Linear undulator taper for EuXFEL

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Standard scaling

\[ \hat{C} = \left( k_w - \frac{\omega (1 + K^2)}{2c\gamma^2} \right) \Gamma^{-1} \]  
detuning parameter

\[ \hat{z} = \Gamma z \]  
normalized longitudinal coordinate

\[ \Gamma = \frac{4\pi \rho}{\lambda_w} \]  
gain parameter (≈inverse gain length at resonance)

Now let K be linear function of z:

\[ \hat{C}'(\hat{z}) = \beta \hat{z} \]

\[ \beta = -\frac{\lambda_w}{4\pi \rho^2} \frac{K(0)}{1 + K(0)^2} \frac{dK}{dz} \]
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
- to compensate for energy chirp and to use in attosecond schemes for X-ray FELs combining taper and energy chirp in a short slice
- 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

\[
\beta = -\frac{\lambda_w}{4\pi \rho^2} \left[ \frac{K(0)}{1 + K(0)^2} \frac{dK}{dz} - \frac{1}{\gamma(0)} \frac{d\gamma}{dz} \right]
\]
### Energy loss to compensate (keV/m)

<table>
<thead>
<tr>
<th>Peak current, kA</th>
<th>Gauss</th>
<th>Rectangular</th>
<th>Triangular (falling)</th>
<th>Triangular (raising)</th>
<th>S2E</th>
</tr>
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<td>115</td>
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<td>5</td>
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<td>200</td>
<td>198</td>
<td>216</td>
<td>264</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta E \text{ [keV]} \]

I. Zagorodnov
Some expected numbers for XFEL

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

Saturation

Optimal $\beta$ 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.

$\langle \hat{\eta} \rangle \approx \exp \left\{ \sqrt{3} \hat{\xi} \left[ 1 - \frac{\hat{\alpha} \hat{\xi}}{12} \right] \right\} \frac{3^{5/4}}{\sqrt{\pi} \hat{\xi} N_c}$

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

• 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?
• 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
bunching (0<b<1)

\[ \hat{\eta} = \frac{P}{\rho P_{\text{beam}}} \]  

normalized power (efficiency)

\[ \hat{\Lambda}_T = \frac{\sigma_\gamma}{\gamma \rho} = 0.2 \]  

energy spread parameter

Bunching and power at saturation

Relative increase of the saturation length
Reverse taper experiment at FLASH2 (cont’d)

Simulations for SASE3

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

"Afterburner"

Pulse energy (\text{\mu J})

\[ \approx 200 \quad (x \ 2) \]

\[ \approx 400 \]
Reverse (negative) taper

- Undulator K increases along the undulator length;
- Two applications were proposed for FELs:
  - to increase efficiency of FEL oscillators
  - to use in an attosecond scheme for X-ray FELs combining taper
    and energy chirp in a short slice