL, large reverse paper

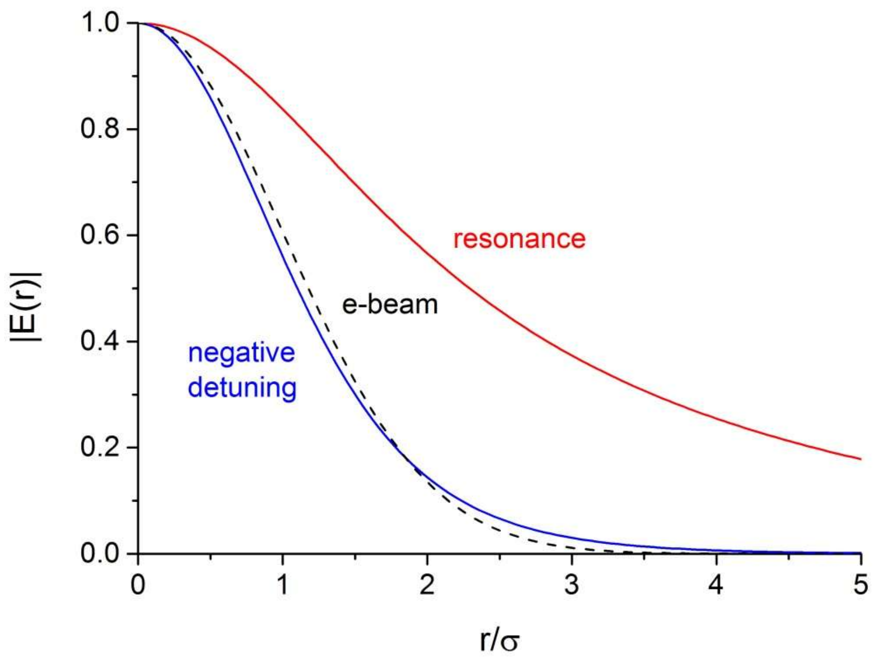
Now SASE and large reverse taper. The FEL frequency band stays close to resonance at the undulator entrance (and not at the present position), i.e. detuning increases as the beam propagates through the undulator. Gain length also increases and the ratio is

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

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

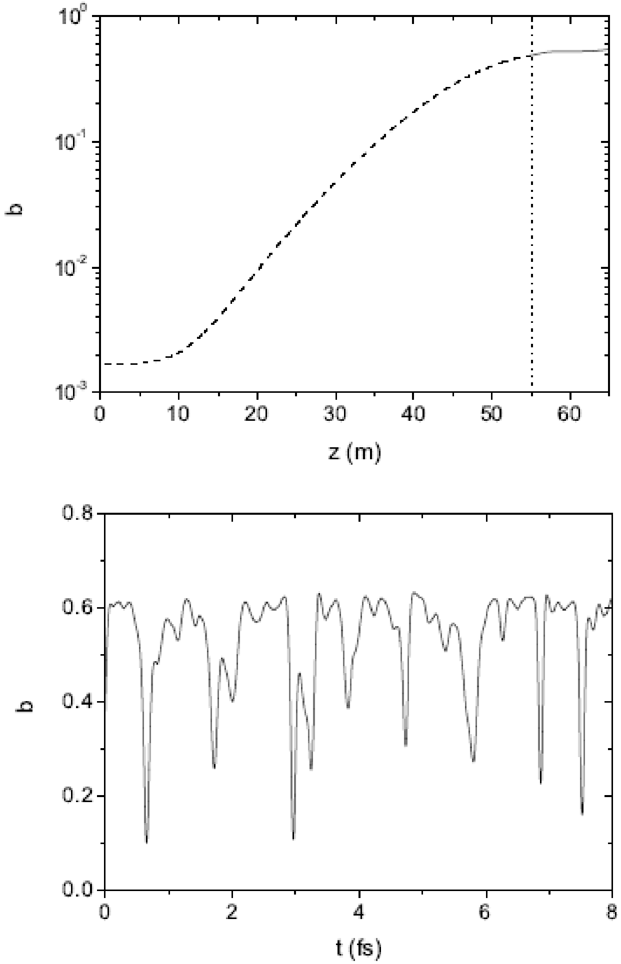
C = 0

C=-20

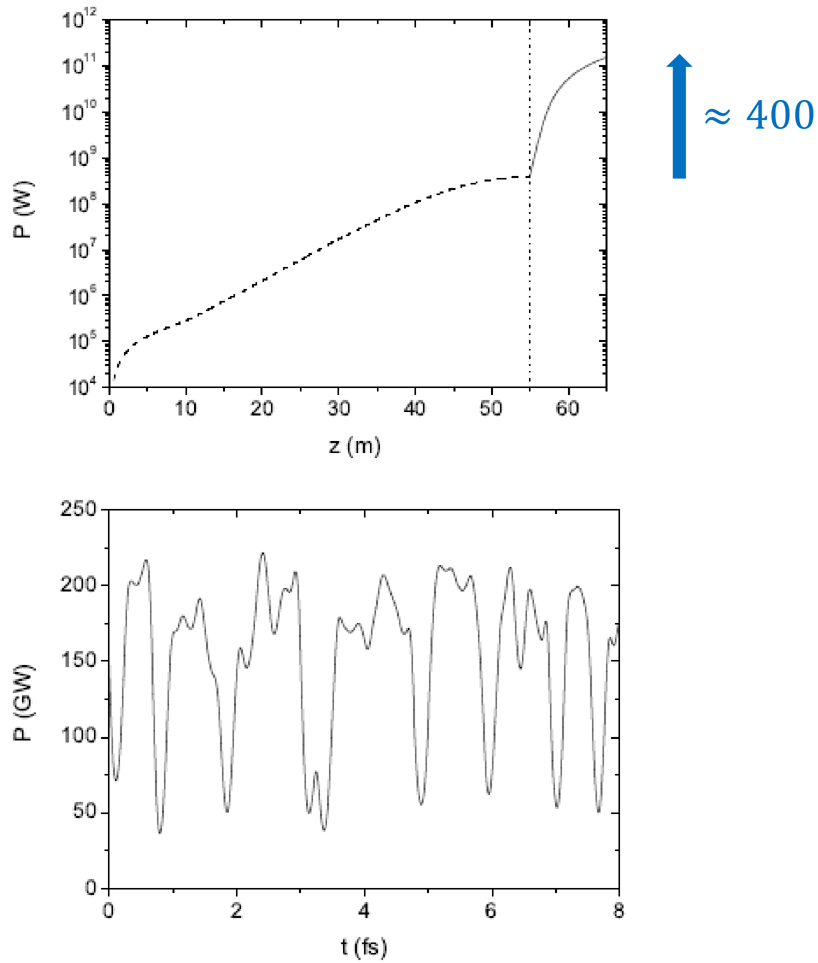
Parameters for 3D simulations of SASE3

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

Results of simulations with FAST



bunching



power

Reverse taper at LCLS

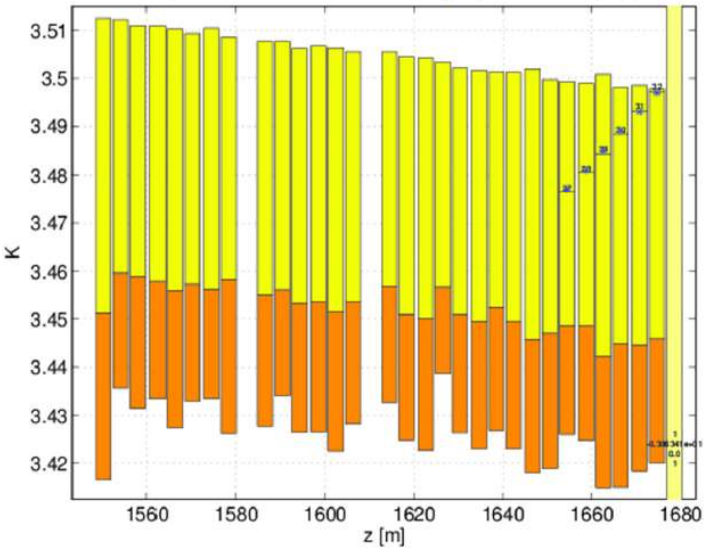
FEL2015 Daejeon Korea, 23rd – 28th August 2015 Heinz-Dieter Nuhn

Delta in Enhanced Afterburner Configuration at 710 eV

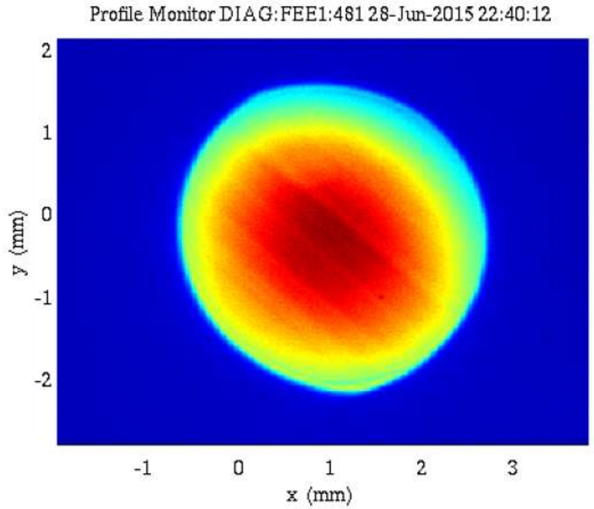
SLAC

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



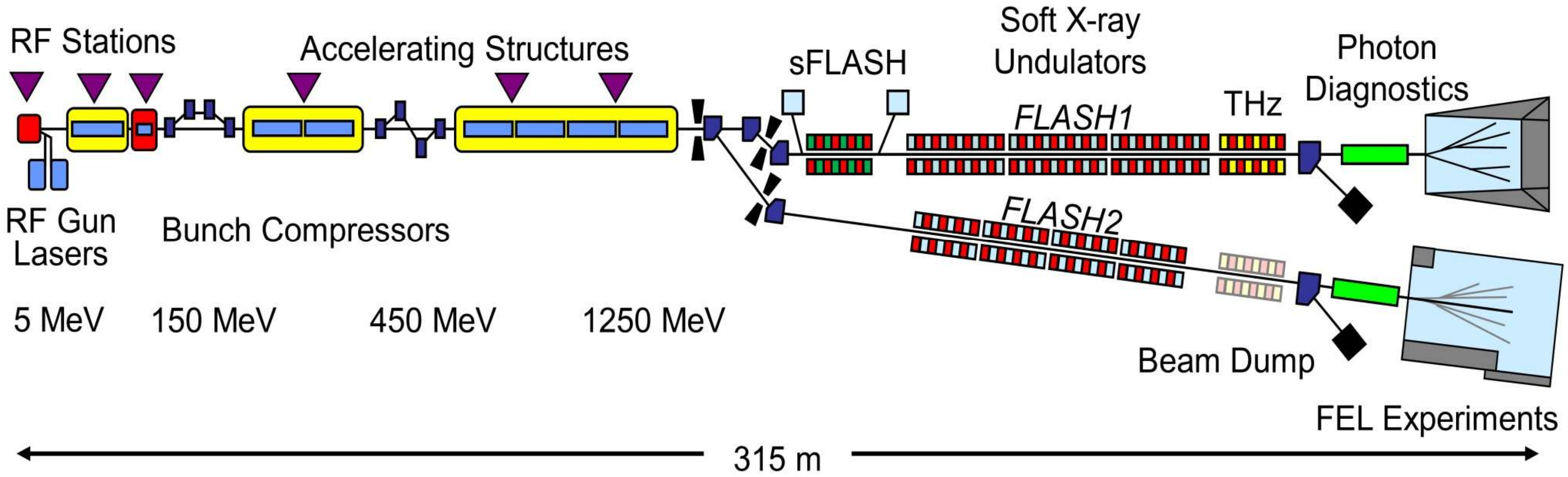
- 30 μJ with Delta off
- 510 μJ with Delta on

Peak Current increased above 4 kA

FEL2015 James MacArthur WEP004 24

Courtesy H.-D. Nuhn

FLASH layout

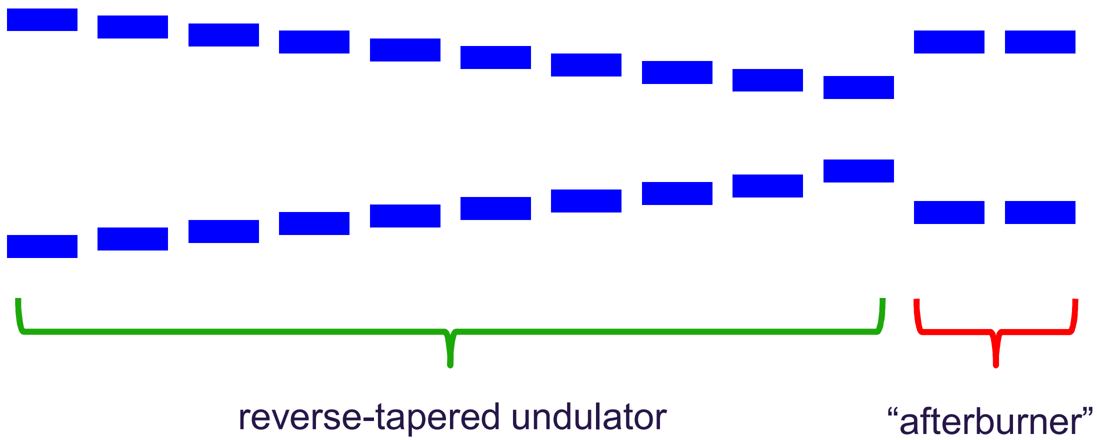


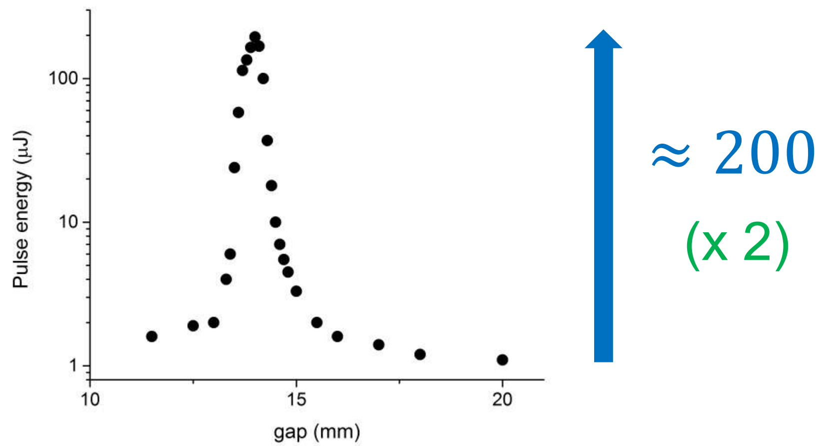
Undulators

	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





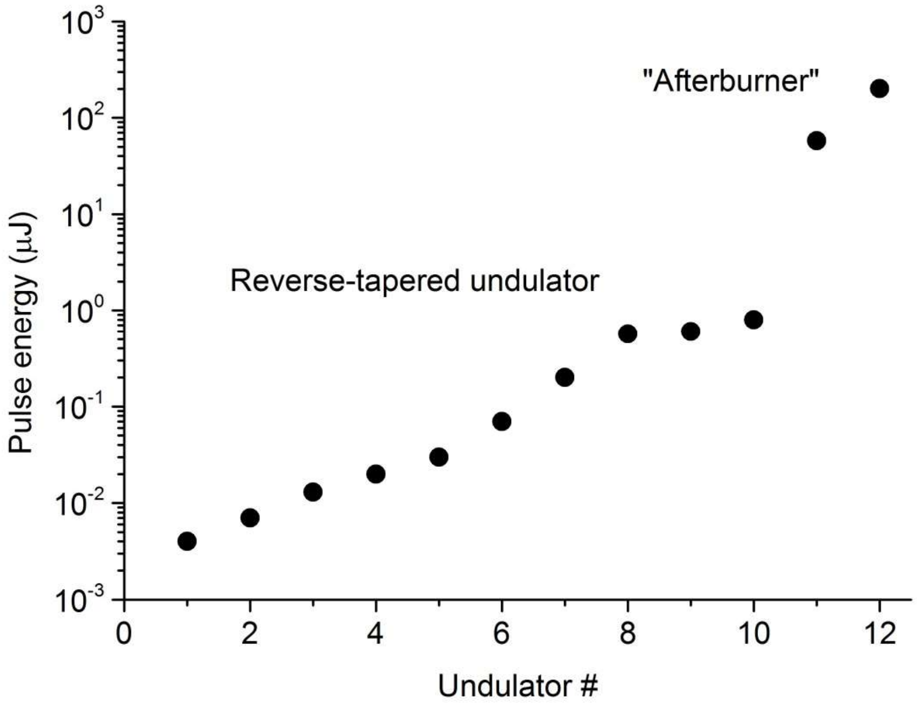
Beam energy 720 MeV, wavelength 17 nm.

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

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

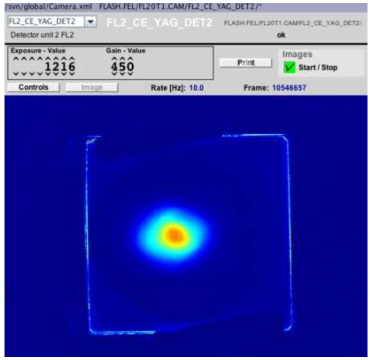
Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.

Reverse taper experiment at FLASH2 (cont'd)



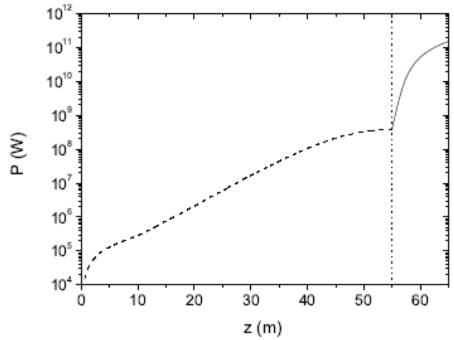
≈ 200

(x 2)



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

Simulations for SASE3



≈ 400

Experiment at FLASH2 on March 12

- We repeated the reverse taper experiment at the same wavelength but at a higher electron energy (930 MeV) on March 12.
- Rms undulator parameter was 1.6, and the ten undulator sections were reverse-tapered by 5 %.
- The pulse energy was 0.25 microjoules, while after tuning the 11th and the 12th sections to the resonance it reached 60 microjoules, i.e. the contrast above 200 was demonstrated again.
- We could also tune the "afterburner" to the second harmonic and measure 1.8 microjoules.
- This is an important demonstration because a harmonic afterburner with variable polarization might be installed at FLASH2. Reverse tapering in the main undulator will provide background-free radiation from the afterburner.

Conclusion

- A method for suppression of linearly polarized background and obtaining high degree of circular polarization is proposed
- 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