



Reverse undulator tapering for polarization control at X-ray FELs

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FEL Seminar, DESY

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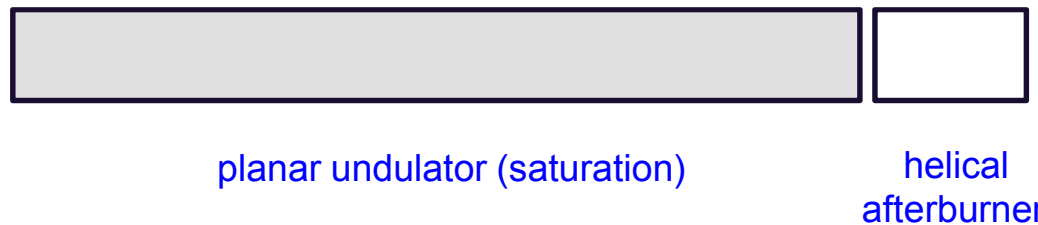




- Strongly requested by the user community
- Especially interesting is soft X-ray regime
- Undulators are planar
- There are many ideas for circular polarization production (following K.-J. Kim's cross-planar configuration)



- 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



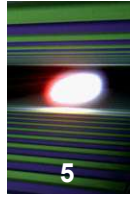
reverse-tapered planar undulator (saturation)

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

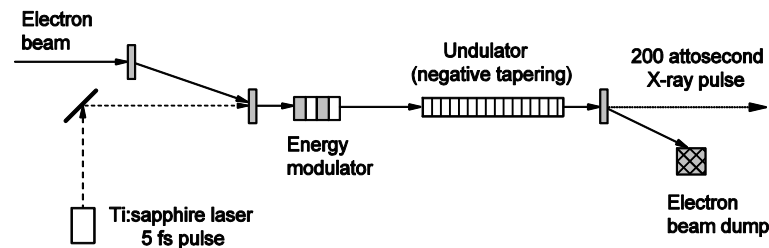
Standard (positive) taper



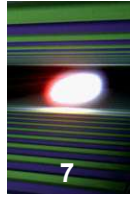
- Undulator K decreases along the undulator length;
- Positive taper is used to
 - compensate beam energy loss due to spontaneous undulator radiation and wakefields;
 - increase power of a high-gain FEL after saturation (post-saturation taper)



- 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



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

Detuning parameter

$$\hat{z} = \Gamma z$$

Normalized longitudinal coordinate

$$\Gamma = 4\pi\rho/\lambda_w$$

Gain parameter (\approx inverse gain length at resonance)

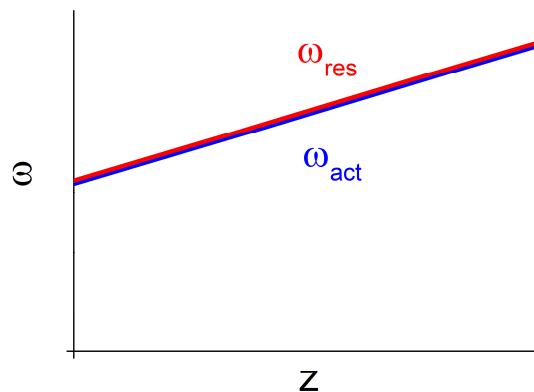
Now let K be linear function of z:

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

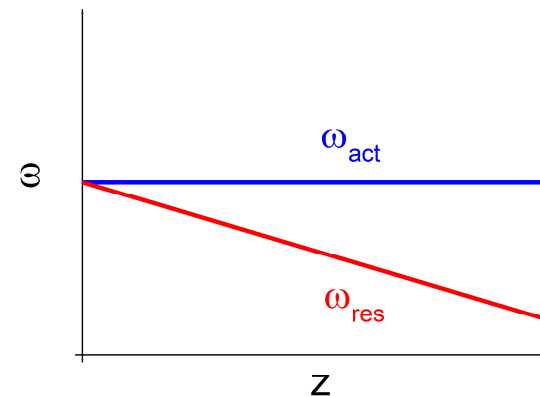


In a SASE FEL the evolution of the amplified frequency band depends on tapering. Consider the asymptote of a large parameter $|\beta|$.

$$\beta > 0$$



$$\beta < 0$$



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.

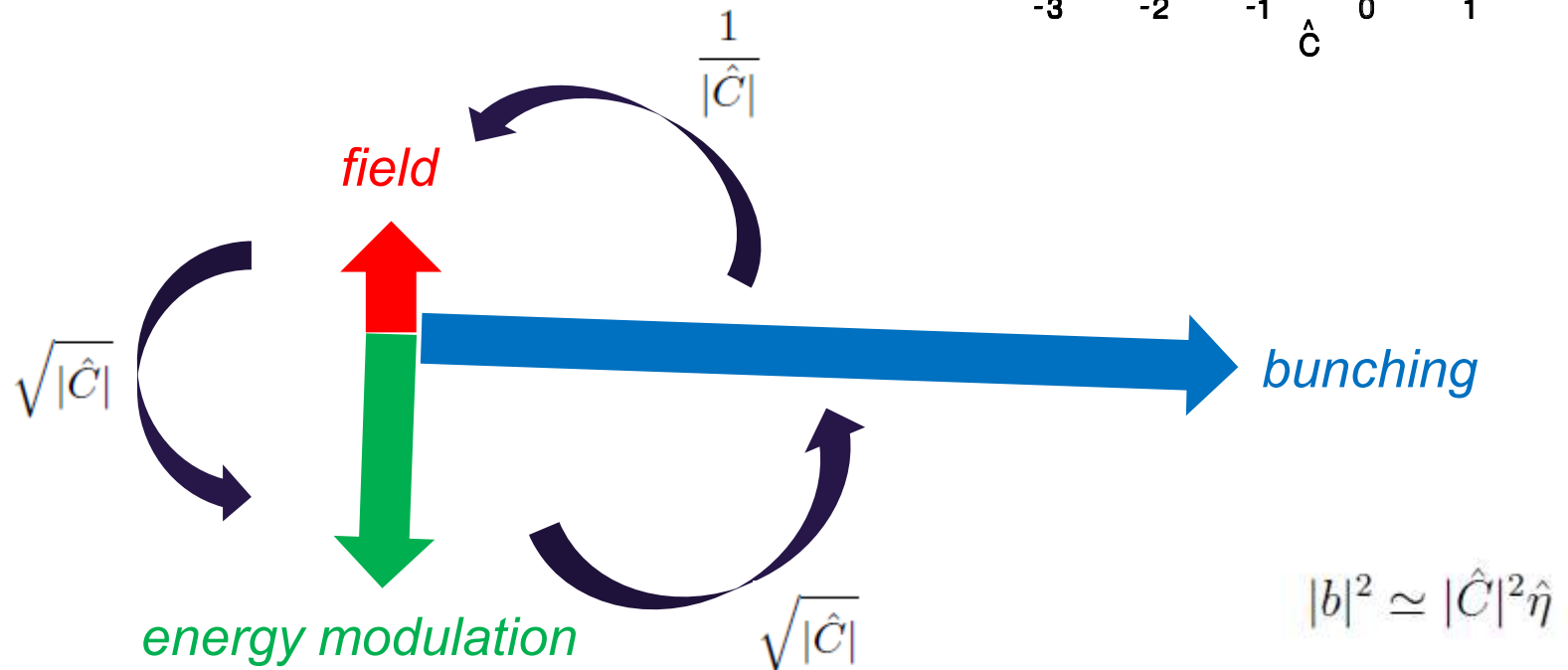
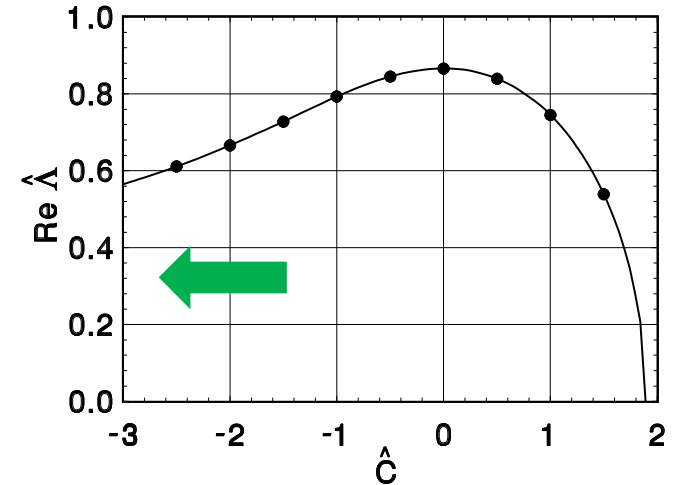
Steady-state, exponential gain regime



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

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

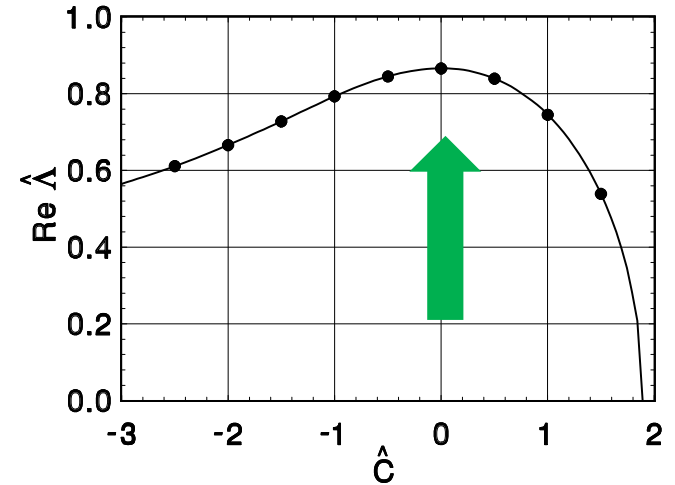
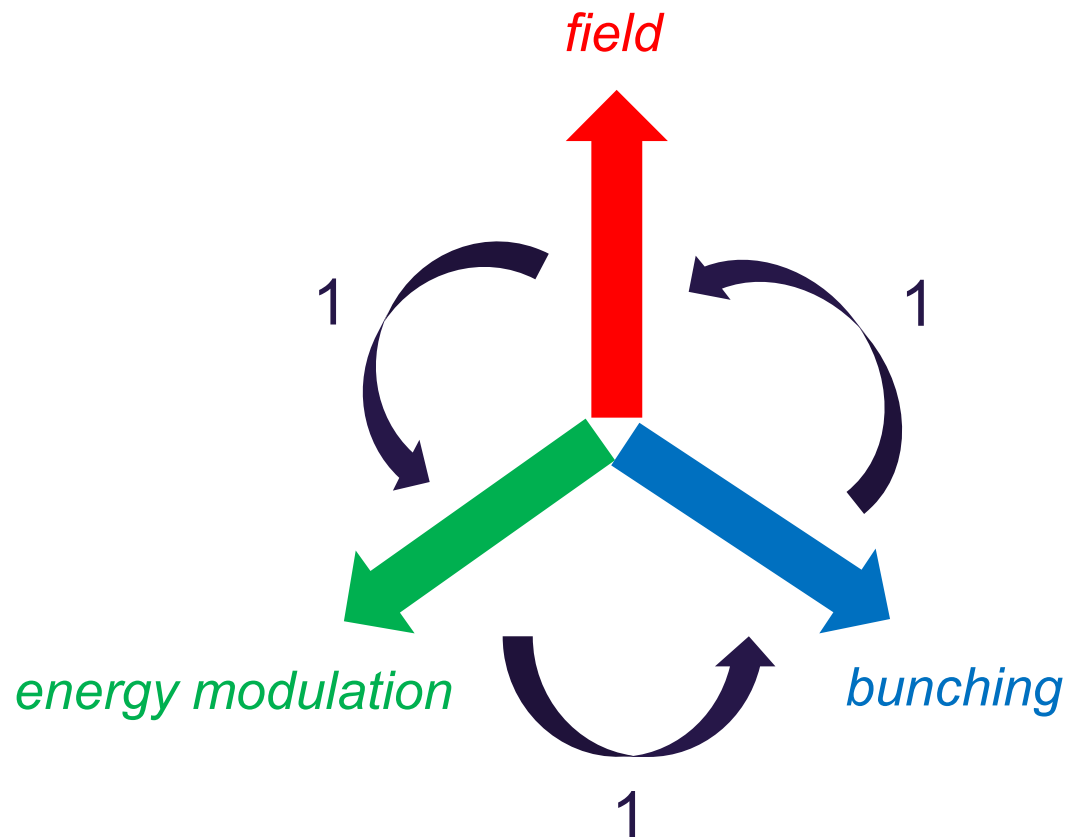
One can solve initial-value problem and find for the exponential gain regime:



Steady-state, exponential gain regime: resonance



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





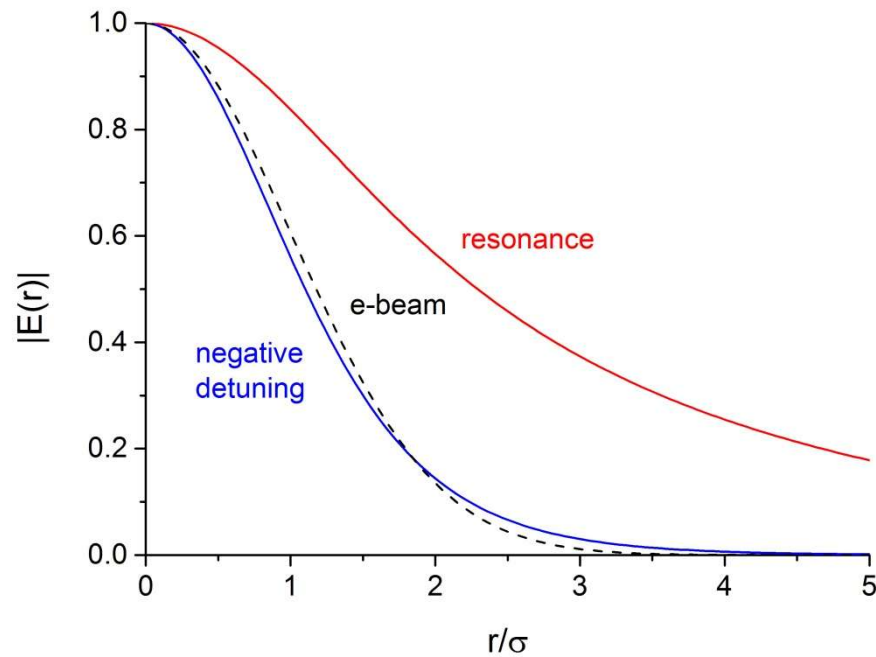
Now SASE and large reverse taper. The FEL frequency band stays close to resonance at the undulator entrance (and not at the present position), i.e. detuning increases as the beam propagates through the undulator. Gain length also increases and the ratio is

$$\langle |b|^2 \rangle \simeq |\beta|^2 \hat{z}^2 \langle \hat{\eta} \rangle$$

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



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



$$B = 0.1$$

$$C = 0$$

$$C = -20$$



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

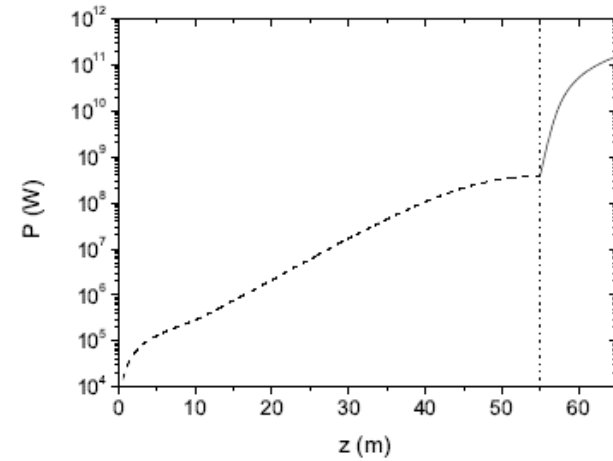
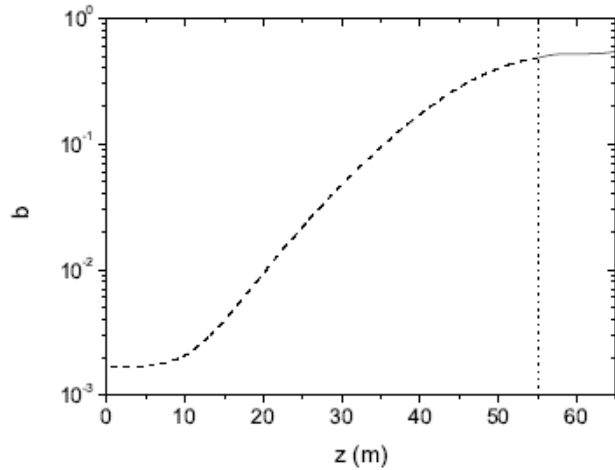
Period	6.8 cm
K_{rms}	5.7
Beta-function	15 m
Active magnetic length	55 m
Taper $\Delta K_{\text{rms}}/K_{\text{rms}}(0)$	2.1 %

Helical afterburner

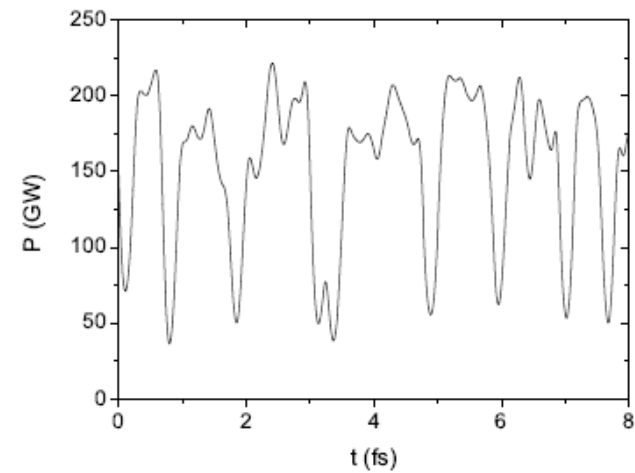
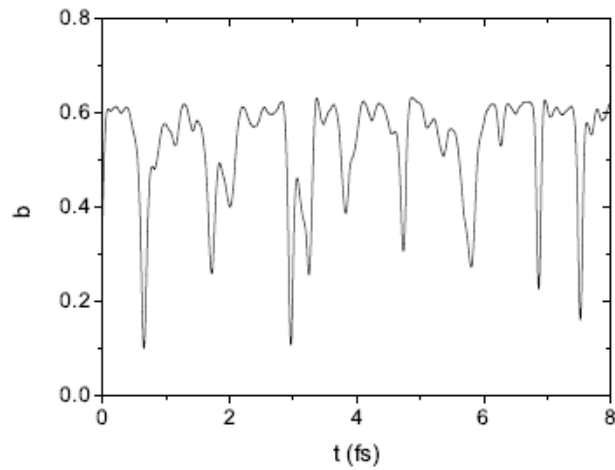
Period	16 cm
K	3.6
Beta-function	15 m
Magnetic length	10 m

Radiation

Wavelength	1.5 nm
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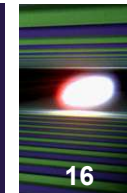


↑
≈ 400



bunching

power



FEL2015 Daejeon Korea, 23rd – 28th August 2015

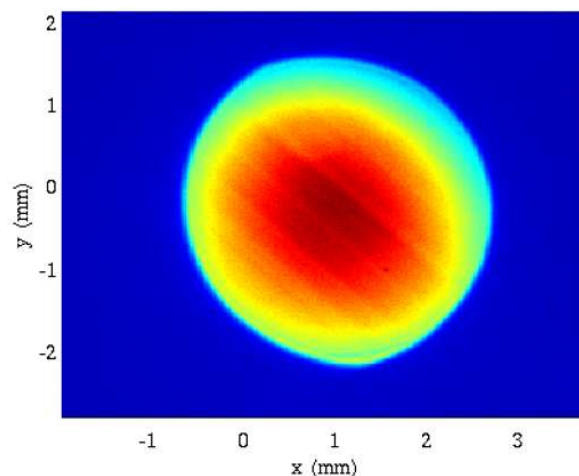
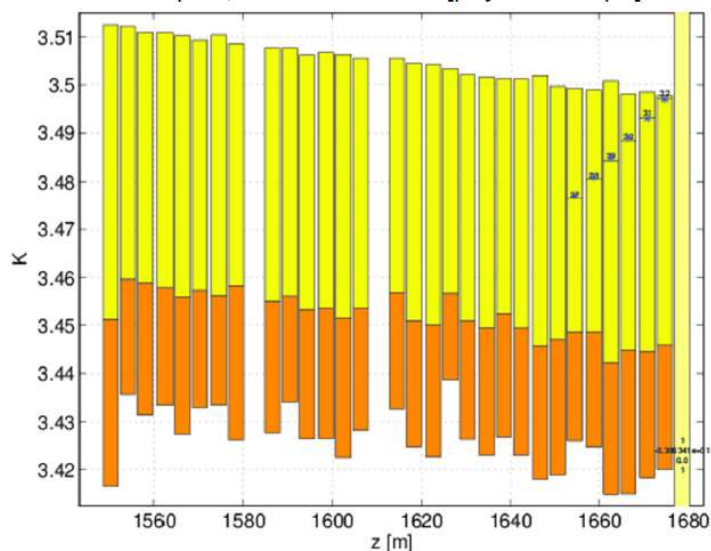
Heinz-Dieter Nuhn

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

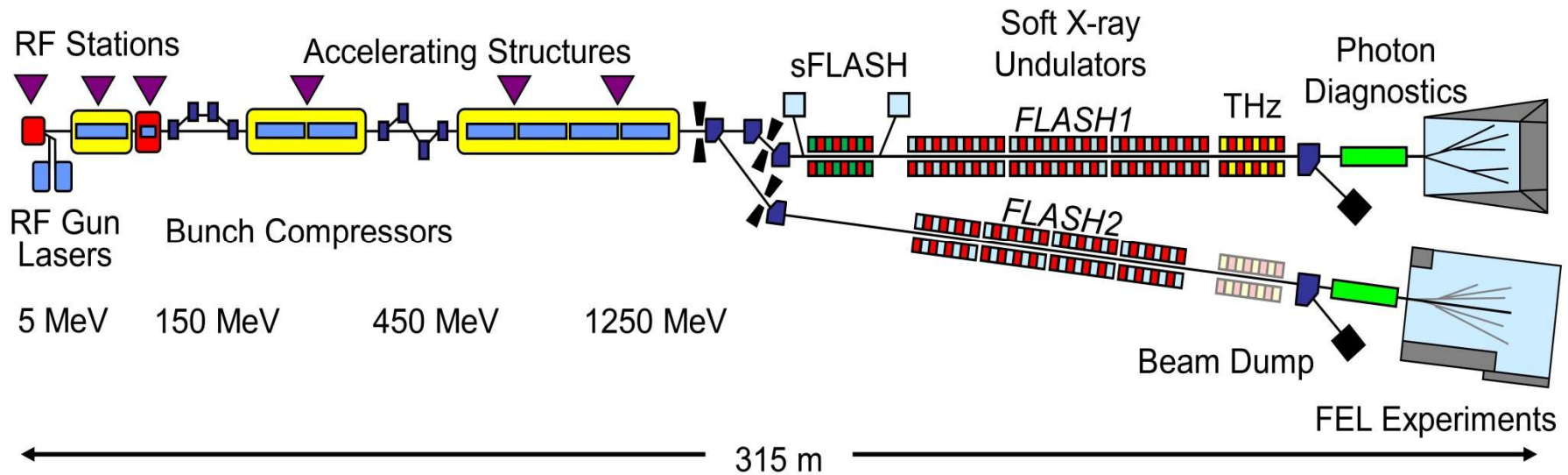
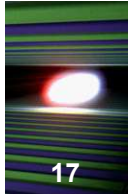
- 30 μ J with Delta off
 - 510 μ J with Delta on
- Peak Current increased above 4 kA



James MacArthur WEP004

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Courtesy
H.-D. Nuhn

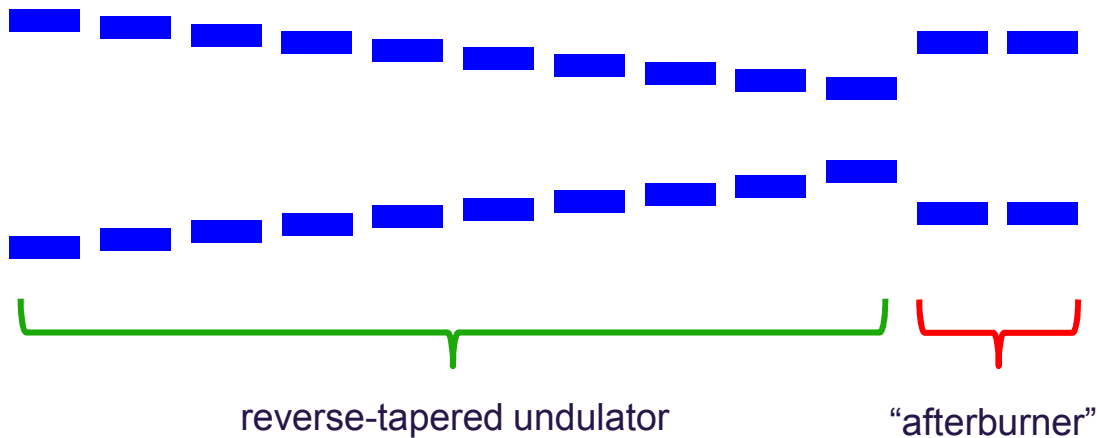


Undulators

	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

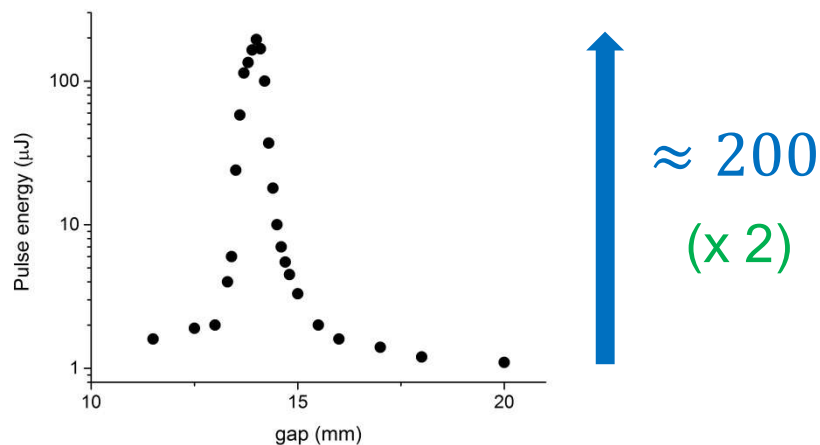


23.01.2016

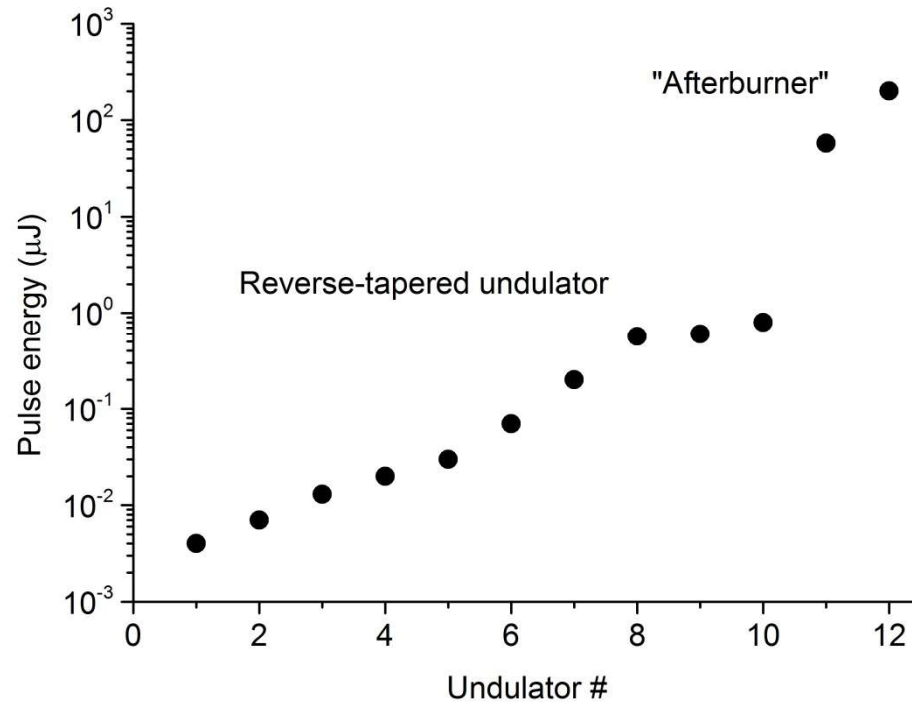
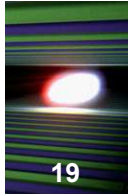


Beam energy 720 MeV,
wavelength 17 nm.

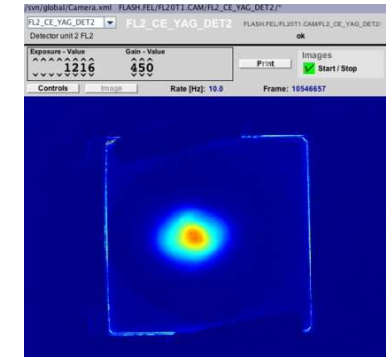
Reverse taper (10%) was
applied to the 10 undulator
segments;
the gap of the 11th and 12th
segments was scanned.



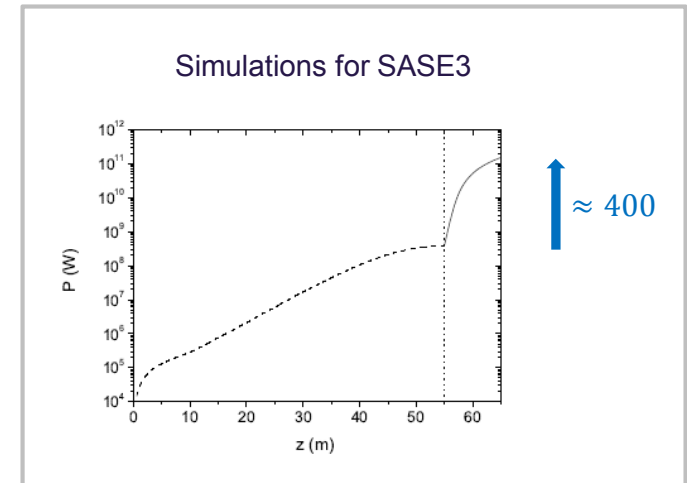
Power ratio of 200 was
obtained. For a helical
afterburner it would be
larger by a factor of 2.



↑
≈ 200
(x 2)



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





- 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.



- 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