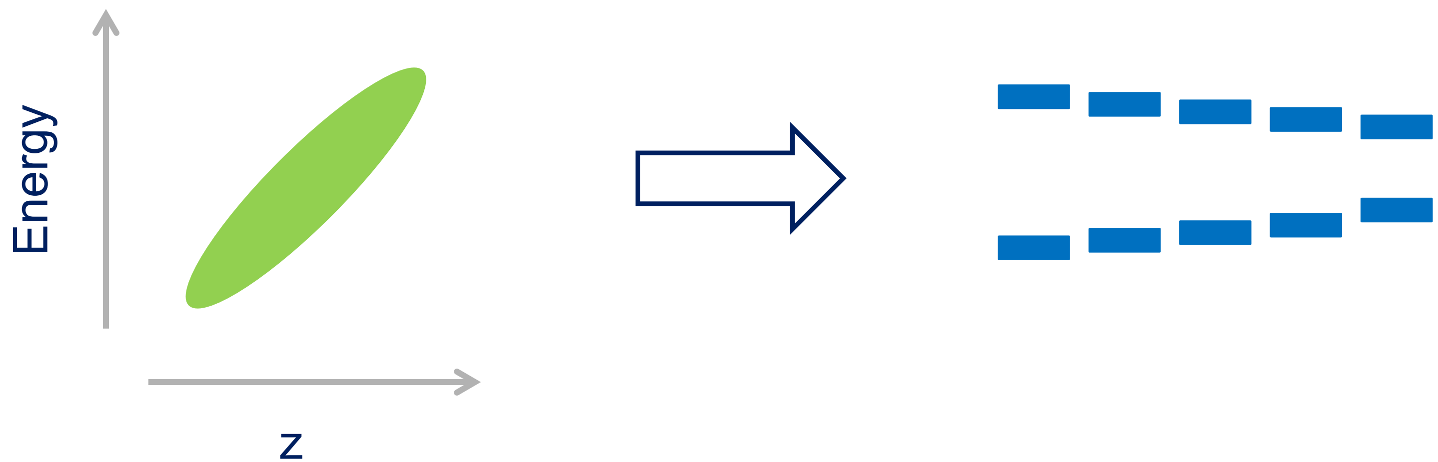
Energy chirp and undulator taper in FELs

E. Schneidmiller



August 21, 2017

Outlook

- Reverse taper in FEL oscillators
- Energy chirp effects at FLASH
- Chirp-taper compensation effect
- Chirp-taper attosecond scheme
- Reverse taper for
  - polarization control
  - background-free harmonic generation
- Proposals for
  - enhanced X-ray pulse compression (HLSS based)
  - strongly chirped X-ray pulses (LSCA based)

Sign convention

Chirp

positive

negative

Taper

positive, standard

negative, reverse

Reverse taper in FEL oscillators (I)

- Optimizing numerically a linear taper for efficiency enhancement we have found that:

- standard way of tapering (positive) often leads to efficiency reduction;
- reverse (negative) taper helps improve FEL efficiency

E. Saldin, E. Schneidmiller , M. Yurkov, Opt. Comm. 103(1993)297

- In the experiments in 1980s only positive taper was tried – and it did not work as expected

In past lasing experiments with tapered wigglers [2], the extraction efficiency has been less than expected. We have not observed the behavior expected from a simple model of FELs, i.e., the trapping of a significant fraction of the electrons and their deceleration by an amount consistent with the taper of the wiggler. This behavior was observed in amplifier experiments with the same wiggler [3].

Reverse taper in FEL oscillators (II)

- Maximum of small-signal gain curve (defining the lasing frequency) shifts depending on sign and magnitude of the taper applied:

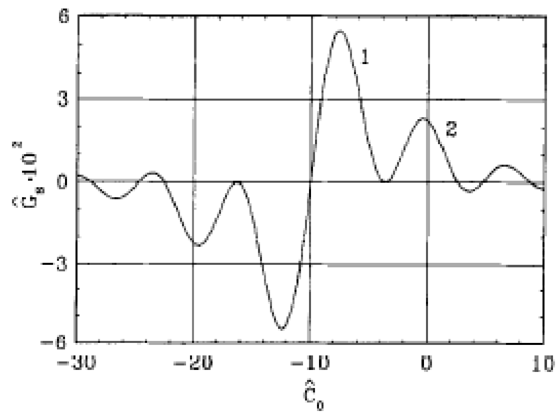


Fig. 1. The reduced small-signal gain versus the reduced detuning at the undulator entrance. Here $\hat{b} = 20$, (1) – the first maximum, (2) – the second maximum.

- For positive taper: the detuning is negative in the first half of the undulator; the beam gets bunched at accelerating phase of the field, and only in the second half it gives the energy back to the field
- For negative taper this process is reversed what allows to reach higher field in the cavity and higher efficiency

E. Saldin, E. Schneidmiller , M. Yurkov, Opt. Comm. 103(1993)297

Reverse taper in FEL oscillators (III)

- Reverse taper was tested at different labs:
  - Jefferson lab: A. Christodoulou et al., Phys. Rev. E66, 056502 (2002)
  - Darmstadt: S. Khodyachykh et ai., NIM A530 (2004)205
  - ELBE (Rossendorf): V. Asgekar, U. Lehnert, P. Michel, Rev. Sci. Instrum. 83(2012)015116

- The reverse taper generally works better!

ELBE

V. Asgekar, U. Lehnert, P. Michel, Rev. Sci. Instrum. 83(2012)015116

TABLE I. Peak power values for different gap tapers.

Gap taper (mm)	$\hat{\alpha}$	Power (a.u.)	Gain (%)	Efficiency (%)
−1.5	−21.37	…	22	2.51
−1.0	−14.56	305	46	1.30
−0.5	−07.06	250	62	0.86
0.0	00.00	158	70	0.75
+0.5	06.83	151	64	0.77
+1.0	13.54	152	48	1.26
+1.3	17.56	101	35	1.30
+1.5	20.28	…	25	0.48

3.3

$$\alpha = -2\pi N_u K^2 \Delta B_u / [B_u(1 + K^2/2)]$$

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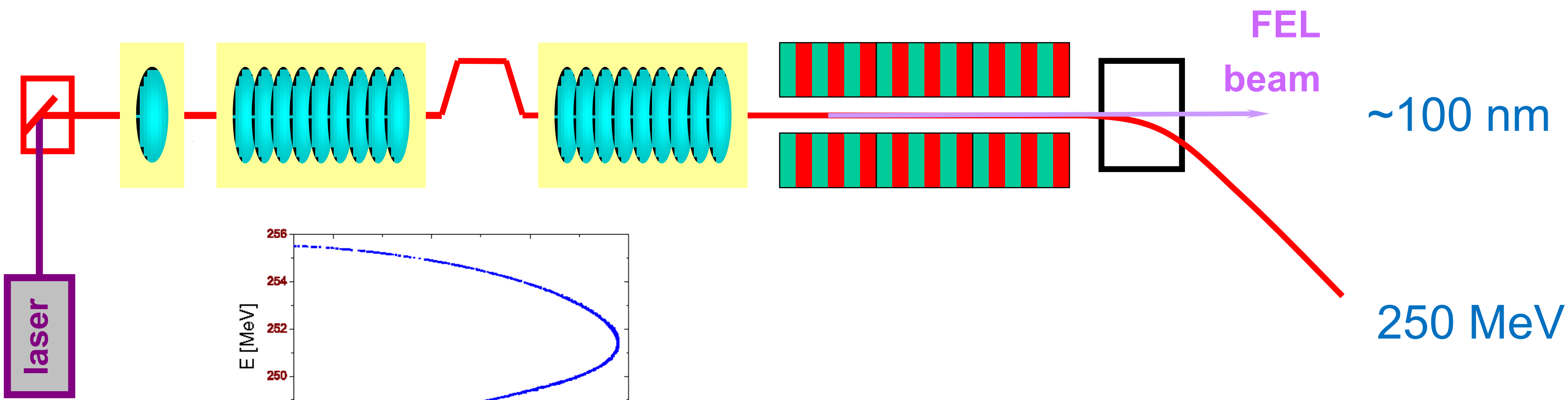
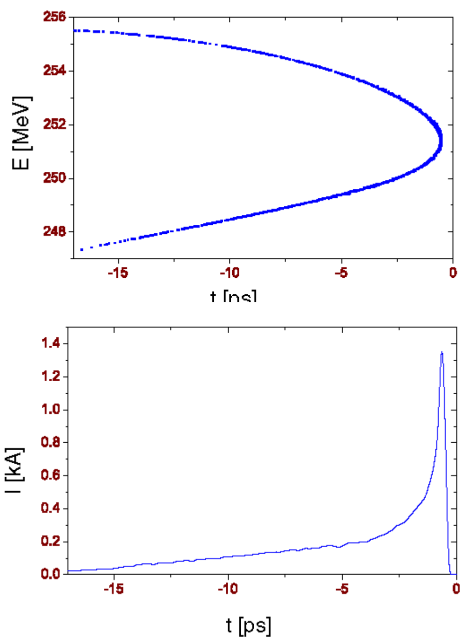
TTF1 FEL (predecessor of FLASH)





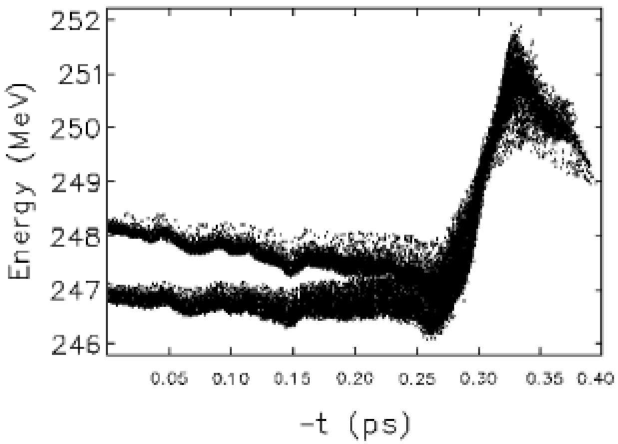
First lasing 2000

Saturation 2001

- Nonlinear bunch compression ➡ short high-current spike ➡ 50 fs long FEL pulses
- Spectrum and divergence are significantly wider than in simulations

Longitudinal space charge (LSC)

- Studies of microbunching instability (uBI) ➡ LSC is the main effect!
- Estimates for FLASH: modulations on 10 um scale (observed now); if saturates, multi-MeV energy modulations to be expected.
- TTF1 spike is in the same range ➡ strong LSC effect was overlooked.
- S2E with space charge effect in all straight sections (Astra):



$$\frac{d(\Delta\gamma)}{dz} \simeq 2.4 \frac{I}{I_A} \frac{\ln(\gamma\sigma_z/\sigma_\perp)}{\sigma_z \gamma^2}$$

- All properties of FEL beam (incl. spectrum and divergence) are in good agreement with measurements

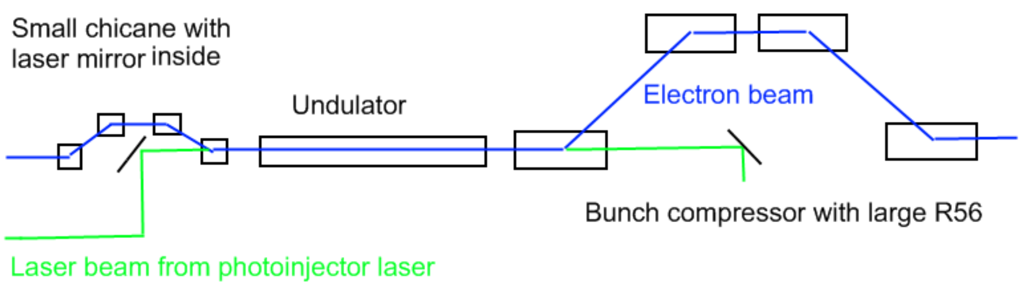
M. Dohlus et al., Nucl. Instrum. and Methods A530(2004)217

Idea of the laser heater (LH)

- Strong dependence of energy chirp on uncorrelated energy spread:

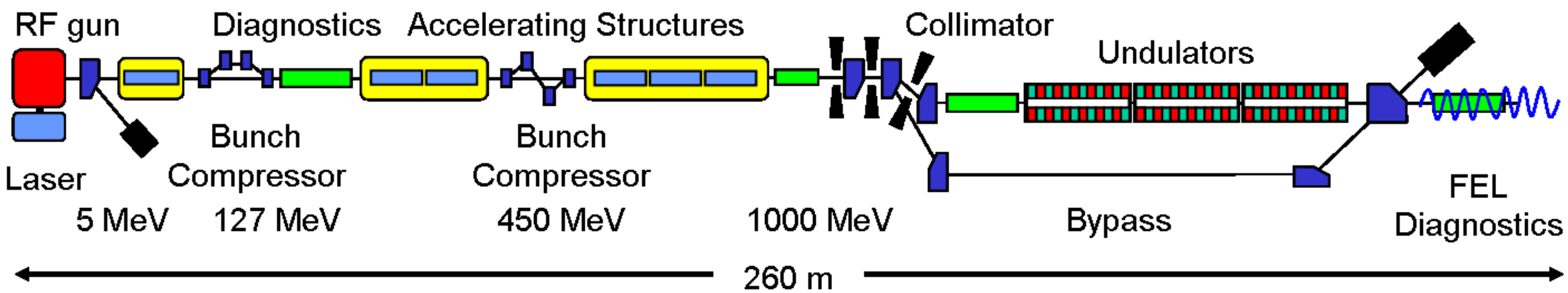
$$\frac{d\delta}{ds} \sim (\sigma_\delta)^{-5/2}$$

- LH can help control parameters of lasing spike (reduce chirp)
- Later it was suggested to use LH for suppression of microbunching instability (E. Saldin, E. Schneidmiller, M. Yurkov, TESLA-FEL-2003-02)

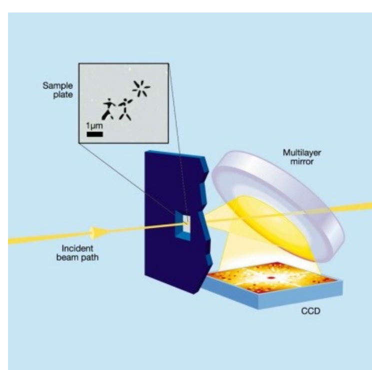


Smearing due to a large R_{56} of BC and natural uncorrelated energy spread

Nonlinear compression at FLASH (2004-2009)



- Form the spike in two compressors: chirp strong but tolerable
- Complicated beam dynamics (incl. compression in the dogleg, long. and transverse space charge etc.), complicated tuning
- But the facility successfully worked for users, they enjoyed pulses on 10 fs scale



H. Chapman et al.

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Chirp-taper similarity: naïve picture

- Electrons with different energies in untapered undulator: red shift due to an energy offset
- Electrons with the same energy in a tapered undulator: red shift because K-value was larger at a retarded position
- The hope: combine chirp and taper with proper sign (positive chirp and negative taper or vice versa) and magnitude for a perfect compensation of gain degradation

Chirp-taper compensation effect

- Consider positive chirp and negative taper, no interaction
- Radiation slips forward towards higher energies, bunch propagates in the undulator towards higher K-values ➡ resonance is preserved
- Bunch is decompressed due to R56 of the undulator ➡ frequencies of density and energy modulations correspond to the radiation frequency at any position along the bunch and the undulator

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0\omega_0\rho^2}$$ energy chirp parameter

$$b_1 = -\frac{\lambda_w}{4\pi\rho^2}\frac{K(0)}{1+K(0)^2}\frac{dK}{dz}$$ taper parameter

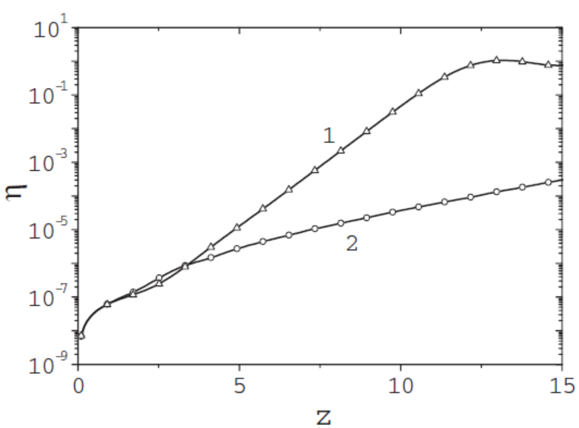
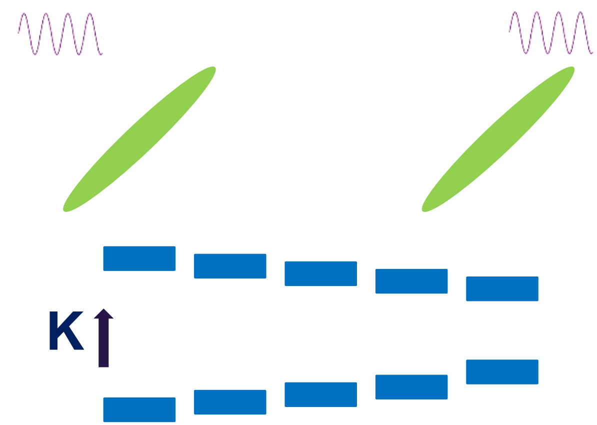


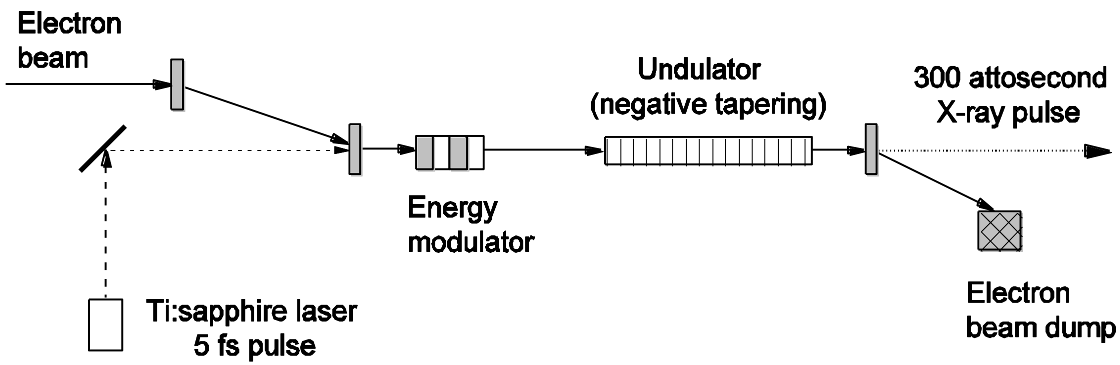
FIG. 3. Normalized power versus undulator length. Solid line 1: $\hat{\alpha} = 0$, $\hat{b}_1 = 0$; triangles: $\hat{\alpha} = 4$, $\hat{b}_1 = -2$; solid line 2: $\hat{\alpha} = 4$, $\hat{b}_1 = 0$; circles: $\hat{\alpha} = 0$, $\hat{b}_1 = 2$.

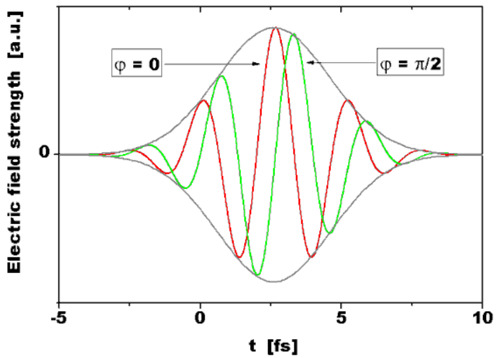


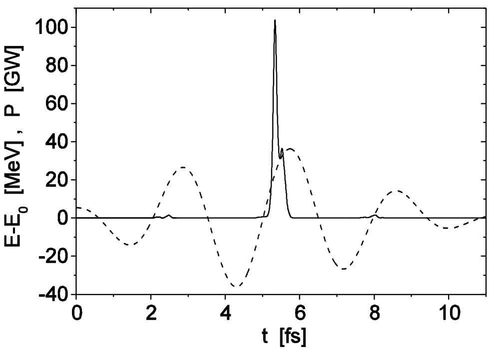
$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{c\,dt}$$

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

Chirp-taper attosecond scheme







Strong energy modulation within a short slice of an electron bunch is produced by few-cycle optical laser pulse in a short undulator, placed in front of the main undulator. Gain degradation within this slice is compensated by an appropriate undulator taper while the rest of the bunch suffers from this taper and does not lase. Three-dimensional simulations predict that short (200 attoseconds) high-power (up to 100 GW) pulses can be produced in Angstroem wavelength range with a high degree of contrast.

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

Chirp-taper experiment in Frascati

- An experiment at SPARC FEL: visible SASE FEL with chirped electron beam and tapered undulator

We report the first experimental implementation of a method based on simultaneous use of an energy chirp in the electron beam and a tapered undulator, for the generation of ultrashort pulses in a self-amplified spontaneous emission mode free-electron laser (SASE FEL). The experiment, performed at the SPARC FEL test facility, demonstrates the possibility of compensating the nominally detrimental effect of the chirp by a proper taper of the undulator gaps. An increase of more than 1 order of magnitude in the pulse energy is observed in comparison to the untapered case, accompanied by FEL spectra where the typical SASE spiking is suppressed.

L. Giannessi et al.,
Phys. Rev. Letters 106(2011)144801

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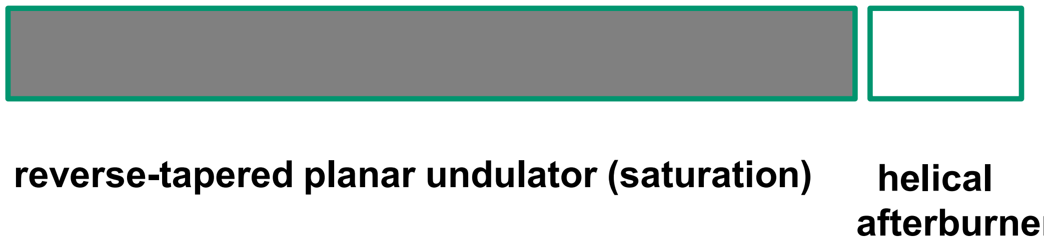
Reverse taper for polarization control



- 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 16(2013)110702

Reverse taper at LCLS

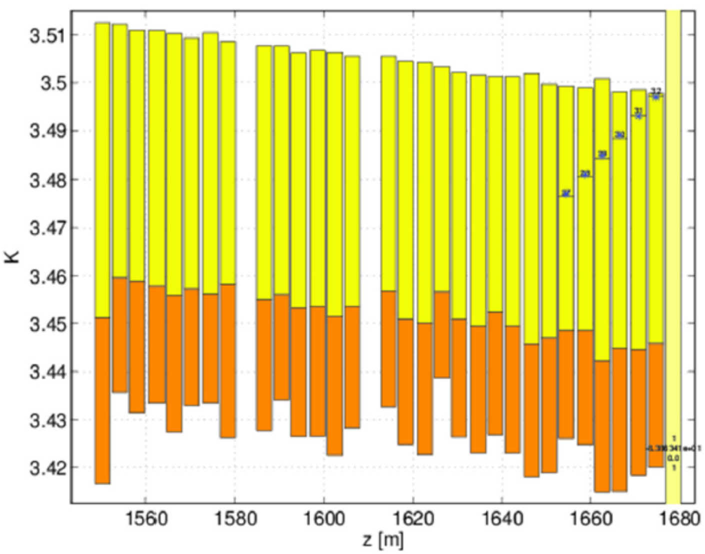
FEL2015 Daejeon Korea, 23rd – 28th August 2015 Heinz-Dieter Nuhn

Delta in Enhanced Afterburner Configuration at 710 eV

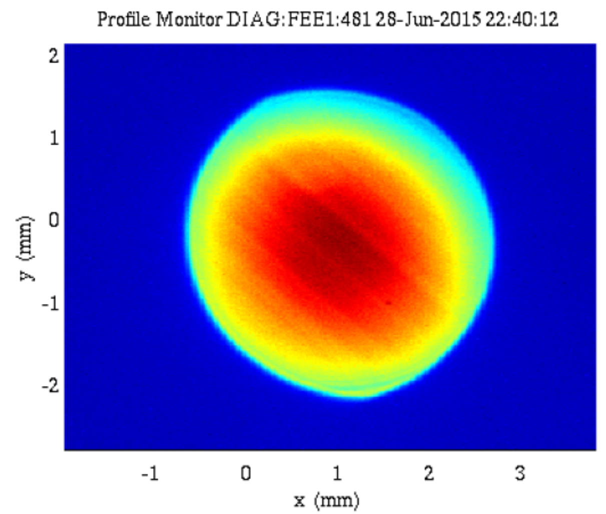
SLAC

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

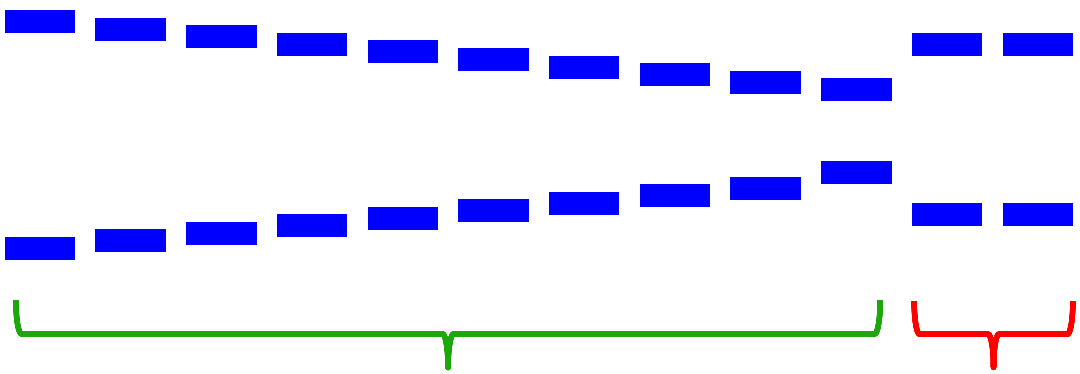
James MacArthur WEP004

24

Courtesy H.-D. Nuhn

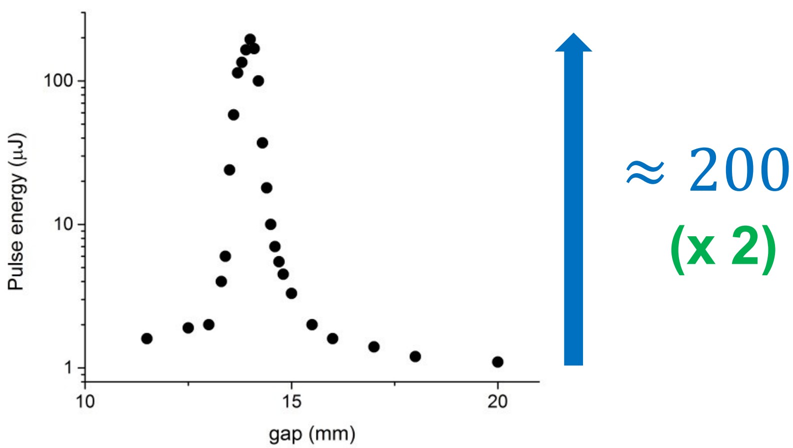
Reverse taper at FLASH

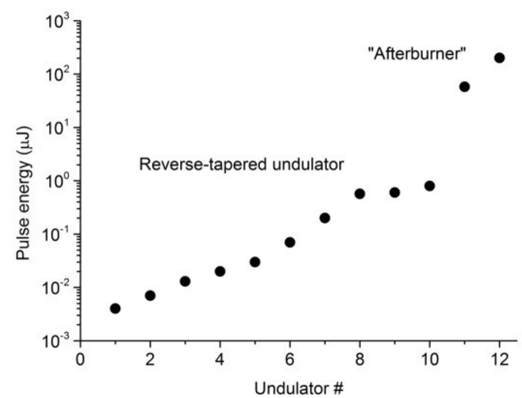
Experiment at FLASH2 on 23.01.2016



reverse-tapered undulator **"afterburner"**

- Beam energy 720 MeV,
- Wavelength 17 nm.
- Reverse taper of 10% along 10 undulator segments;
- The gap of the 11^{th} and 12^{th} segments was scanned.
- Power ratio of 200 was obtained. For a helical afterburner it would be larger by a factor of 2.

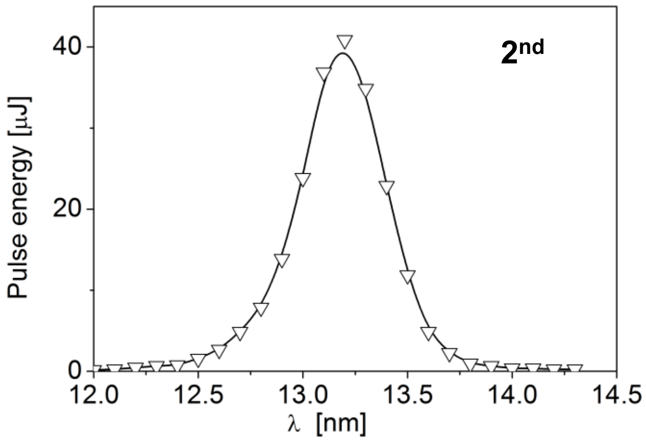


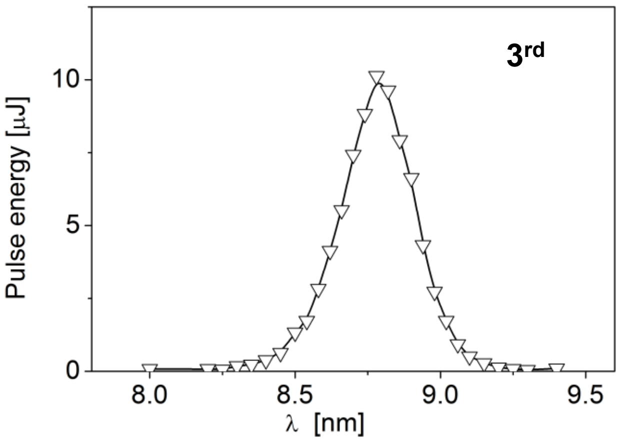


E. Schneidmiller and M. Yurkov, Proc. IPAC2016

Reverse taper plus harmonic afterburber

- Experiment at FLASH2 on Oct. 10, 2016:
- Main undulator: 9 modules, 26.5 nm, -5% taper.
- Afterburner: 2 modules, 26.5 nm, 13.2 nm, 8.8 nm
- Pulse energy after tapered part: < 1 microjoule
- Afterburner on the fundamental: 150 microjoules
- 2nd harmonic: 40 microjoules
- 3rd harmonic: 10 microjoules





Reverse taper can be used for efficient background-free generation of harmonics in an afterburner

Talk by S. Schreiber tomorrow, also our poster MOP032

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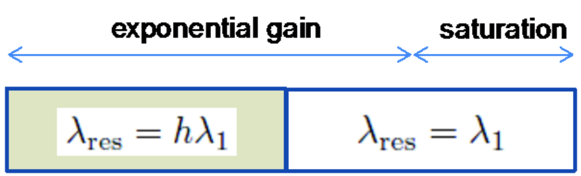
Enhanced X-ray pulse compression

- Old idea (C. Pellegrini): CPA in a SASE FEL and compression in a grating compressor
- Compression is stronger for a smaller intrinsic bandwidth
- For a chirped beam the intrinsic bandwidth can be reduced in advanced FEL schemes (HB SASE, iSASE, pSASE, HLSS …)

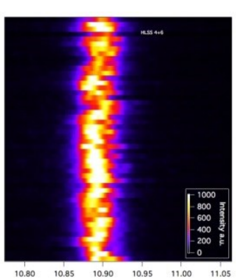
Harmonic lasing self-seeded FEL (HLSS FEL)



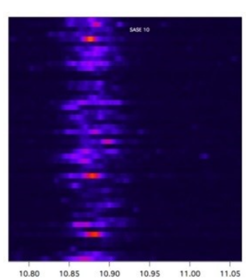
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 15(2012)080702

Successfully demonstrated at FLASH:

HLSS (4+6)



SASE (10)

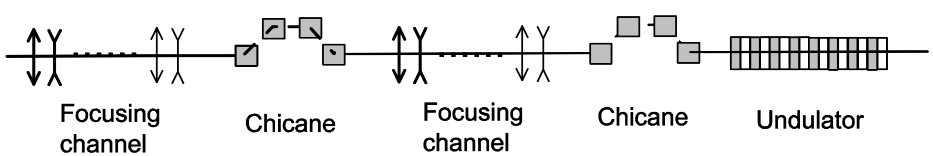


Talk by S. Schreiber tomorrow, also our poster MOP031

Strongly chirped X-ray pulses

- Strongly chirped X-ray pulses can be used for experiments with time-dependent Bragg diffraction (H. Chapman et al.)
- Produce short and broadband pulses and decompress them in a grating compressor
- How to get broadband pulses?

  Use Longitudinal Space Charge Amplifier (LSCA):



E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 13(2010)110701

- Use existing undulator lines, install a couple of compact chicanes and a short undulator: