Self-seeding techniques for hard X-ray FELs using a single-crystal monochromator

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Self-seeding techniques and their importance for XFELs

SASE pulses, baseline mode of operation: poor longitudinal coherence

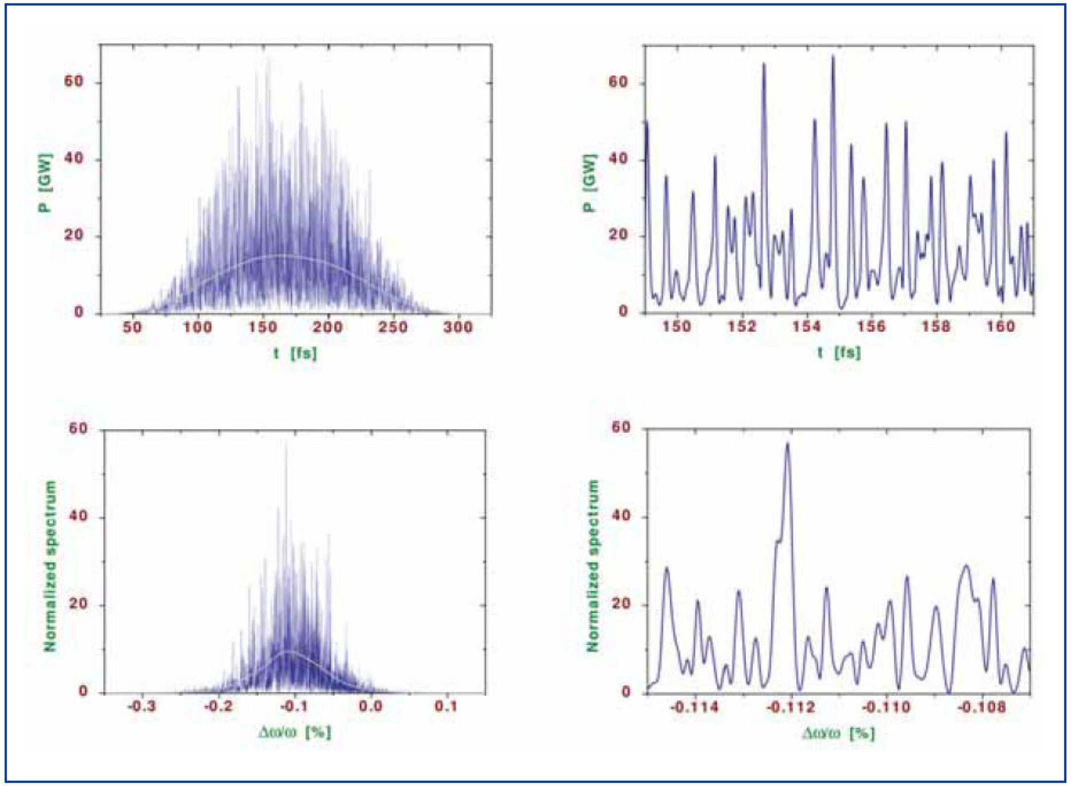


Figure 5.2.4 *Temporal (top) and spectral (bottom) structure for 12.4 keV XFEL radiation from SASE 1. Smooth lines indicate averaged profiles. Right side plots show enlarged view of the left plots. The magnetic undulator length is 130 m.*

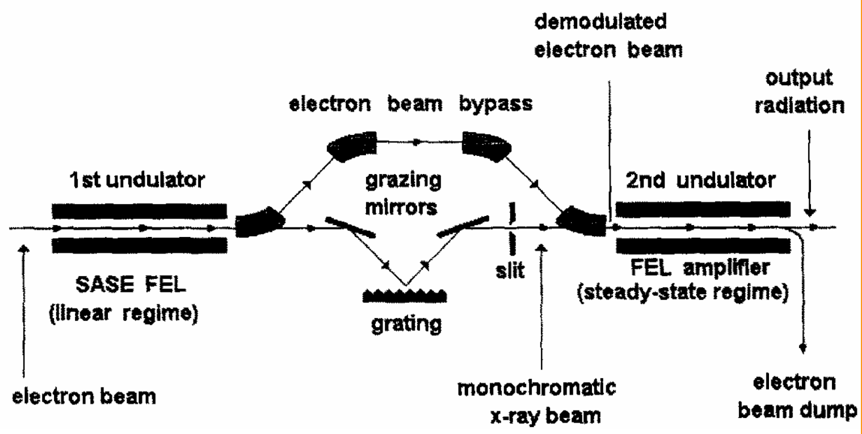
Source: The European XFEL TDR – DESY 2006-097 (2006)

$$\frac{\Delta\omega}{\omega} \sim 2\rho \sim 10^{-3}$$

$$\left(\frac{\Delta\omega}{\omega}\right)_{spike} \sim \frac{1}{\sigma_T \omega} \sim 10^{-5}$$

- Hundreds of longitudinal modes
- A lot of room for improvement
- Self-seeding schemes answer the call for increasing longitudinal coherence

Single-bunch self-seeding with a four-crystal monochromator

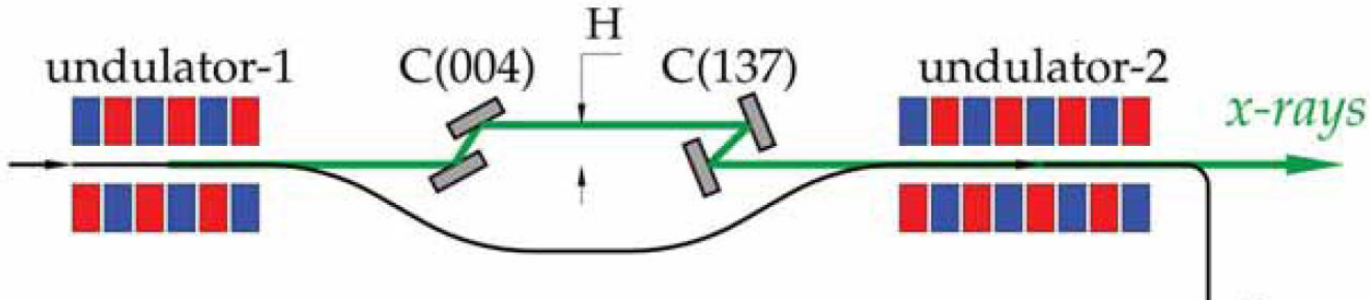


Source: J. Feldhaus et al., Optics Comm. 140 (1997)

- Method historically introduced for soft x-rays in: J. Feldhaus et al., Optics Comm. 140, 341 (1997)
  - Linearly amplified SASE is filtered through a grating monochromator
  - Electron beam bypass washes-out beam microbunch, makes up for x-ray path delay by grating and allows for grating installation
  - Demodulated beam is seeded in the output undulator

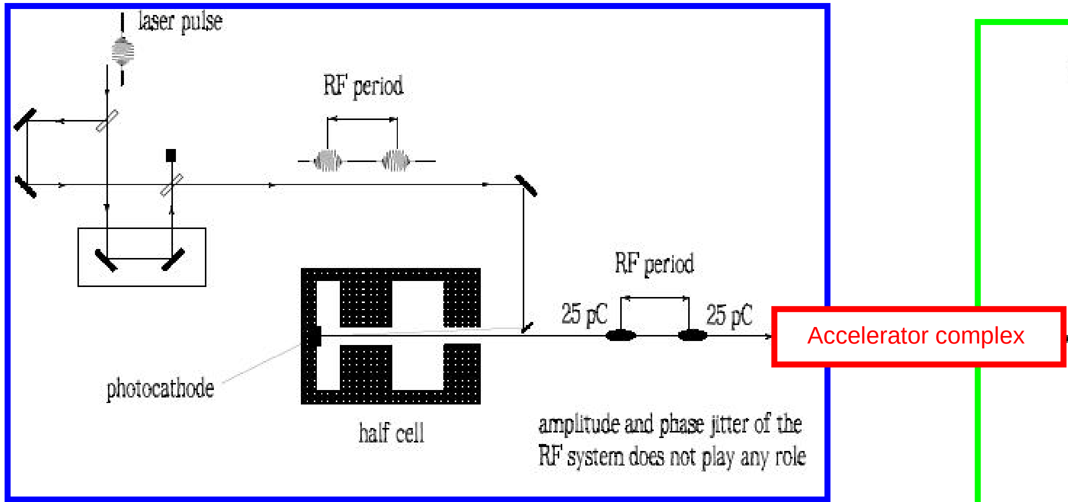
- Grating monochromator substituted by crystal monochromator for applications to hard-x rays: [E. Saldin, E. Schneidmiller, Yu. Shvyd'ko and M. Yurkov, NIM A 475 357 (2001)]

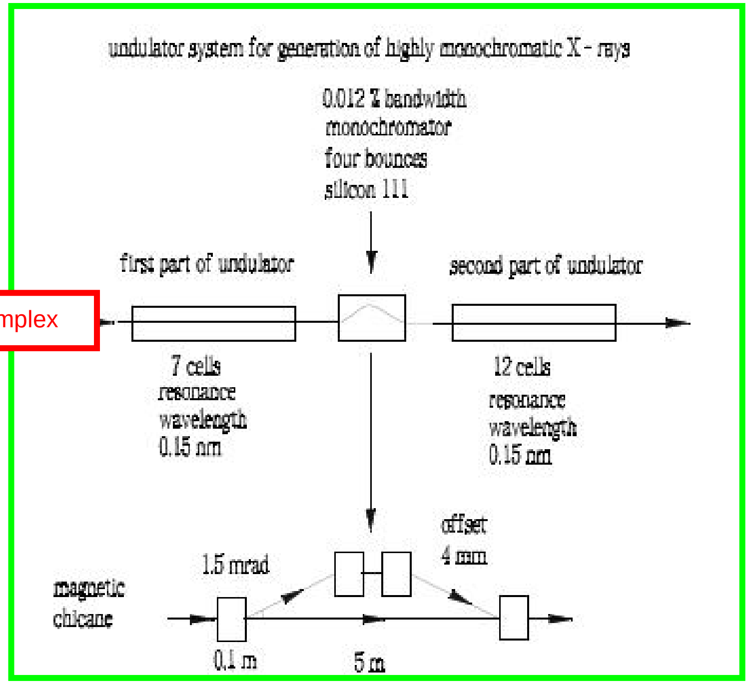
- Extra x-rays path due to monochromator ~1cm. Long electron bypass (tens of meters) needed

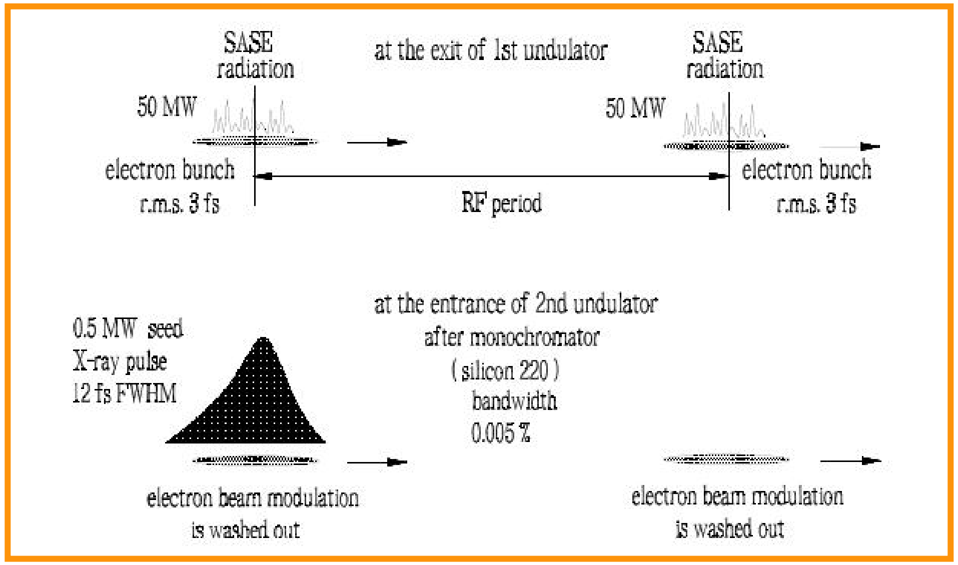


Source: The European XFEL TDR – DESY 2006-097 (2006)

Double-bunch self-seeding with a four-crystal monochromator







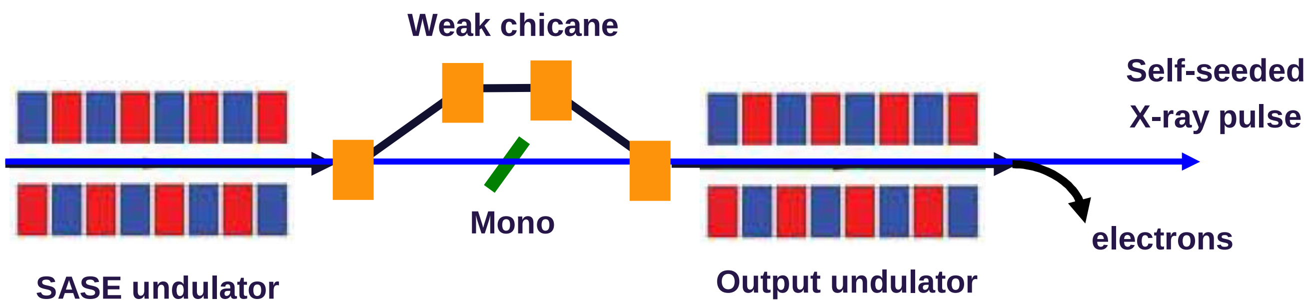
- Method based on production of two identical bunches separated by an RF period [see O. Grimm K. Klose and S. Schreiber, EPAC 2006, THPCH150, Edimburgh]
- Developed independently in:

  - G. Geloni, V. Kocharyan and E. Saldin, DESY 10-053

  - Y. Ding, Z. Huang and R. Ruth, Phys.Rev.ST Accel.Beams, vol. 13, p. 060703 (2010)

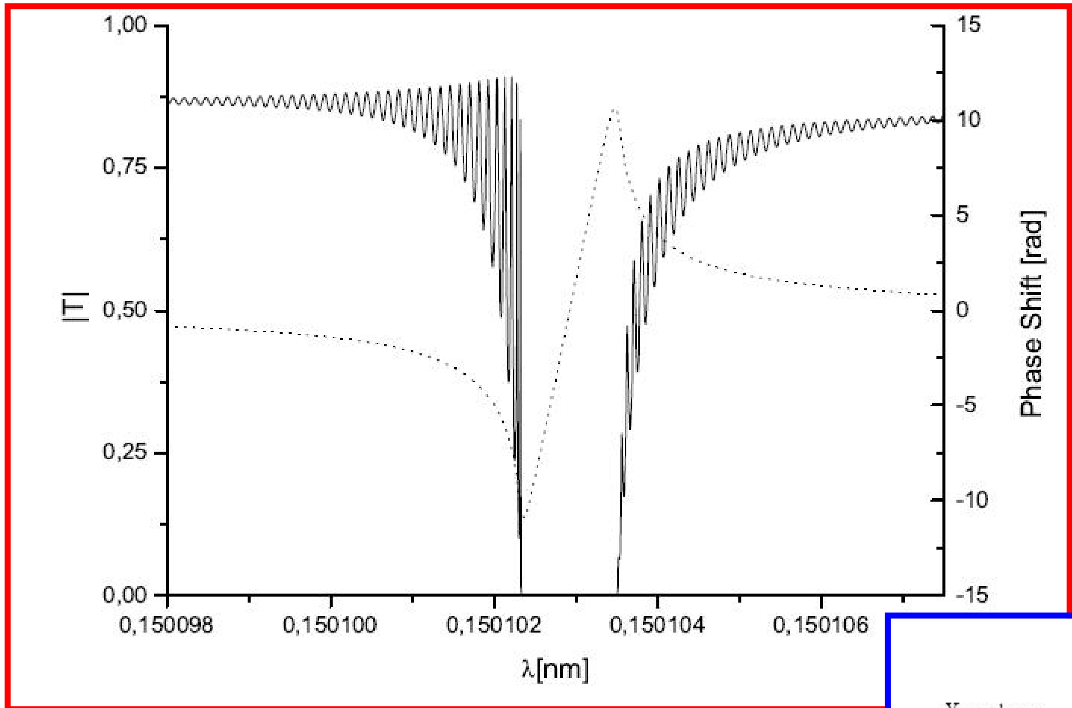
Self-seeding techniques with a single-crystal monochromator

Working principle (I)



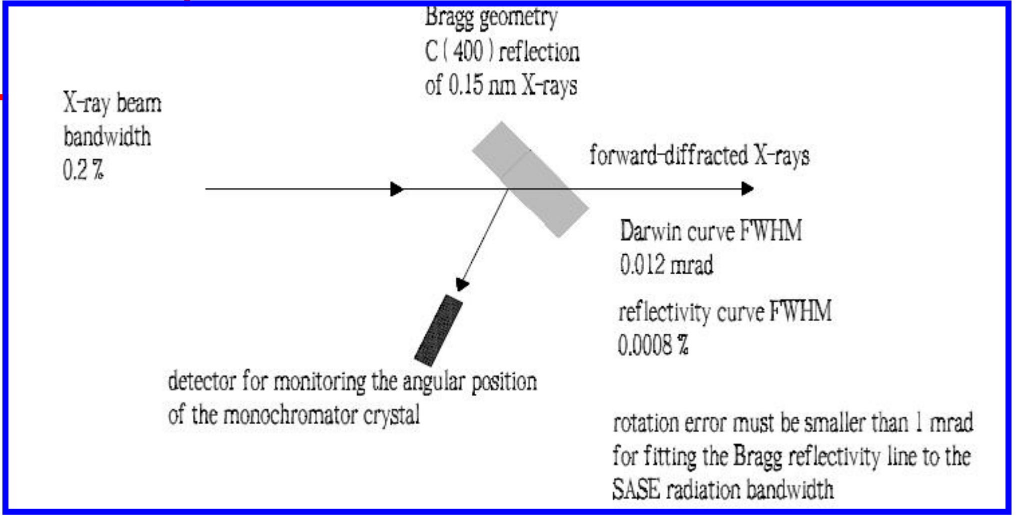
- First part: usual SASE → linear regime pulse
- Weak chicane (R_{56} ~ several μm) for:
  - Creating a small offset (a few mm) to insert the monochromator
  - Washing out the electron beam microbunching
  - Acting as a tunable delay line
- The photon pulse from SASE goes through the monochromator
- Photon and electron pulses are recombined

Working principle (II)



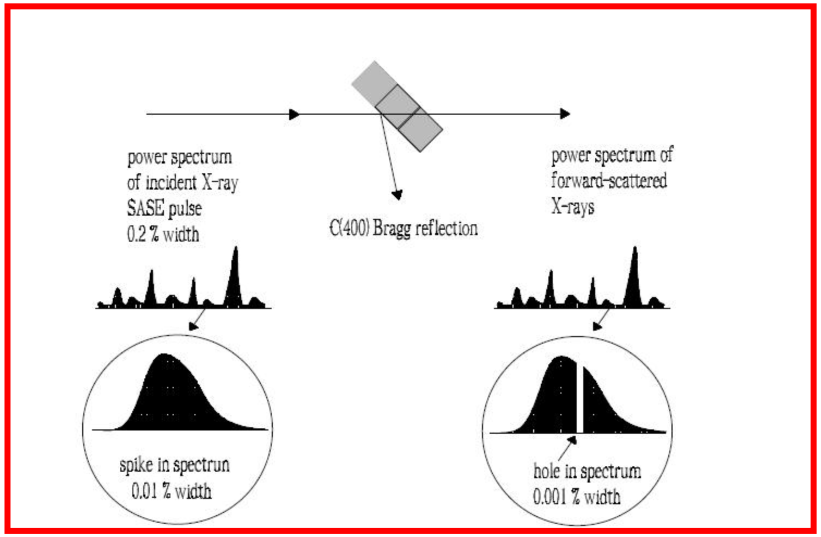
The monochromator hardware is constituted by a single crystal in Bragg geometry. The forward diffracted beam is considered. Transmissivity (modulus and phase) can be calculated using the dynamical theory of X-ray diffraction

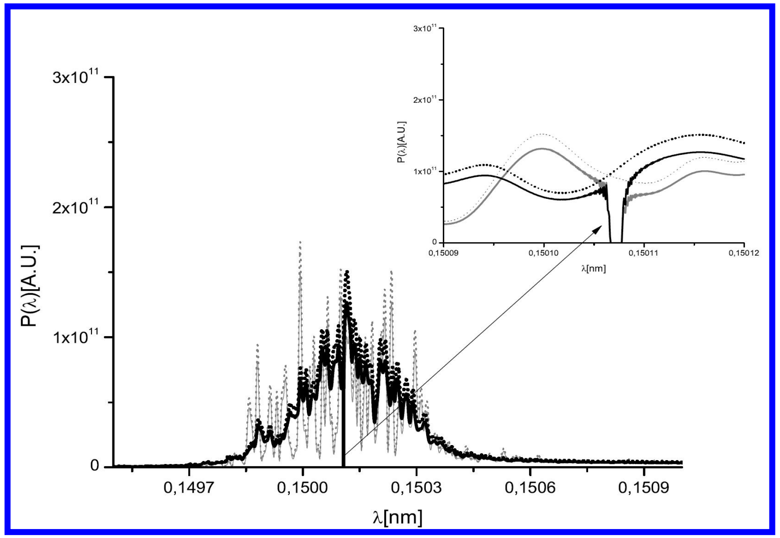
Alignment can be performed With the help of a suitable detector. This Fixes the central frequency of the filter transmittance

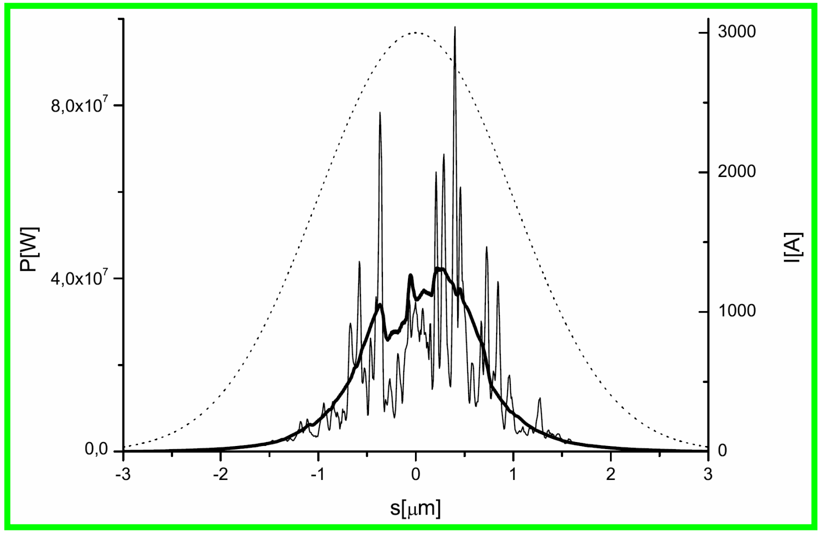


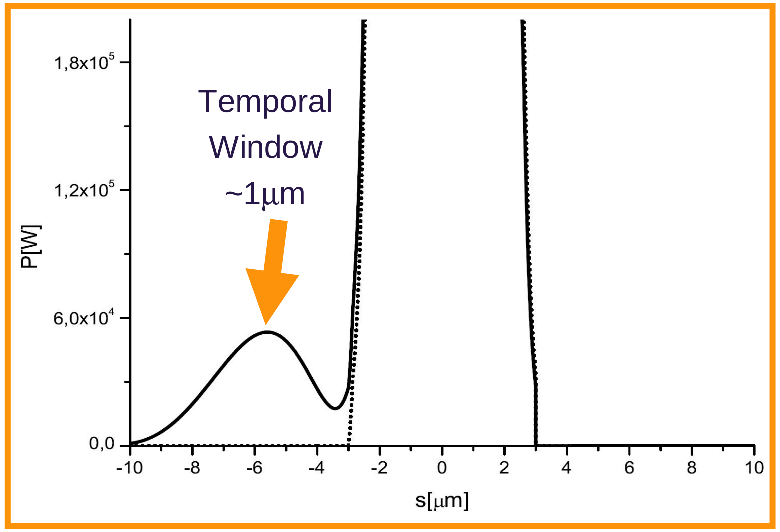
Working principle (III)

The single-crystal monochromator principle: frequency vs. time

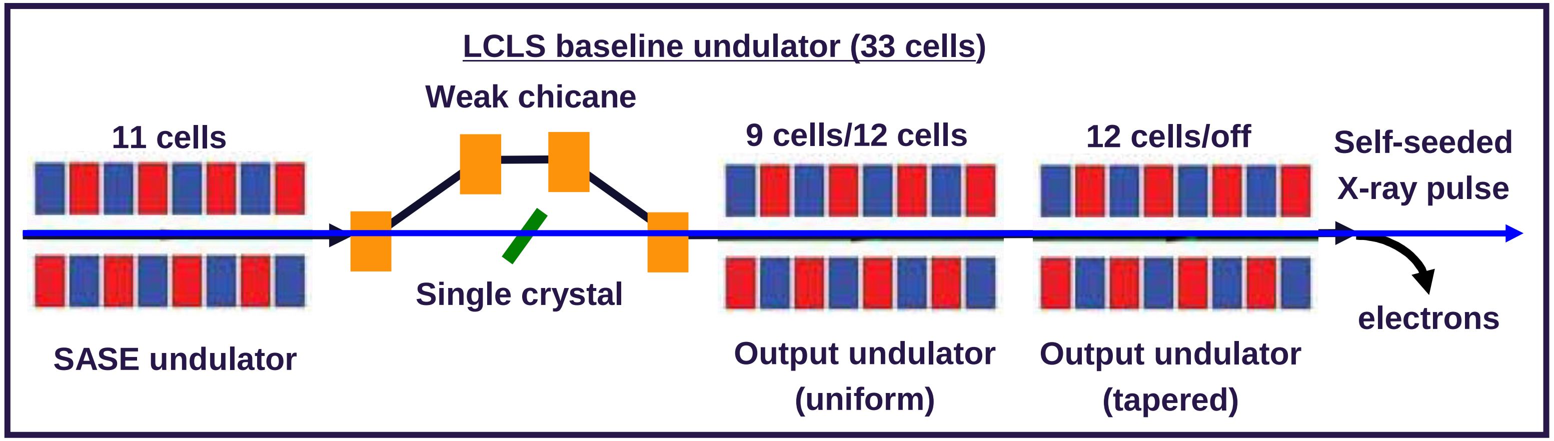








Feasibility study for LCLS (I)



Single mode hard X-ray FEL

100 GW-level
Fully-coherent
Self-seeded
X-ray pulse

$4 \cdot 10^{11}$ photons
5 fs (FWHM)
at 0.15 nm

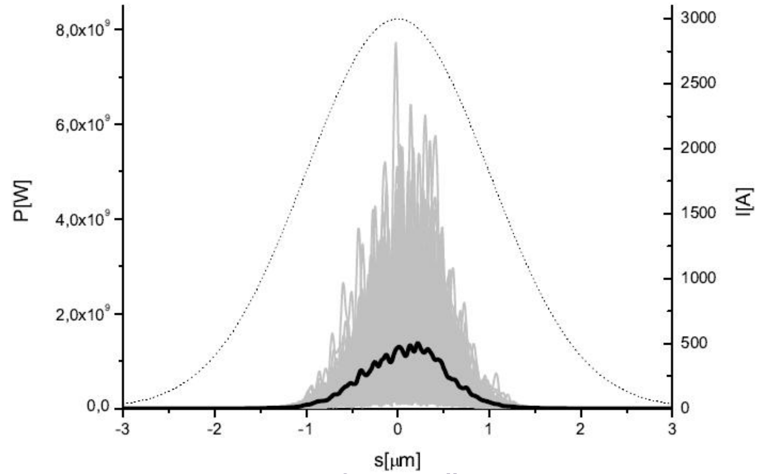
low charge
(0.02 nC) mode of
operation

Parameters for the low-charge mode of operation at LCLS

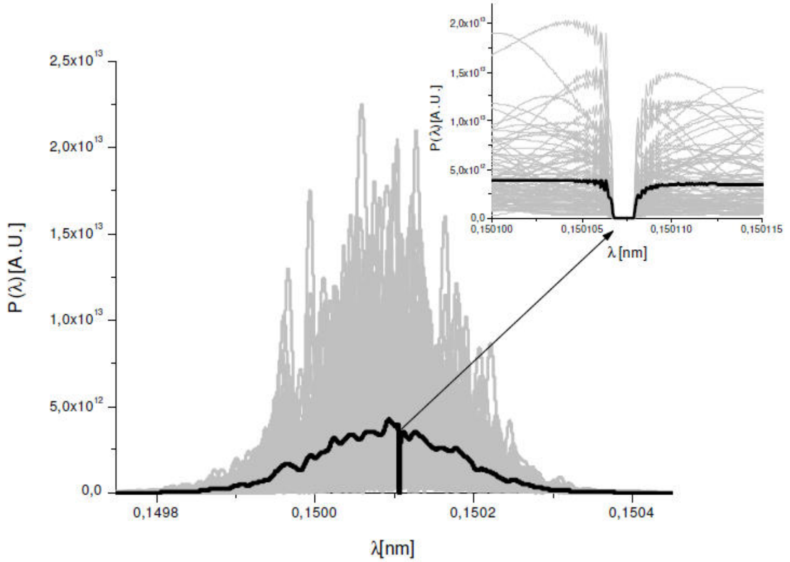
	Units	
Undulator period	mm	30
K parameter (rms)	-	2.466
Wavelength	nm	0.15
Energy	GeV	13.6
Charge	nC	0.02
Bunch length (rms)	μm	1
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

- 4m-long magnetic chicane
- R_{56}=12µm

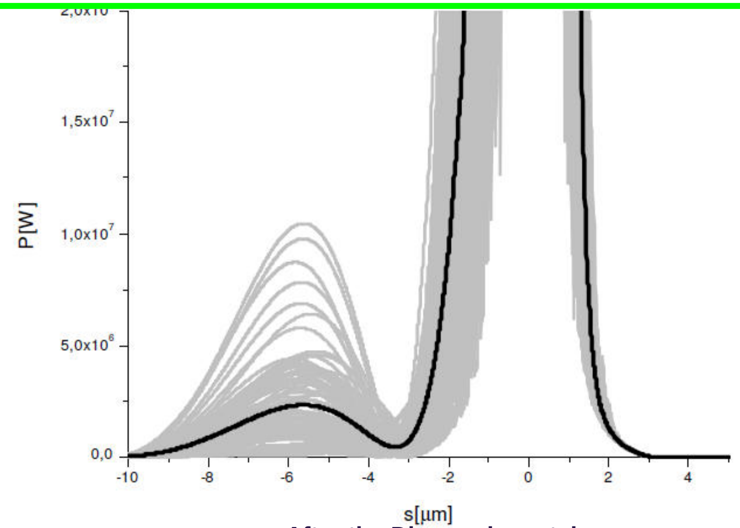
Feasibility study for LCLS (II)



After 11 cells



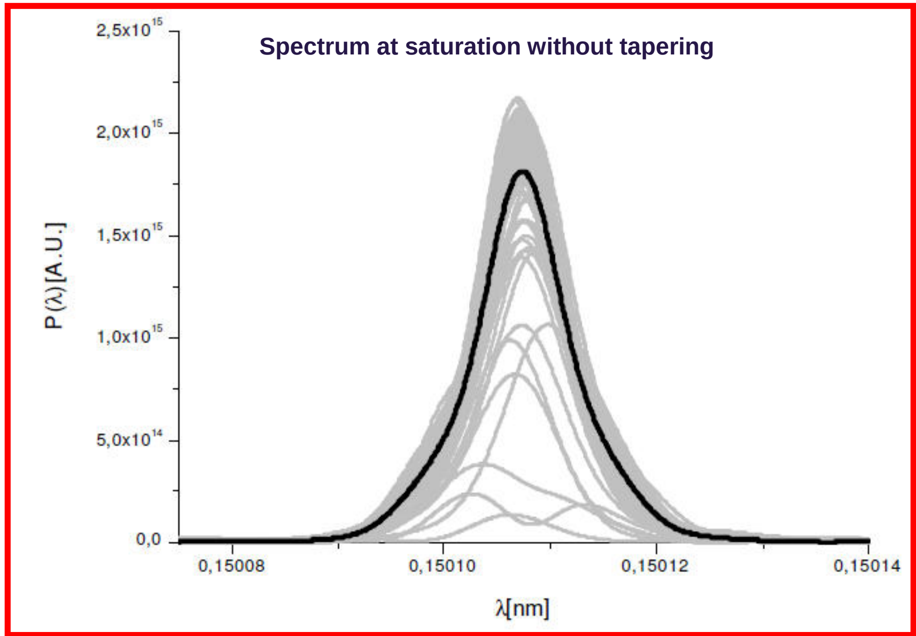
After the Diamond crystal

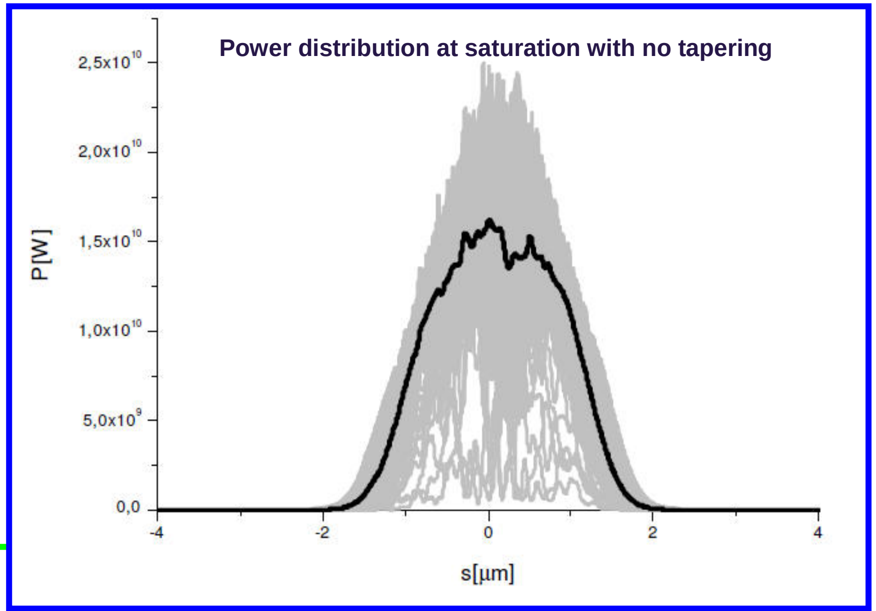


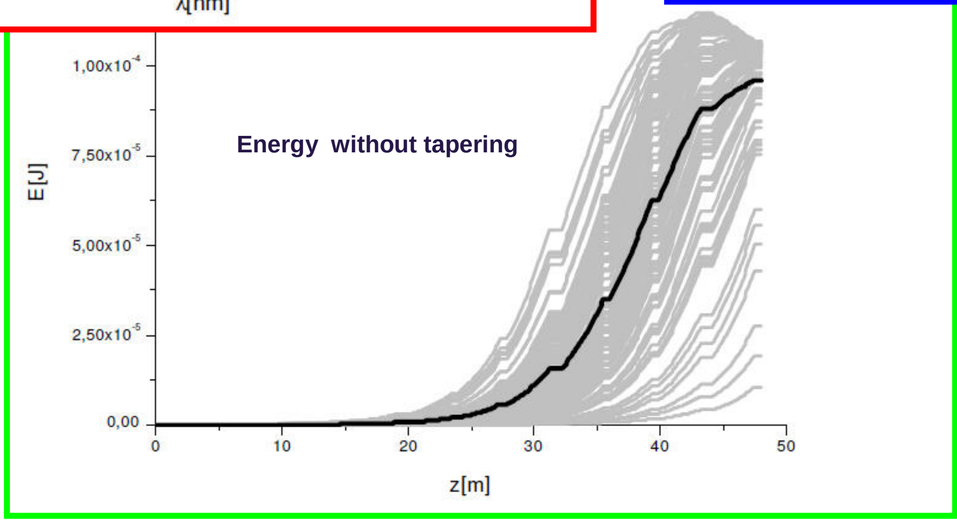
After the Diamond crystal

Efficient seeding mechanism (monochromatic tail much larger than shot noise) is achieved

Feasibility study for LCLS (III)

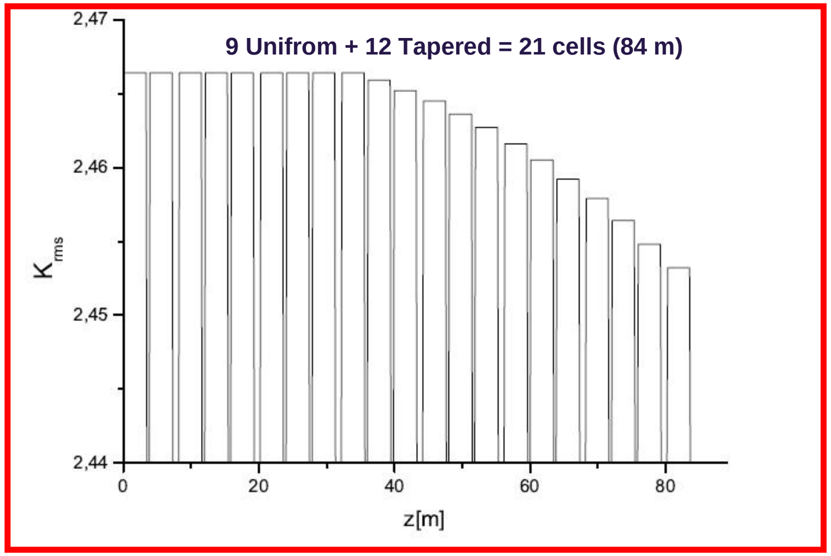


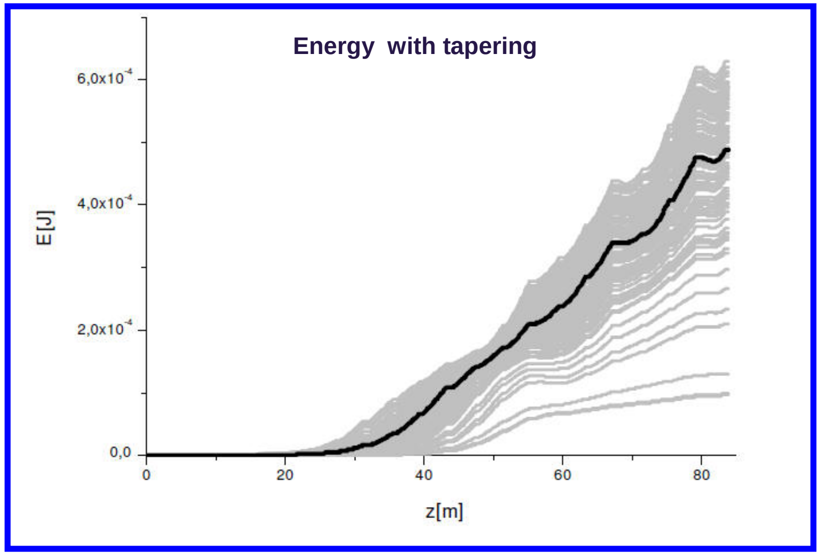


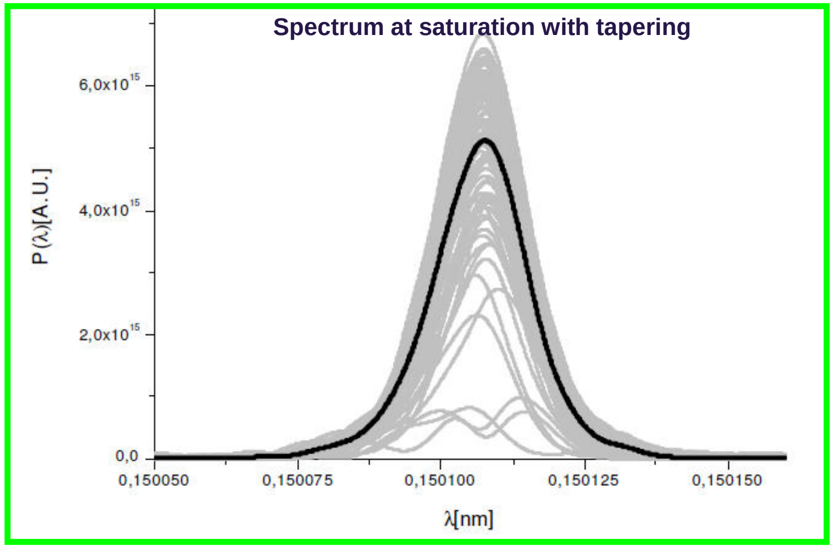


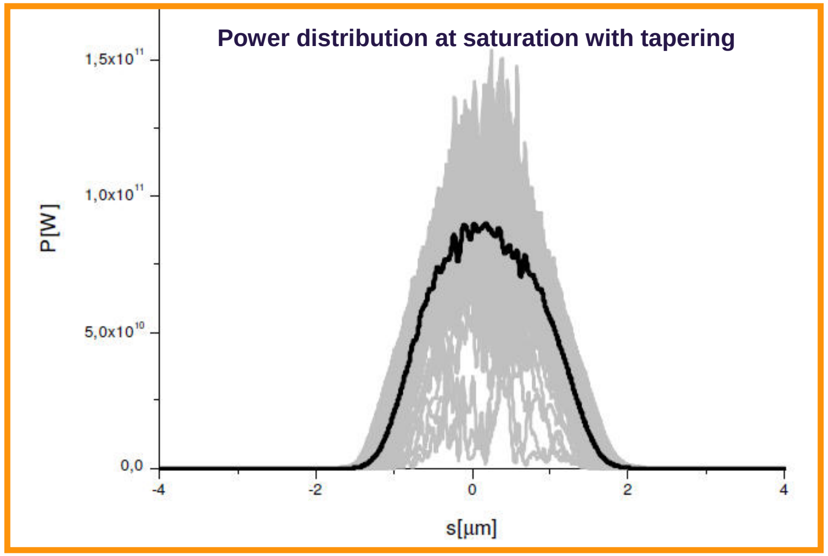
12 cells
Output
Undulator
(no tapering)

Feasibility study for LCLS (IV)

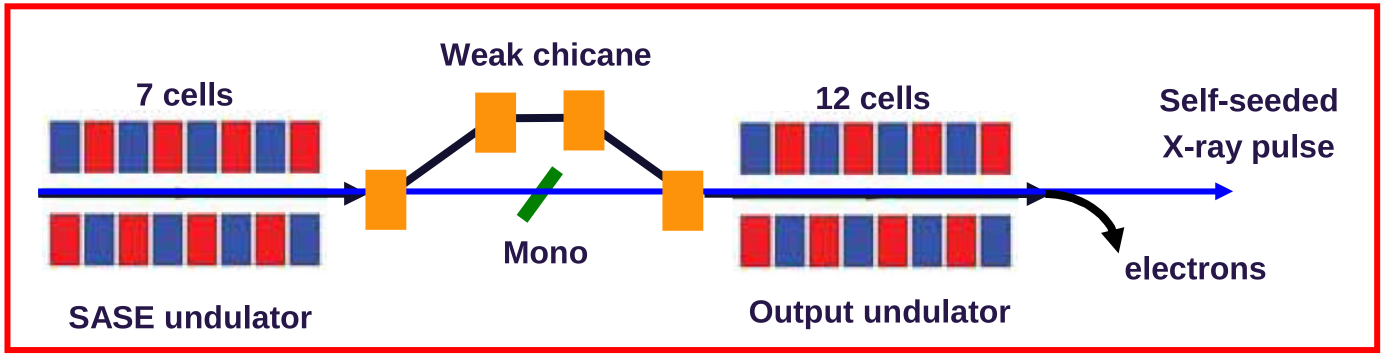








Feasibility study for the European XFEL (I)

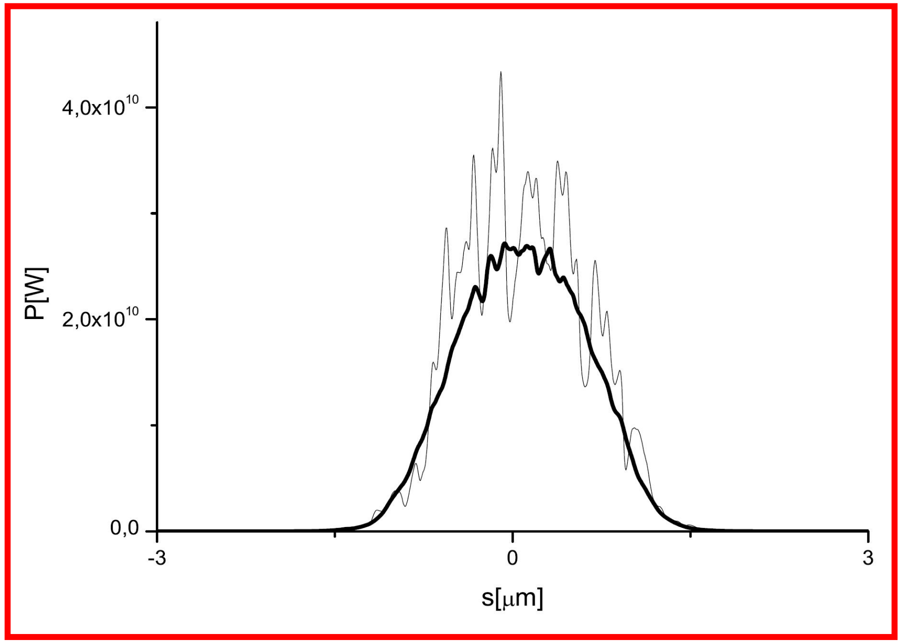


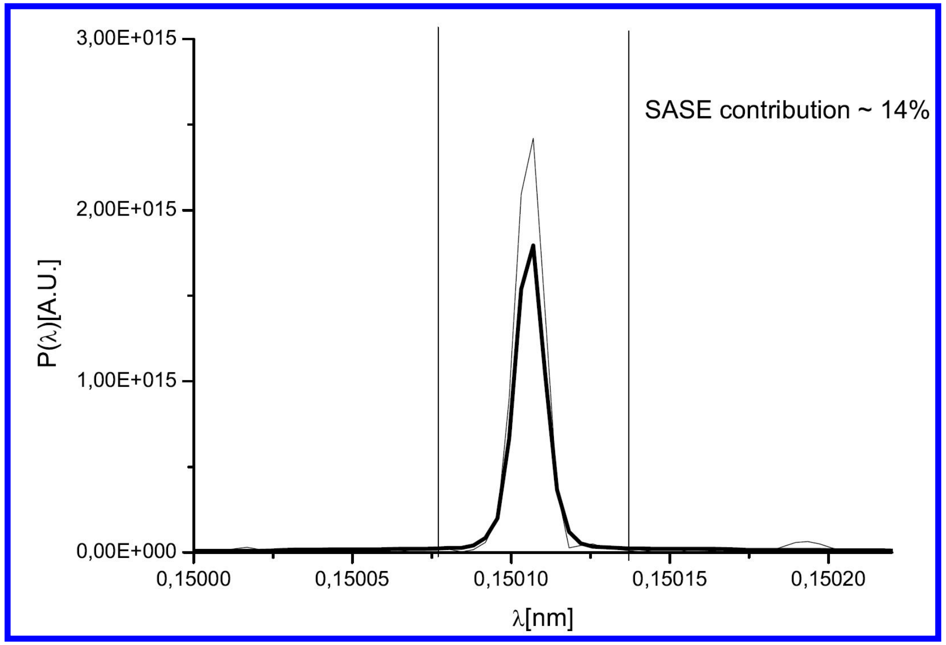
Parameters for the short pulse mode of operation

	Units	
Undulator period	mm	48
K parameter (rms)	-	2.516
Wavelength	nm	0.15
Energy	GeV	17.5
Charge	nC	0.025
Bunch length (rms)	μm	1.0
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

- 5m-long magnetic chicane
- R_{56}=12µm

Feasibility study for the European XFEL (II)





About 30000 bunches/s vs. 10 bunches/s

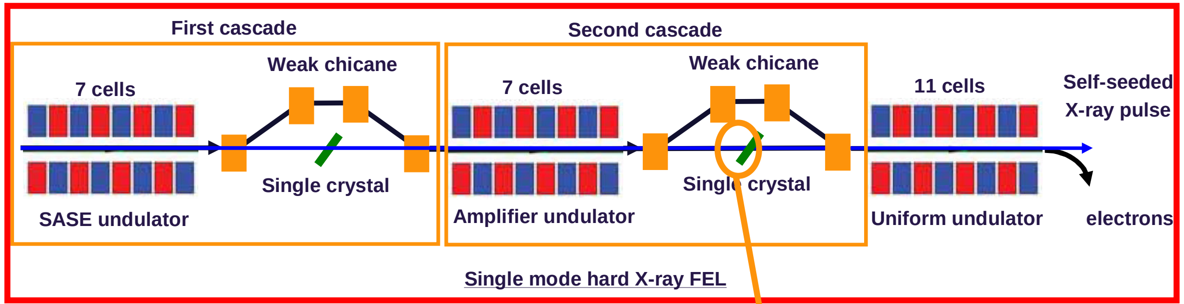
→ Heat loading much more severe for European XFEL

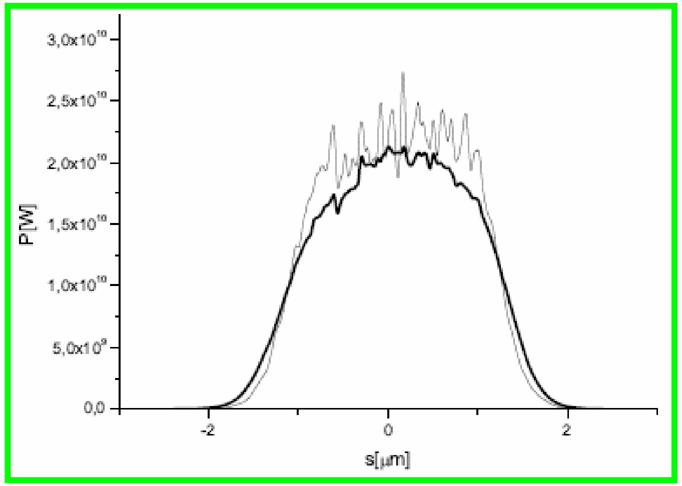
→ Cannot increase length of first undulator part

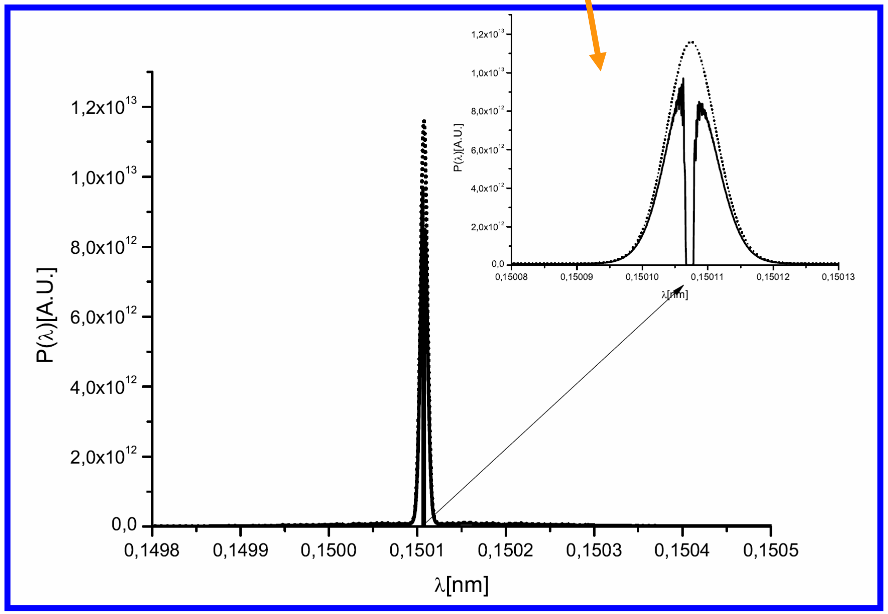
→ Relevant SASE contribution

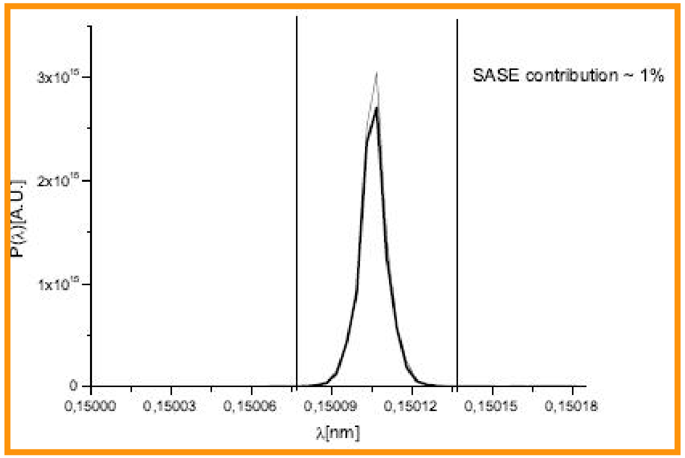
Feasibility study for the European XFEL (III)

Three-undulator setup





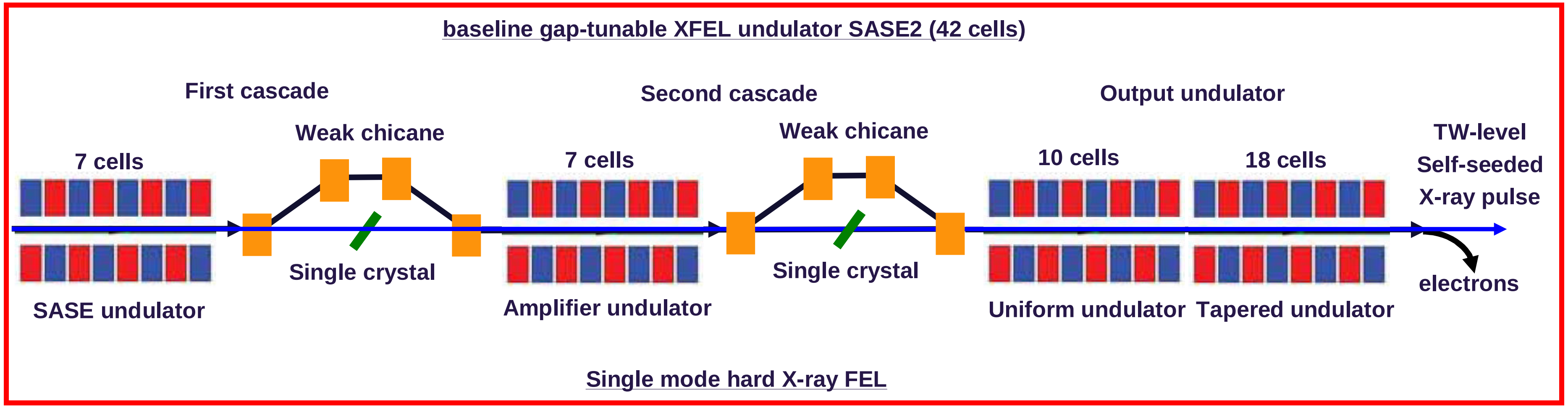




Small SASE contribution: at the second filter BW nearly Fourier limited already

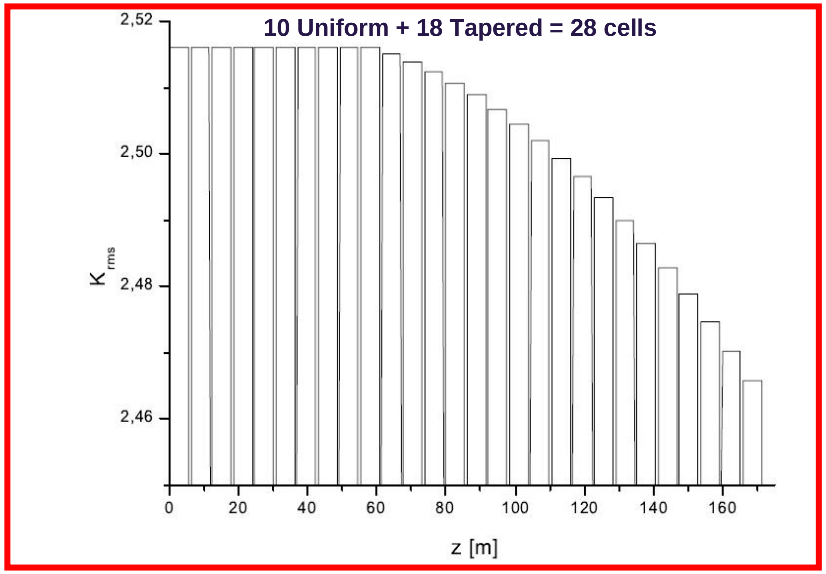
Feasibility study for the European XFEL (IV)

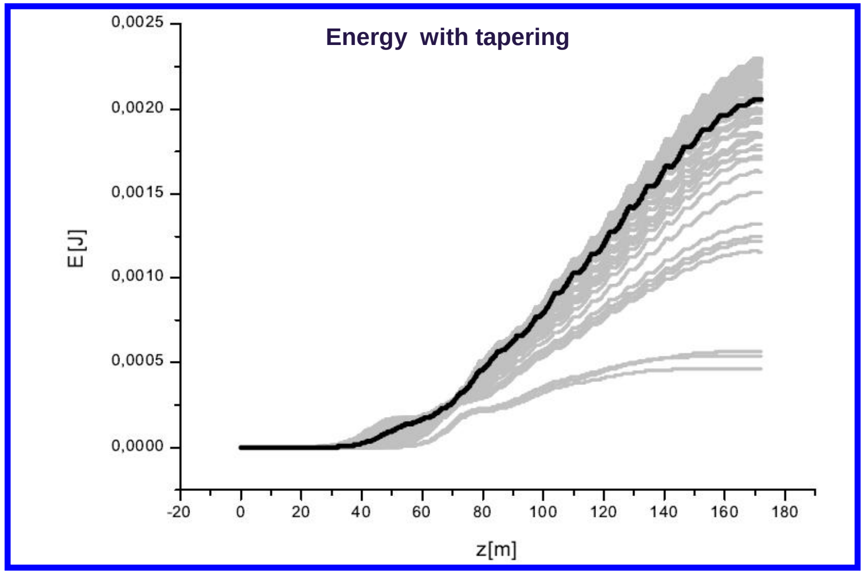
Tapering scheme

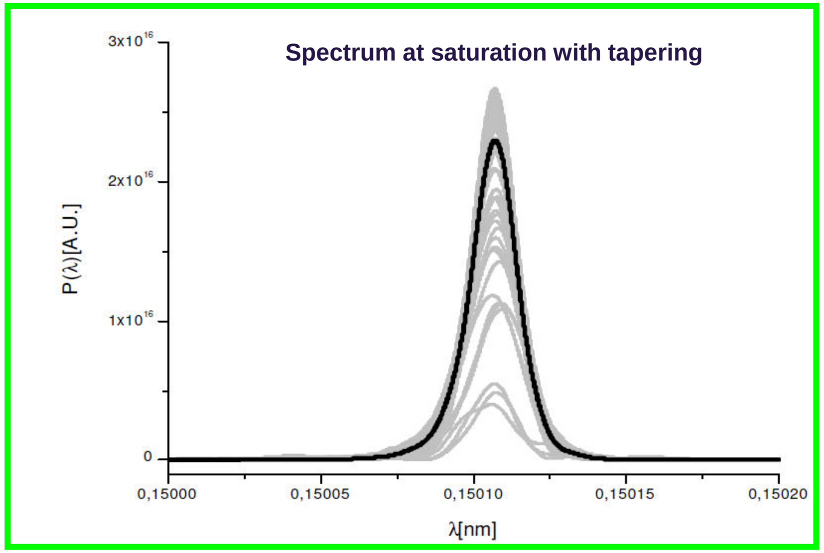


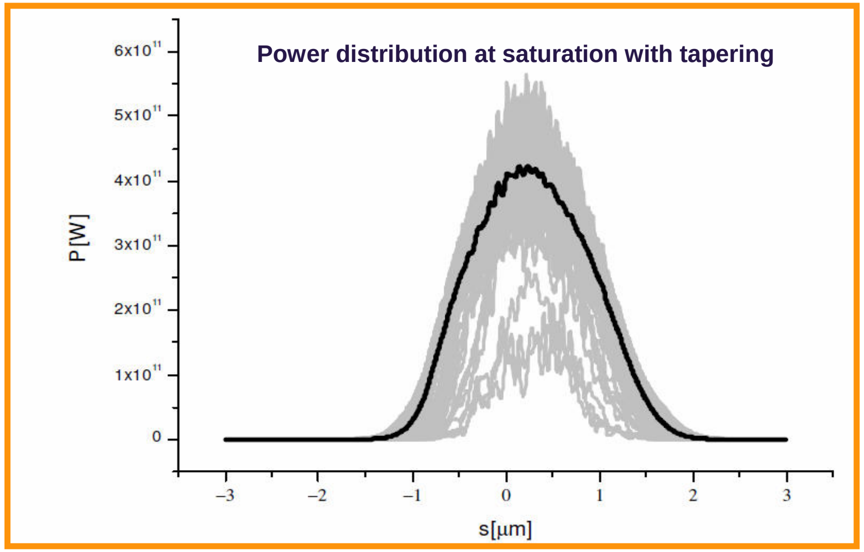
Similarly as for LCLS to increase output power/brightness

Feasibility study for the European XFEL (V)









Conclusions

- Solves the problem of poor longitudinal coherence for hard x-ray FELs
  - Bandwidth down to 10^{-4} for Q=0.02 nC
- Low cost
  - No need for long electron bypass
  - No need for special photo-injector setup
  - Only needs: 1 weak chicane + 1 crystal within a single segment
- Robust
  - Baseline mode of operation is not disturbed