Circular polarization control by reverse undulator tapering

E. Schneidmiller and M. Yurkov

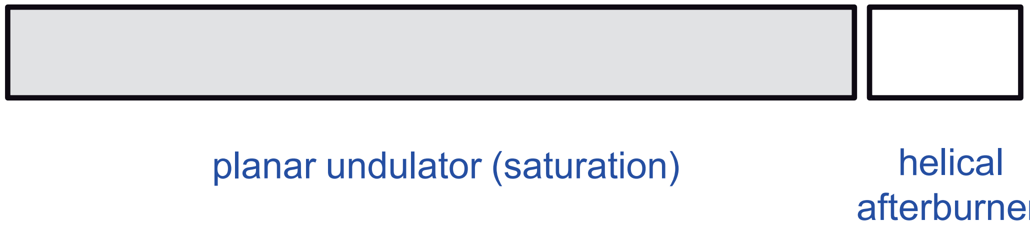
36th FEL Conference, Basel, August 25, 2014

Circular polarization for X-ray FEL facilities

- Strongly requested by the user community
- Especially interesting is soft X-ray regime
- In general, full polarization control is desirable (including fast switching)
- Typically the X-ray undulators are planar
- There are many ideas for circular polarization production (starting with 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



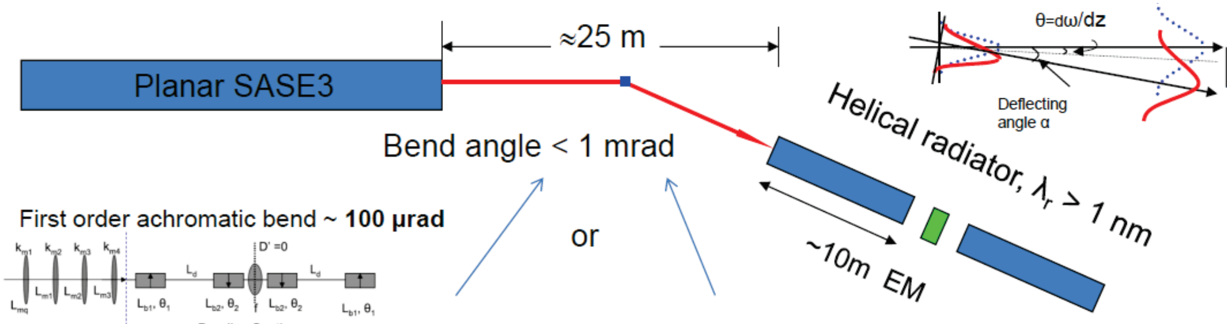
Suppression (separation) of linearly polarized background

European XFEL: three approaches were considered most seriously in the context of SASE3 (soft X-ray undulator) upgrade:

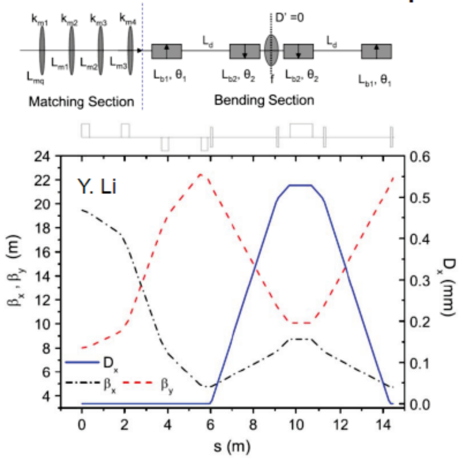
- Achromatic bend
- Second harmonic afterburner
- Slits for spatial filtering

Main candidate for the SASE3 afterburner: electromagnetic undulator being developed by BINP (Novosibirsk)

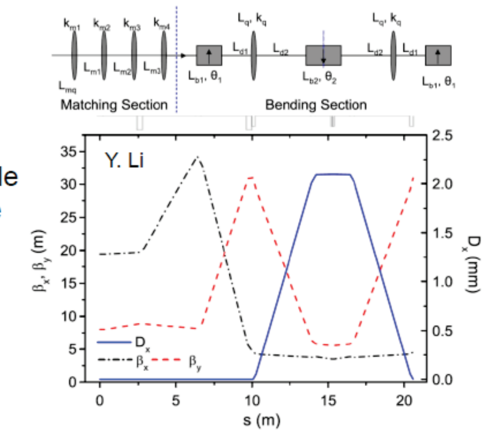
Achromatic bend



First order achromatic bend ~ **100 μrad**



First order isochronous bend ~ **1000 μrad**



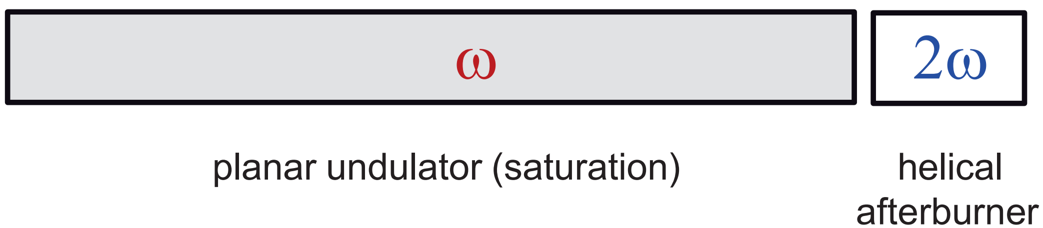
Works better the
- smaller bend angle
- smaller emittance
- longer the wavelength

More details:
Y. Li, W. Decking, B. Faatz, J. Pflüger, Phys. Rev. STAB 13, 080705 (2010)

Y. Li et al., Proc. of FEL2008

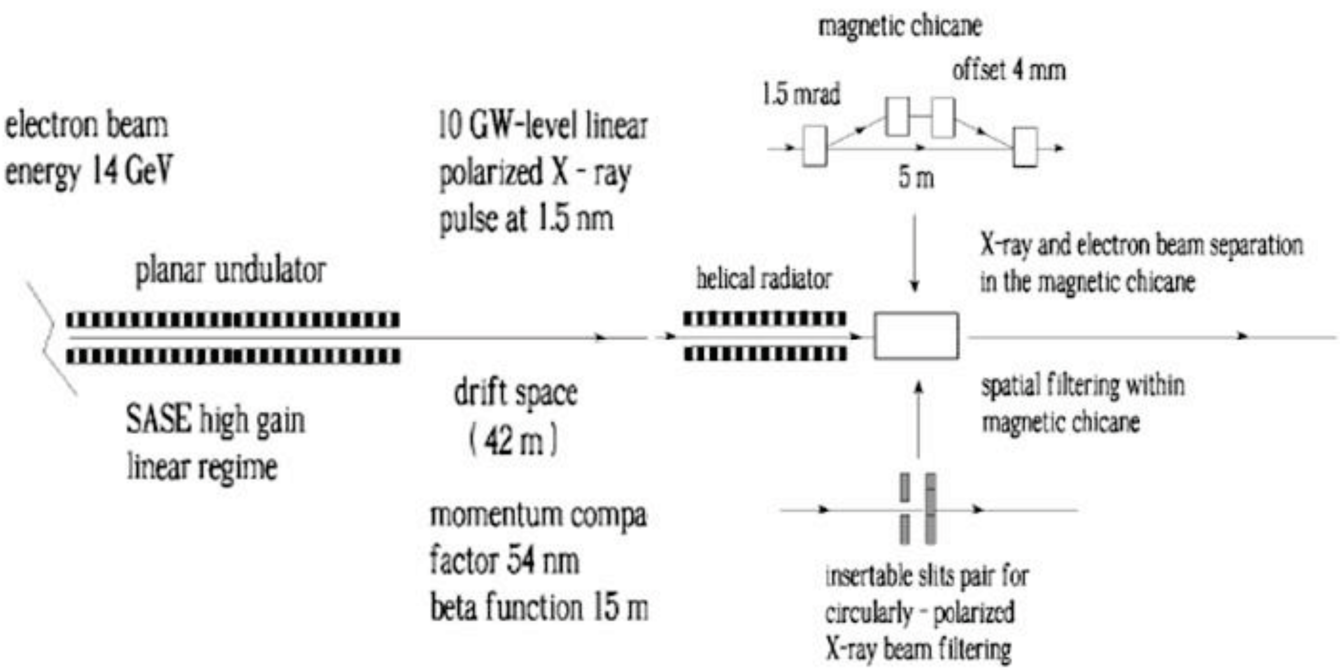
Y. Li, W. Decking, B. Faatz, J. Pflueger, Phys. Rev. ST-AB 080705(2010)13

Second harmonic afterburner



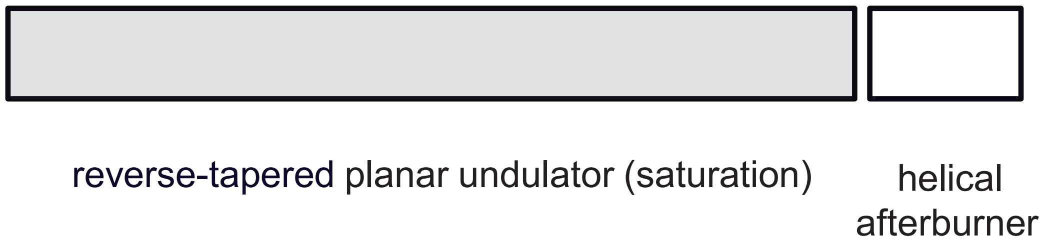
Z. Huang and S. Reiche, Proc. of FEL2004

Slits for spatial filtering



G. Geloni, V. Kocharyan, E. Saldin, preprint DESY-11-096

New 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

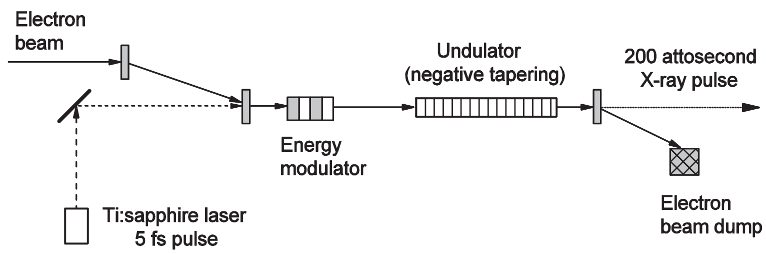
- Undulator K increases along the undulator length;
- Two applications were proposed for FELs:

- 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:

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

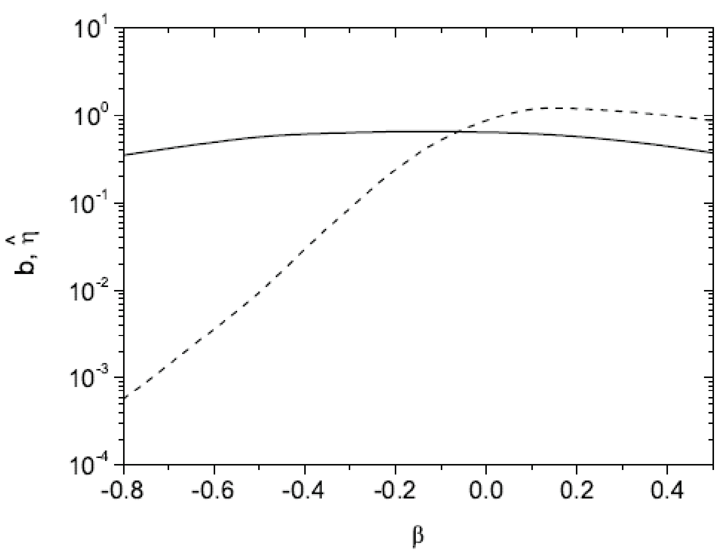
$$\beta = -\frac{\lambda_{\mathrm{w}}}{4\pi\rho^2}\frac{K(0)}{1+K(0)^2}\frac{dK}{dz}$$

SASE FEL: 1D simulations

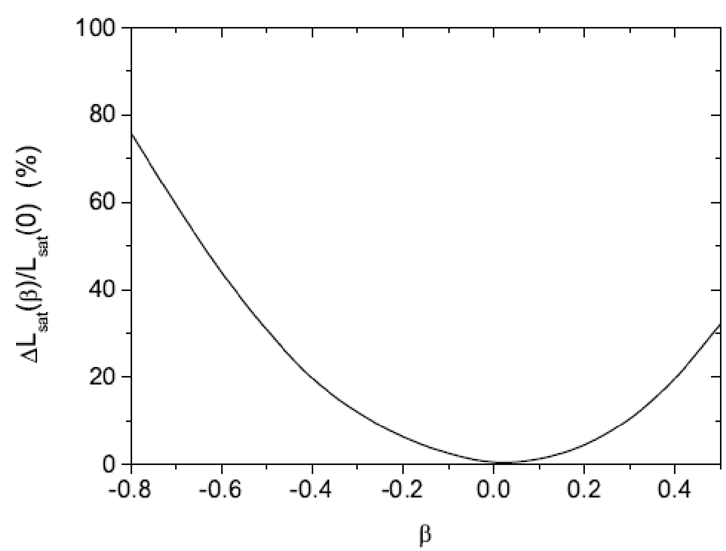
b bunching (0<b<1)

$\hat{\eta} = P/(\rho P_{\mathrm{beam}})$ 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.

For weak tapering, $|\beta| \ll 1$, the central frequency follows change of resonance frequency (due to K or energy change) with half of the rate

(Z.Huang and G. Stupakov, Phys. Rev. ST-AB 040702(2005)8)

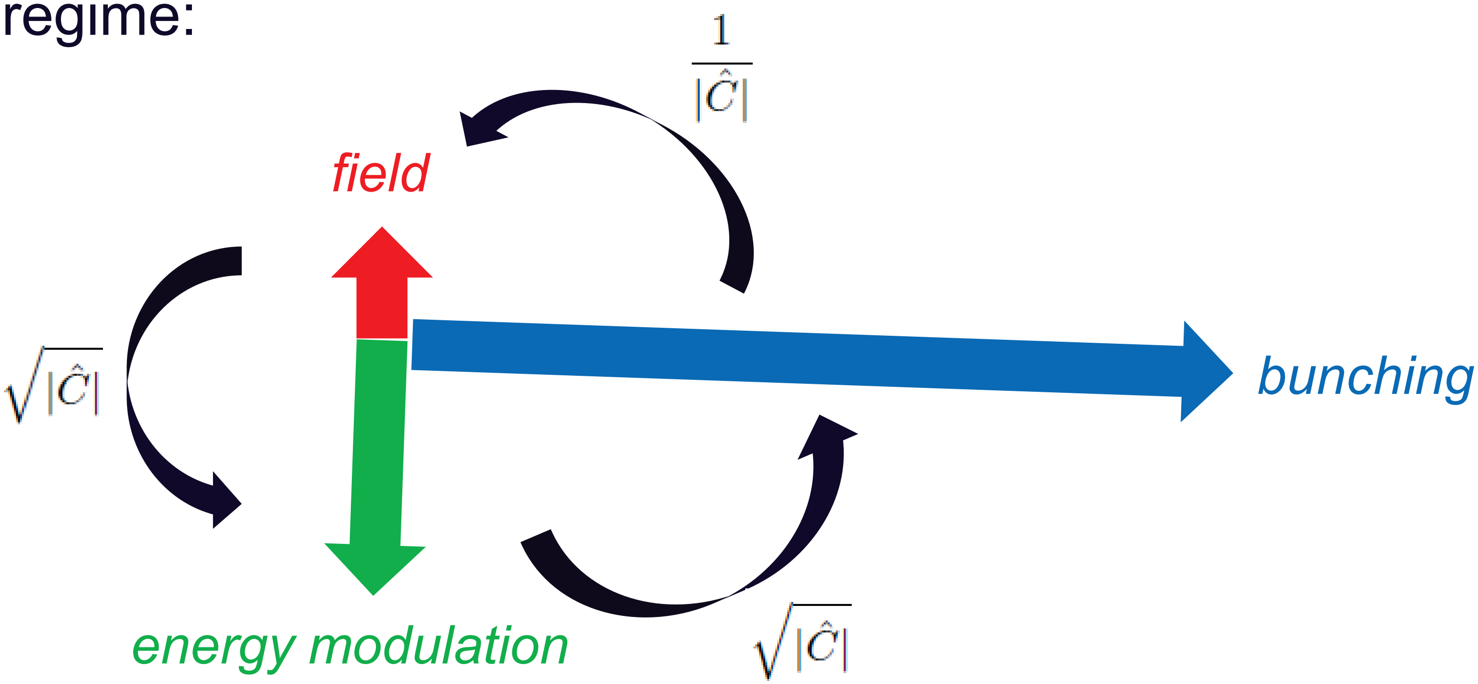
For strong tapering, there is no symmetry. For positive parameter, the frequency follows the change of resonance completely. For negative parameter, it doesn't follow current resonance at all; it stays at the resonance with undulator parameters at its entrance.

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:



Steady-state, exponential gain regime (cont'd)

The ratio between squared amplitudes:

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

It is proportional to the 4th power of gain length (which is $\sqrt{|\hat{C}|}$.)

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

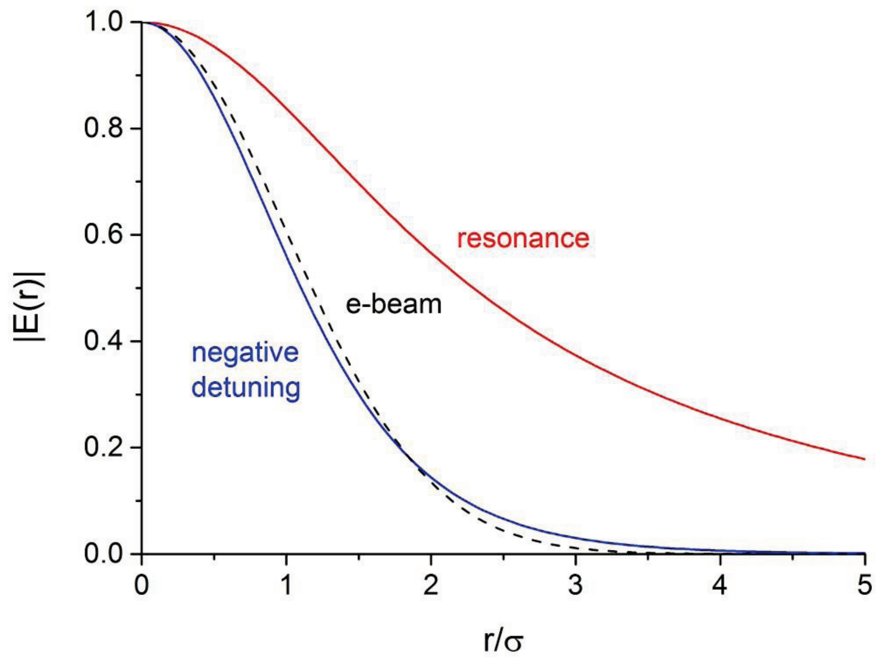
$$< |b|^2 > \simeq |\beta|^2 \hat{z}^2 < \hat{\eta} >$$

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

The asymptote is considered only for better understanding. In practical simulations we deal with moderate values of the taper strength.

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

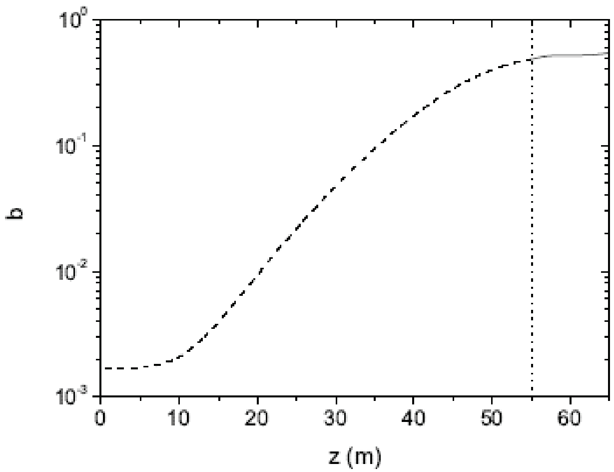
C = 0

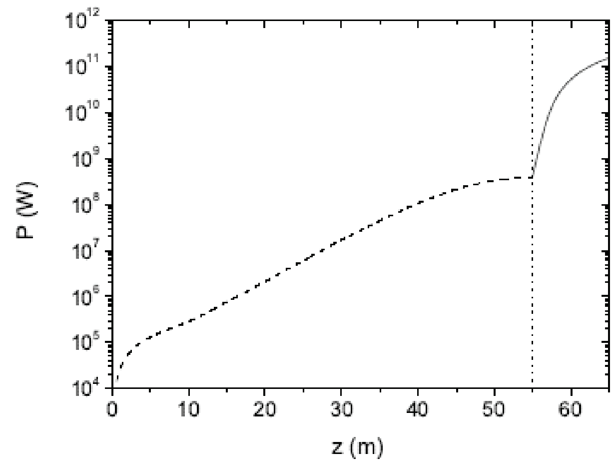
C=-20

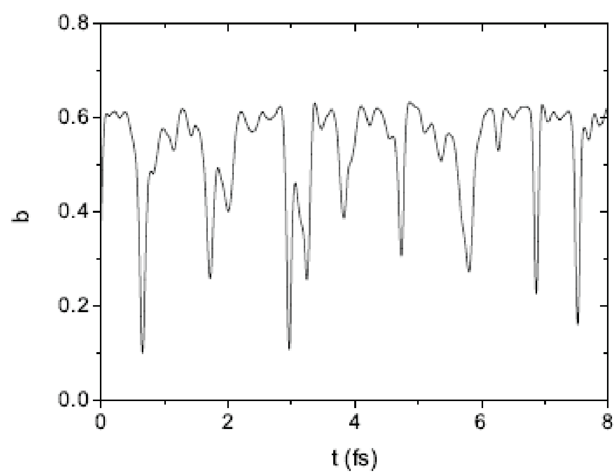
Parameters for 3D simulations of SASE3

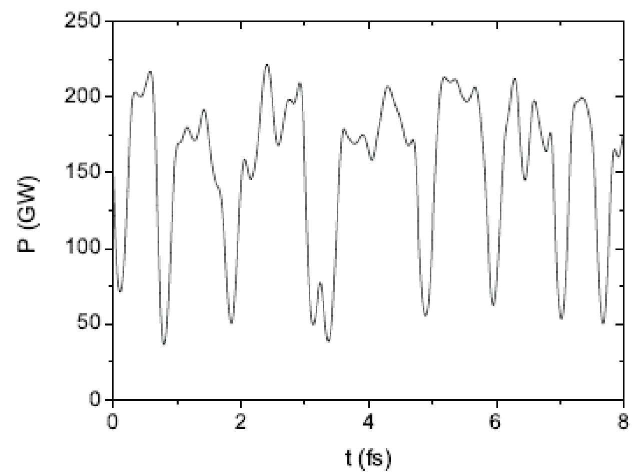
Electron beam	
Energy	14 GeV
Charge	0.5 nC
Peak current	5 kA
Rms normalized slice emittance	0.7 μm
Rms slice energy spread	2.2 MeV
Planar undulator	
Period	6.8 cm
K_{rms}	5.7
Beta-function	15 m
Active magnetic length	55 m
Taper $\Delta K_{\mathrm{rms}}/K_{\mathrm{rms}}(0)$	2.1 %
Helical afterburner	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

Results of simulations with FAST





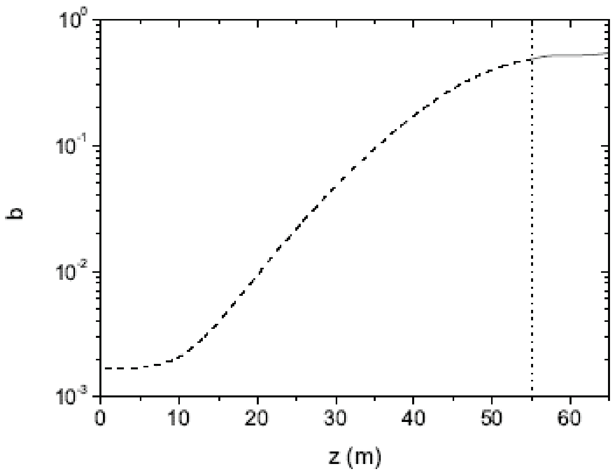


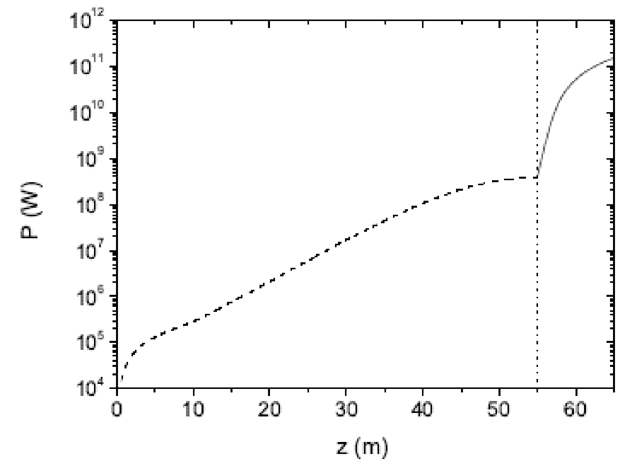


bunching

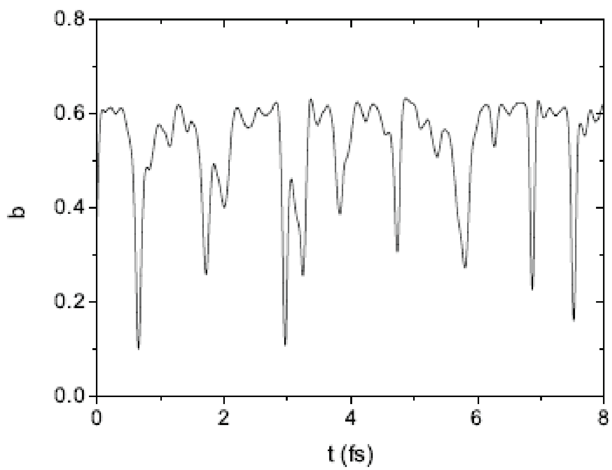
power

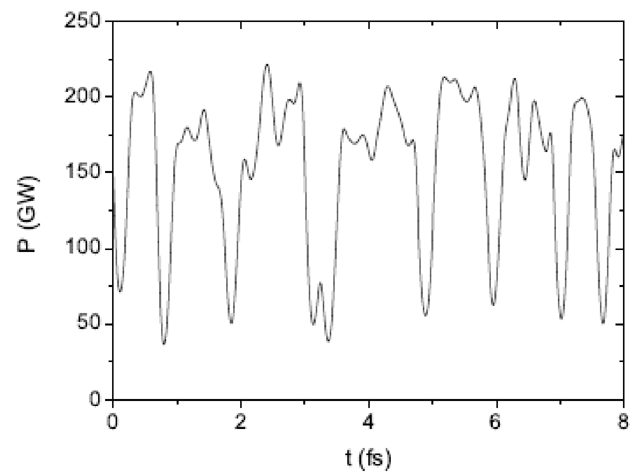
Results of simulations with FAST





400:1





bunching

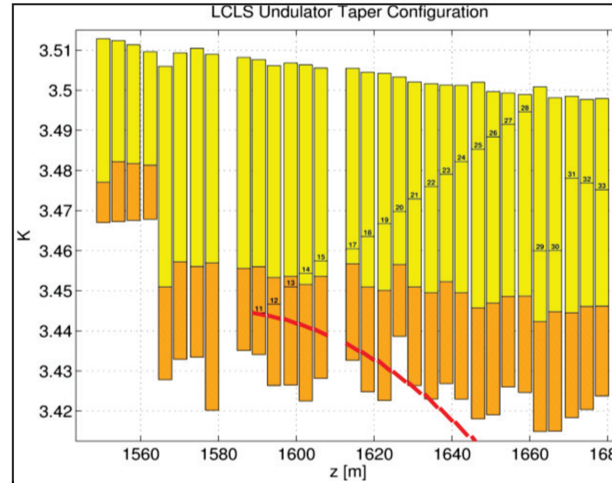
power

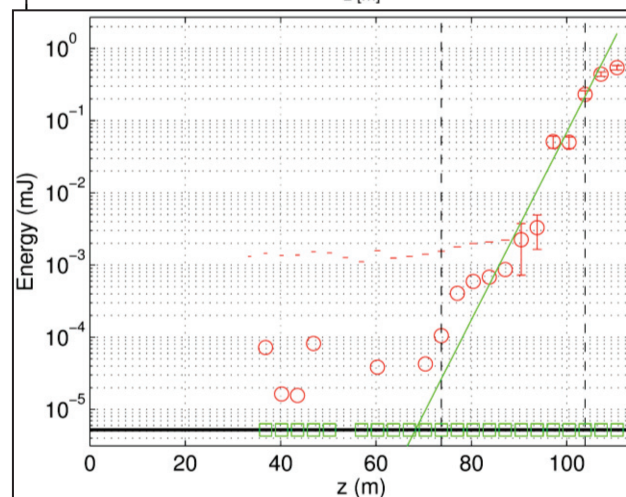
European XFEL

Test at LCLS

- Helical afterburner (DELTA) will be installed at LCLS this fall for production of circularly polarized radiation
- First tests with reverse tapered undulator and planar afterburner were performed recently
- In the best case the power ratio 15:1 was obtained; this would correspond to the ratio 30:1 with helical afterburner

Poster TUP035 by J. MacArthur et al.



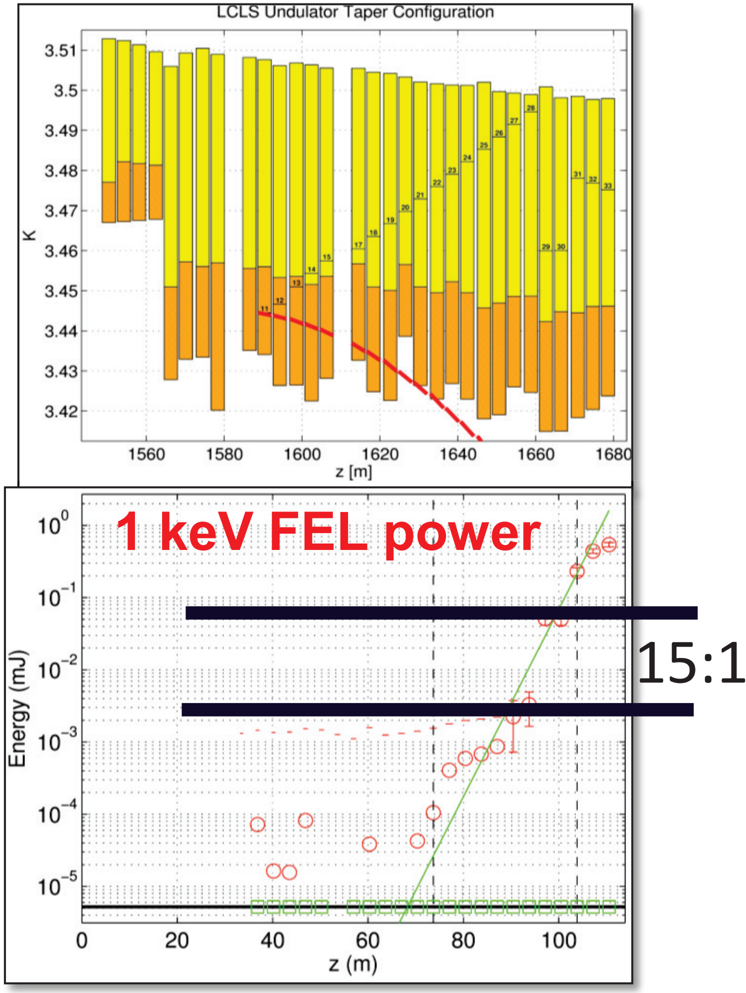


Courtesy Z. Huang

Test at LCLS

- Helical afterburner (DELTA) will be installed at LCLS this fall for production of circularly polarized radiation
- First tests with reverse tapered undulator and planar afterburner were performed recently
- In the best case the power ratio 15:1 was obtained; this would correspond to the ratio 30:1 with helical afterburner

Poster TUP035 by J. MacArthur et al.



Courtesy Z. Huang

Conclusion

- A new method for suppression of linearly polarized background and obtaining high degree of circular polarization is proposed.
- The method is free and easy to implement.
- First tests at LCLS are encouraging; we will learn more after installation of helical afterburner this fall.
- Then the method can be used at other X-ray FEL facilities.
- The method can be used in other FEL schemes (also with energy chirp instead of undulator taper).