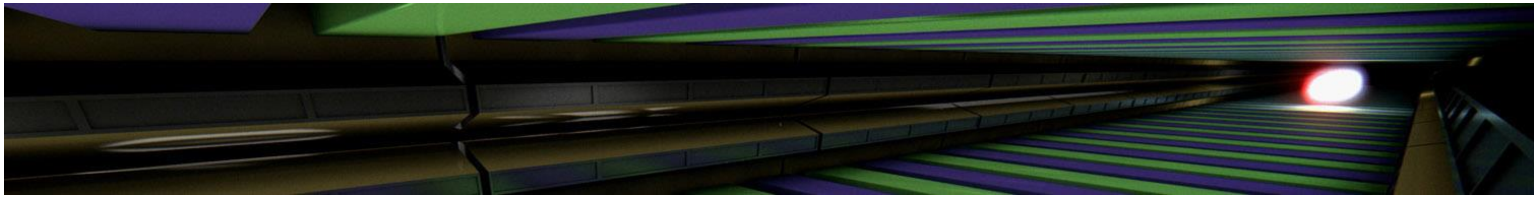


Linear undulator taper for EuXFEL

E. Schneidmiller, M. Yurkov, I. Zagorodnov

DESY Beam Dynamics Meeting

June 16, 2020

Standard scaling

$$\boxed{\lambda = \frac{\lambda_\mathrm{w}(1+K^2)}{2\gamma^2}}$$

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

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

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 – this talk

  \- increase power of a high-gain FEL after saturation (post-saturation taper) – talk by Mikhail

Reverse (negative) taper

Undulator K increases along the undulator length;

- to increase efficiency of FEL oscillators

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

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

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

- to suppress the radiation while keeping strong microbunching: for polarization control (e.g. SASE3) and in other schemes

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

Energy loss

- Spontaneous undulator radiation (can be precisely calculated)

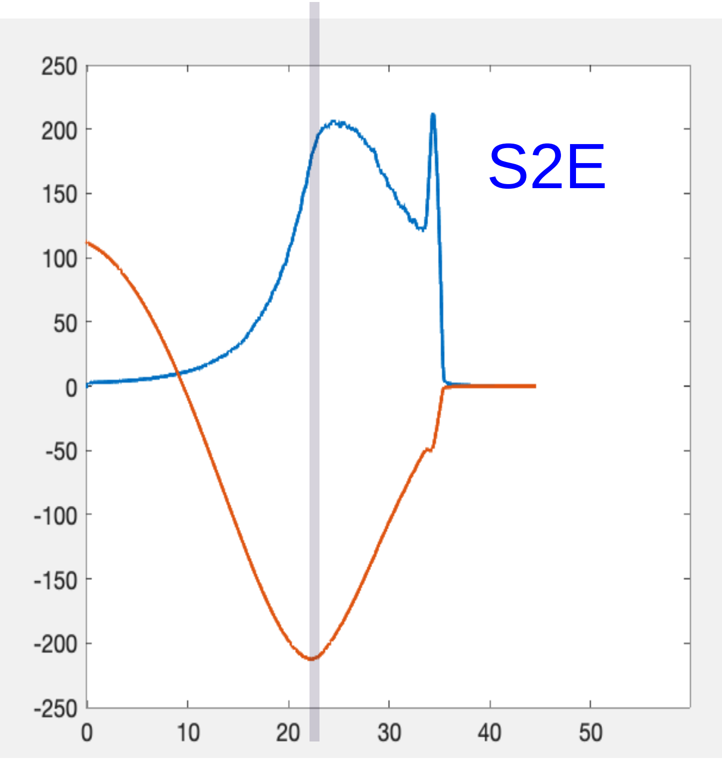
$$dE/dz = 2r_e^2\gamma^2 H(z)^2/3$$

- Wakefields (depend on how we compress the bunch), next slide

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

Energy loss to compensate (keV/m)

Peak current, kA	Gauss	Rectangular	Triangular (falling)	Triangular (raising)	S2E
3	121	115	119	86	
5	**172**	**170**	**174**	**186**	**195**
7	200	198	216	264	



I. Zagorodnov

Some expected numbers for XFEL

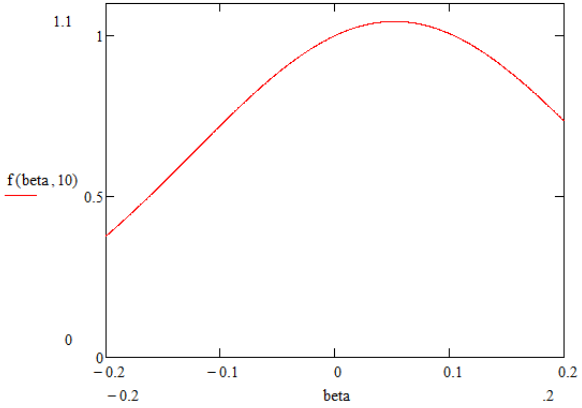
- Consider operation at 14 GeV, 9 keV (SASE1/2)
- Spontaneous radiation: 74keV/m * 5 m = 370 keV/segment
- Wakefields: take 200 keV/m * 6.1 m = 1.27 MeV/segment
- Total: 1.65 MeV/segment or relative loss 12* 10^(-5) per segment
- Equivalent taper to compensate (K= 2) : 15* 10^(-5) per segment
- For uncompensated effect: β = - 0.2 for ρ = 6* 10^(-4)

SASE in liner regime with taper

- In linear regime of SASE FEL operation the central frequency of radiation evolves along the undulator length depending on sign and magnitude of linear taper
- When taper parameter β is small, the central frequency follows the “nominal” resonance (given by K at a given z) with half of the rate independently of sign (Huang and Stupakov, 2004)
- This simmetry is broken when the parameter is large (Schneidmiller and Yurkov, 2013)
- For EuXFEL the parameter is always small except special cases like reverse taper experiments at SASE3
- Positive taper is more beneficial, gives more power (next slide) because it pushes particles towards decelerating phase
- This is especially pronounced at saturation where we get factor of 2 more power just from linear taper

Effect on FEL gain

Linear regime



$$\langle \hat{\eta} \rangle \simeq \frac{\exp\{\sqrt{3}\hat{z}[1 - (\hat{\alpha}\,\hat{z}\,/12)^2/3] + \hat{\alpha}\,\hat{z}\,/12\}}{3^{5/4}\sqrt{\pi \hat{z}} N_c}$$

Saturation

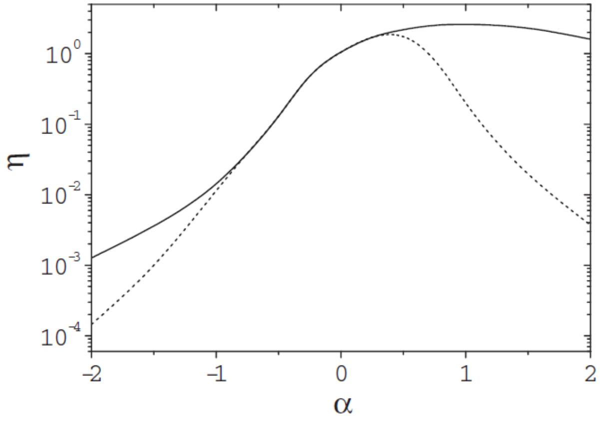


FIG. 2. Normalized output power versus parameter $\hat{\alpha}$. Solid: $\hat{z} = \hat{z}_{\mathrm{sat}}(\hat{\alpha})$ (see Fig. 1); dashed: $\hat{z} = \hat{z}_{\mathrm{sat}}(0) = 13$.

$$\boxed{\hat{\alpha} = 2 * \beta}$$

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

Optimal β is 0.05 for the end of linear regime, about 0.2 at saturation. Power increase is few per cent at the end of linear regime, but about factor of 2 at saturation

Undulator taper and phase shifters

- To some extent the phase shifters can substitute the taper.
- It means that they can (at least partially) compensate for energy loss.
- If we are not sure about phase shifters calibration and about energy loss, we start tuning in the middle of nowhere.

- What can we do about that?

Studies

- Measure phase shifts with K-mono (successfully tested by Lars and Wolfgang), set them to 0.
- (Note that there was the idea to open PSs and choose WL such that the slippage in the drift was a multiple of WL. But the undulator group (Yuhui) reported that the und. fields are not known to this precision).
- Stay at the end of linear regime, at saturation, in a deep saturation; do linear taper scan (pulse energy versus linear term), measure evolution of spectra with HIREX. Compare with simulations, try to extract the most probable value for energy loss
- In parallel do energy loss measurements through the whole undulator by changing compression (like it was reported by Martin)
- Update undulator server to include spontaneous emission loss and the wakefields fitting those measurements

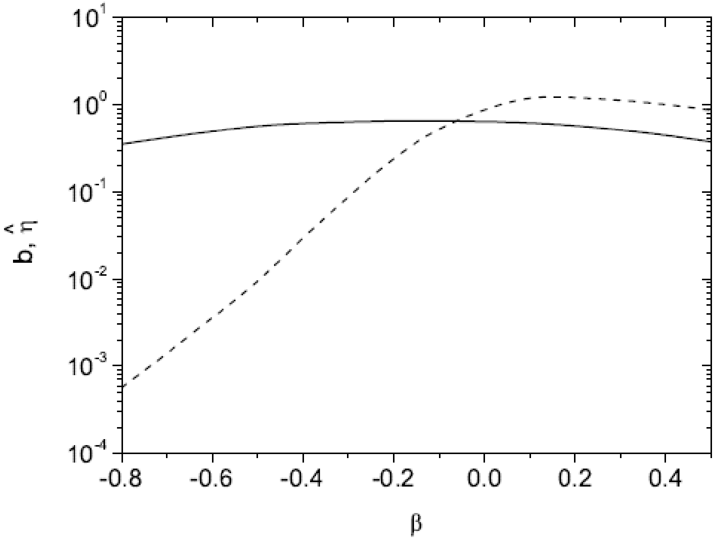
Routine tuning (for the time being)

- Set all PSs to values from magnetic measurements
- Close N undulators to be at the end of linear regime (about 30 uJ for 250 pC). Can go slightly higher (but not more than 100 uJ) to avoid problems with XGM noise and offset
- Do scan of linear taper, set it to optimum (thus slightly overshooting – but should still be OK).
- Do PS scans one by one.
- If intensity goes higher, open the last segment.
- It might me useful to iterate (again taper scan, than PSs) if time allows.
- Slide with active undulators downstream (open first, close (N+1)th), do scan of the next phase shifter; change number of active undulators if intensity is too high or too low.
- After sliding through the whole undulator close all segments and do a quick gain curve measurement (not only pulse energy but also fluctuations should be plotted).
- Define the point with largest fluctuations as the start of quadratic taper
- Scan coefficient to quadratic term
- Might optimize empirically all three parameters (let robot do that?).

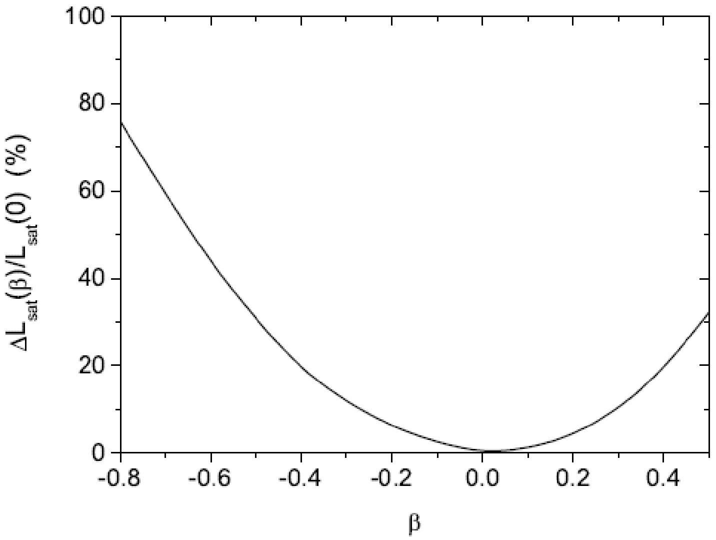
Backup slides

Reverse taper

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

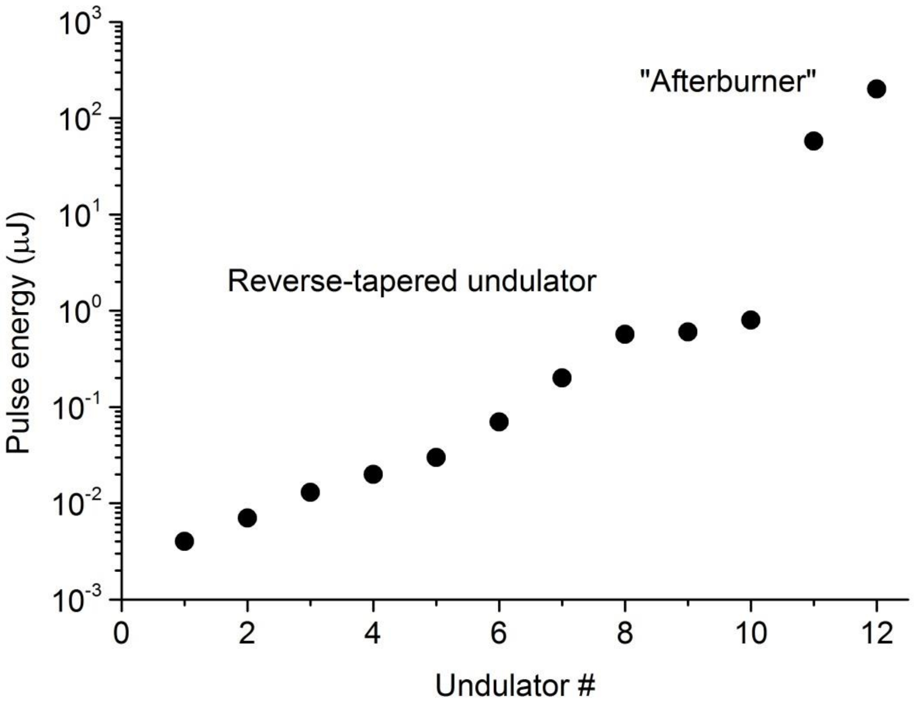


Bunching and power at saturation



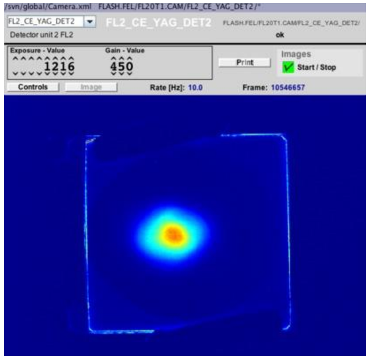
Relative increase of the saturation length

Reverse taper experiment at FLASH2 (cont'd)



≈ 200

(x 2)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FL2_CE_YAG_DET2

FLASH.FEL/FL20T1.CAM/FL2_CE_YAG_DET2/

Detector unit 2 FL2

ok

Exposure - Value 1216

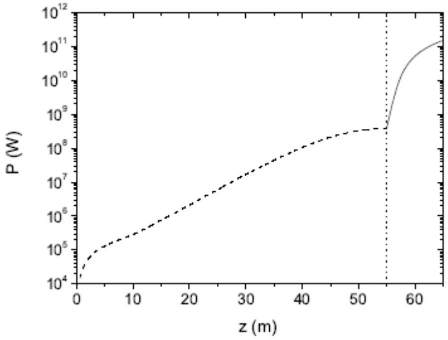
Gain - Value 450

Rate [Hz]: 10.0

Frame: 10546657

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

Simulations for SASE3



≈ 400

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

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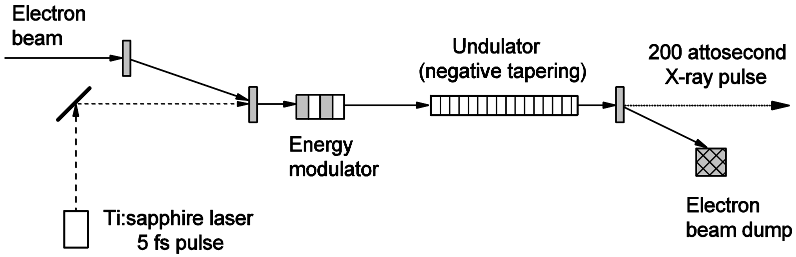

$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{c\,dt}.$$