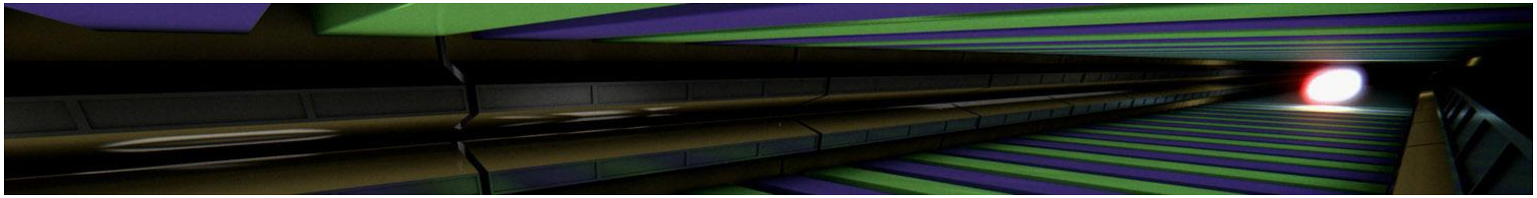

Hard X-ray self-seeding for XFELs: towards coherent FEL pulses

Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin

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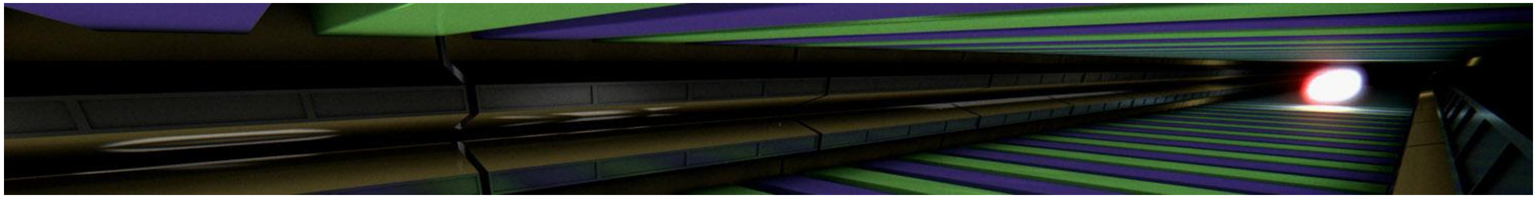
  - Working principle and theory
  - Feasibility study examples (LCLS, European XFEL)
  - Doublet generation
  - Extensions to soft X-rays

- Conclusions



Self-seeding techniques and their importance for XFELs

Self-seeding techniques and their importance for XFELs

SASE pulses, baseline mode of operation: poor longitudinal coherence

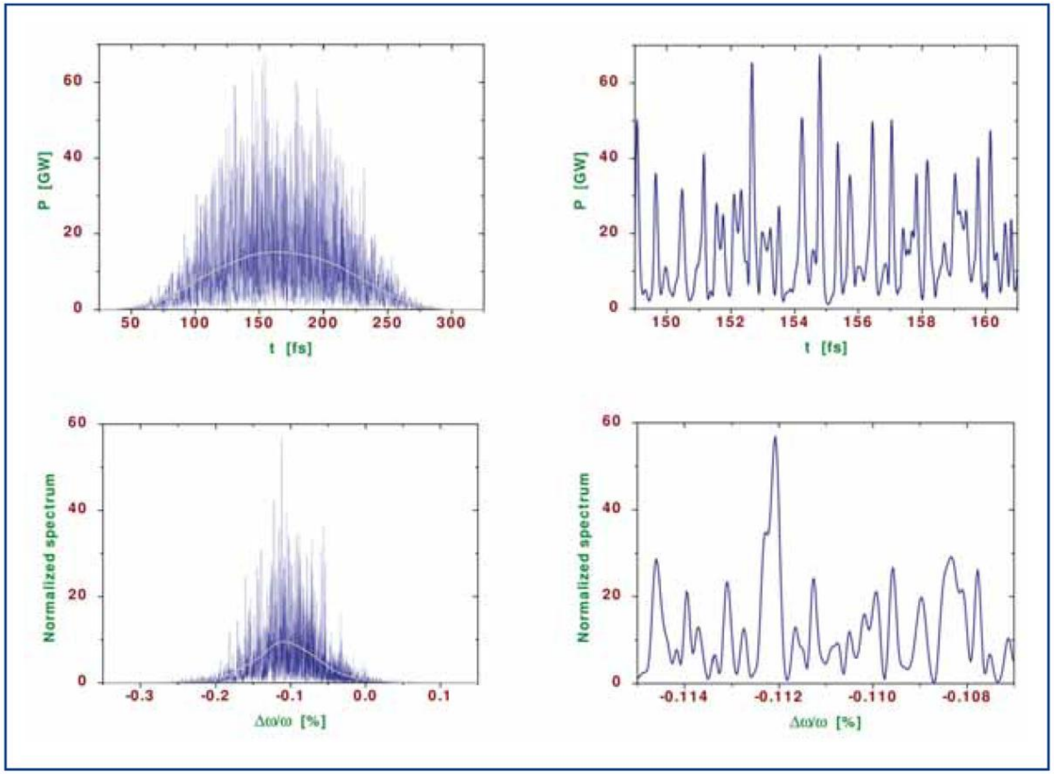


Figure 5.2.4 *Temporal (top) and spectral (bottom) structure for 12.4 keV XFEL radiation from SASE 1. Smooth lines indicate averaged profiles. Right side plots show enlarged view of the left plots. The magnetic undulator length is 130 m.*

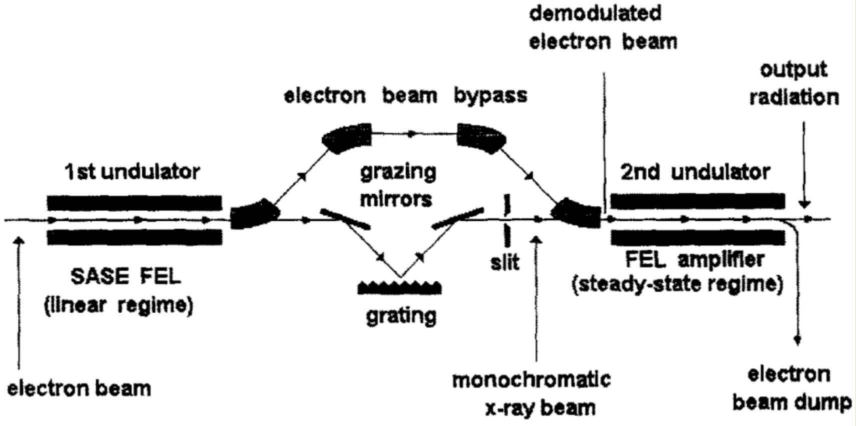
Source: The European XFEL TDR – DESY 2006-097 (2006)

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

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

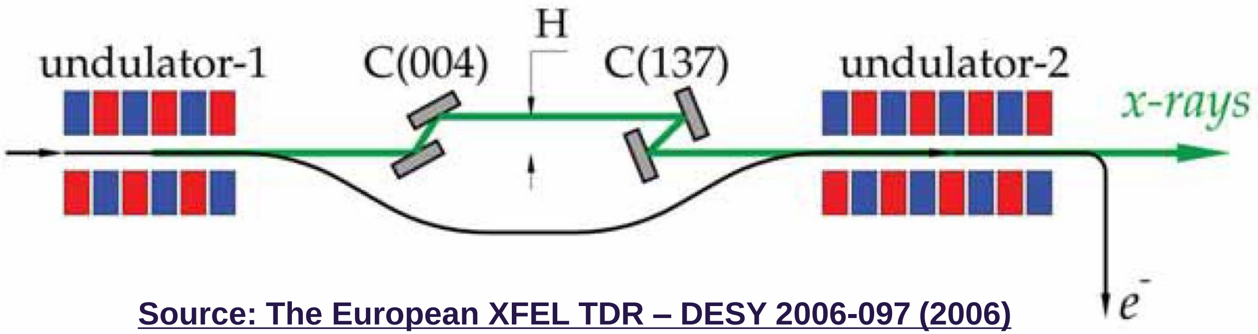
- Hundreds of longitudinal modes
- A lot of room for improvement
- Self-seeding schemes answer the call for increasing longitudinal coherence

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



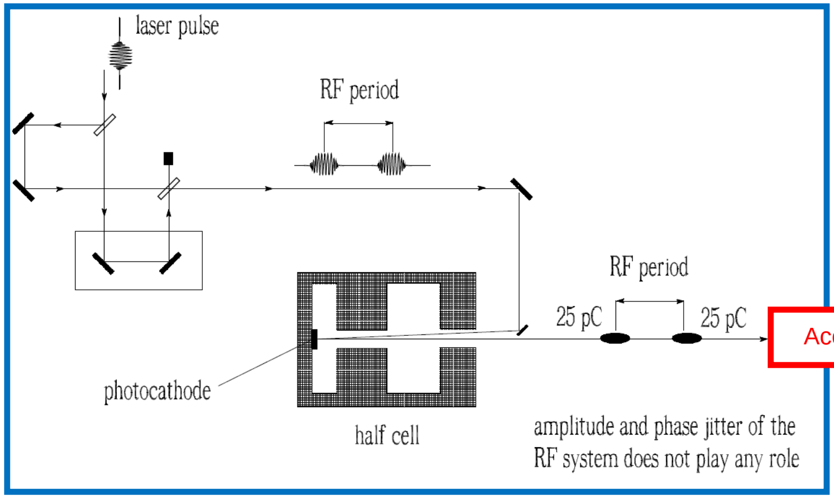
Source: J. Feldhaus et al., Optics Comm. 140 (1997)

- 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

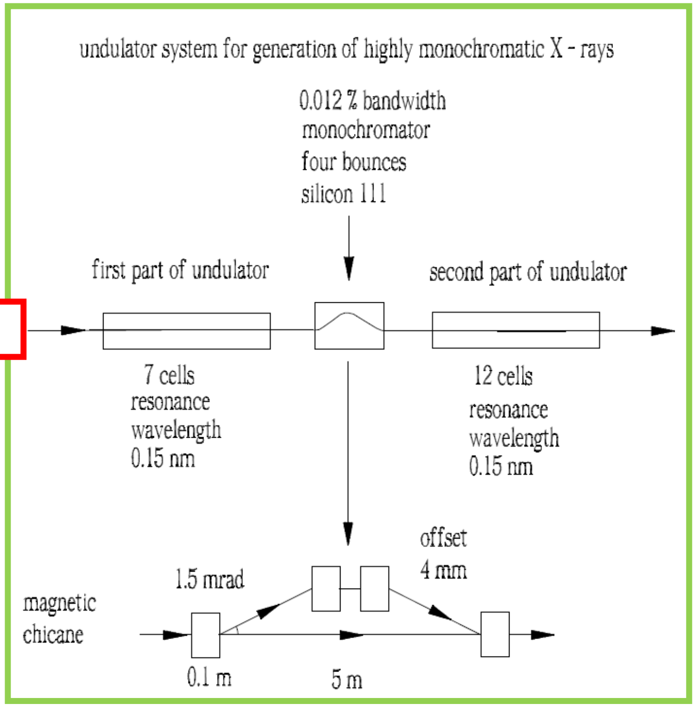


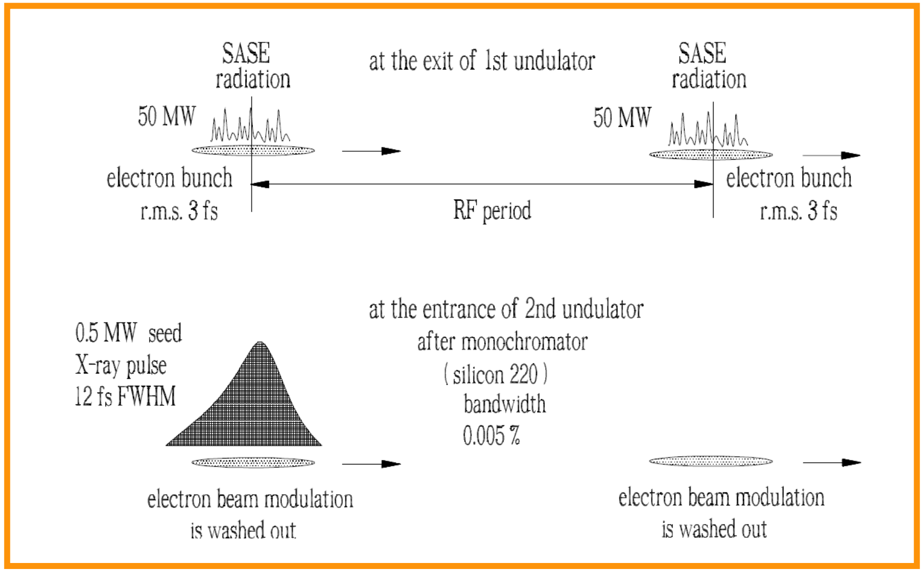
Source: The European XFEL TDR – DESY 2006-097 (2006)

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



Accelerator complex





- 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:

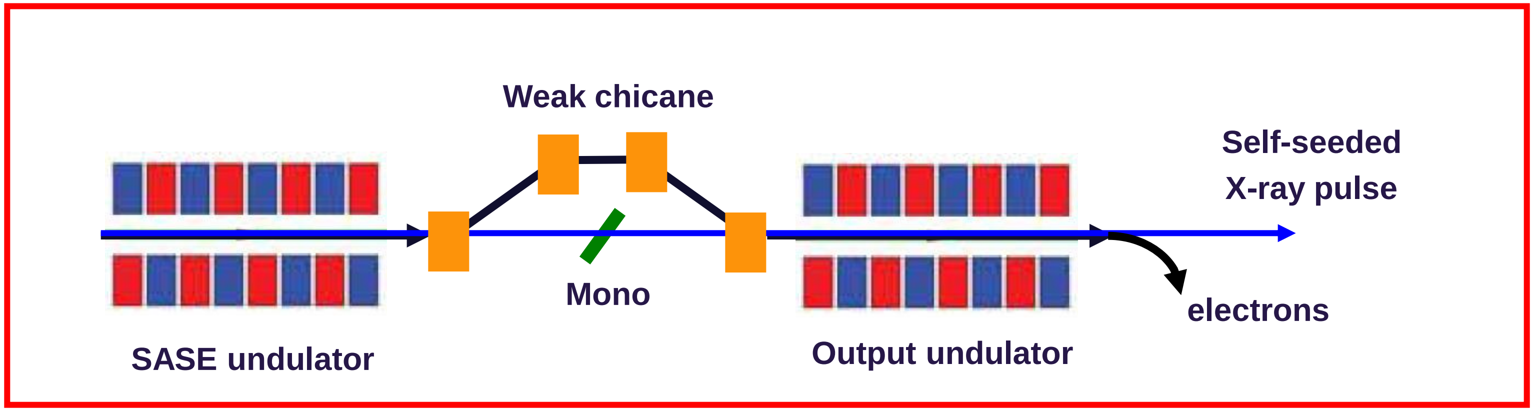
  - G. Geloni, V. Kocharyan and E. Saldin, DESY 10-053

  - 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:

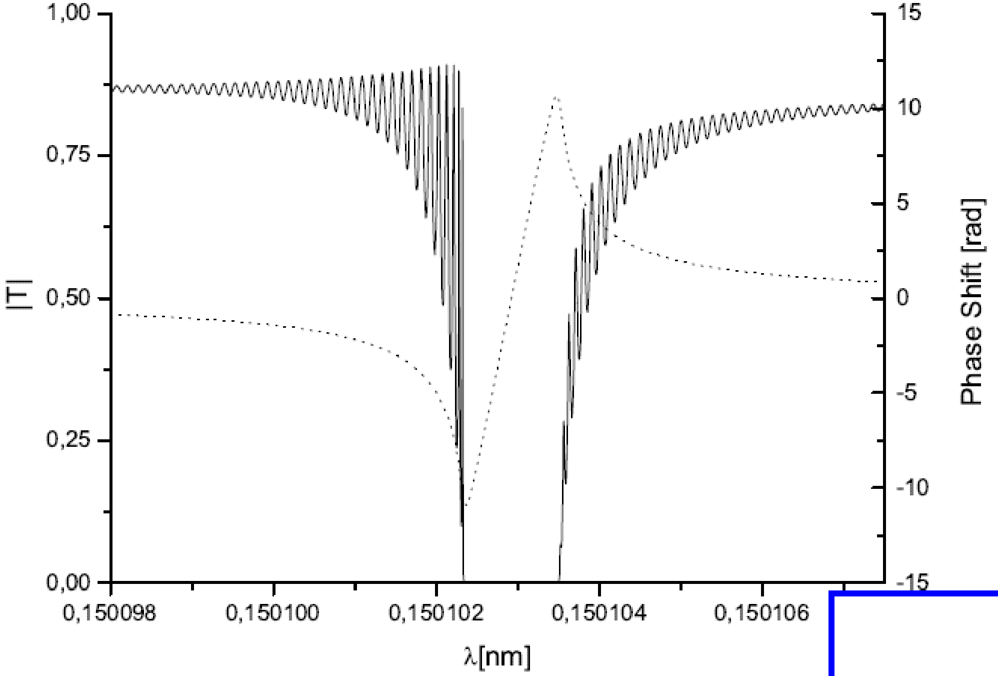
-Working principle-

Working principle (I)



- First part: usual SASE → linear regime pulse
- Weak chicane (R_{56} ~ several μm for short pulse mode of operation) 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

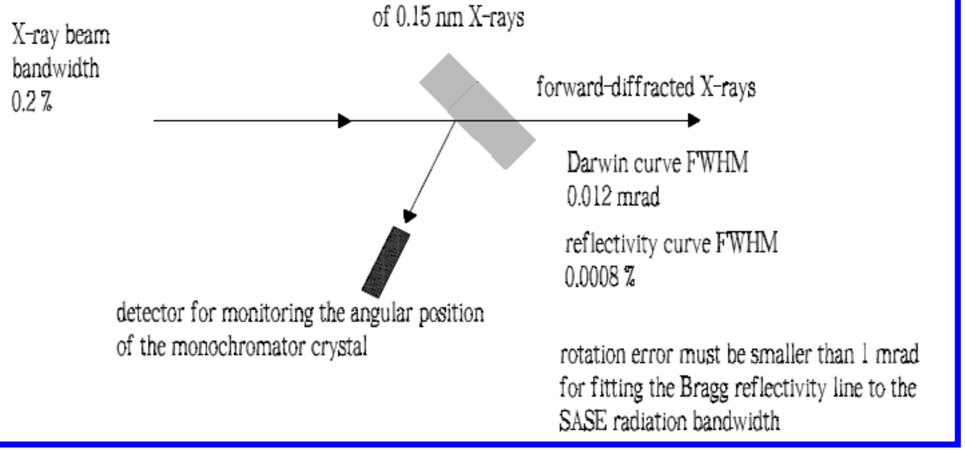
Working principle (II)



The monochromator hardware is constituted by a single crystal in Bragg geometry. The forward diffracted beam is considered. Transmissivity (modulus+phase) → 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

Bragg geometry
C (400) reflection
of 0.15 nm X-rays



detector for monitoring the angular position of the monochromator crystal

rotation error must be smaller than 1 mrad for fitting the Bragg reflectivity line to the SASE radiation bandwidth

Working principle - Intermezzo

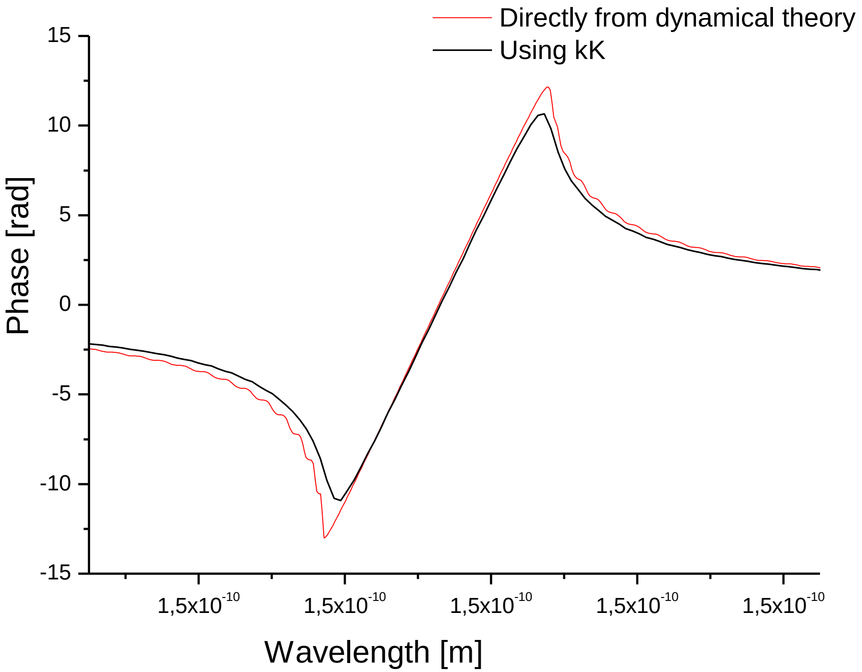
KK realtion link modulus and phase. In fact

$$|T(\eta)| = 2\sqrt{|\eta^2-1|} \times \left|\left(\eta+\sqrt{\eta^2-1}\right)\exp\left[\frac{i\pi t_c}{\Lambda_B}\sqrt{\eta^2-1}\right] - \left(\eta-\sqrt{\eta^2-1}\right)\exp\left[-\frac{i\pi t_c}{\Lambda_B}\sqrt{\eta^2-1}\right]\right|^{-1}$$

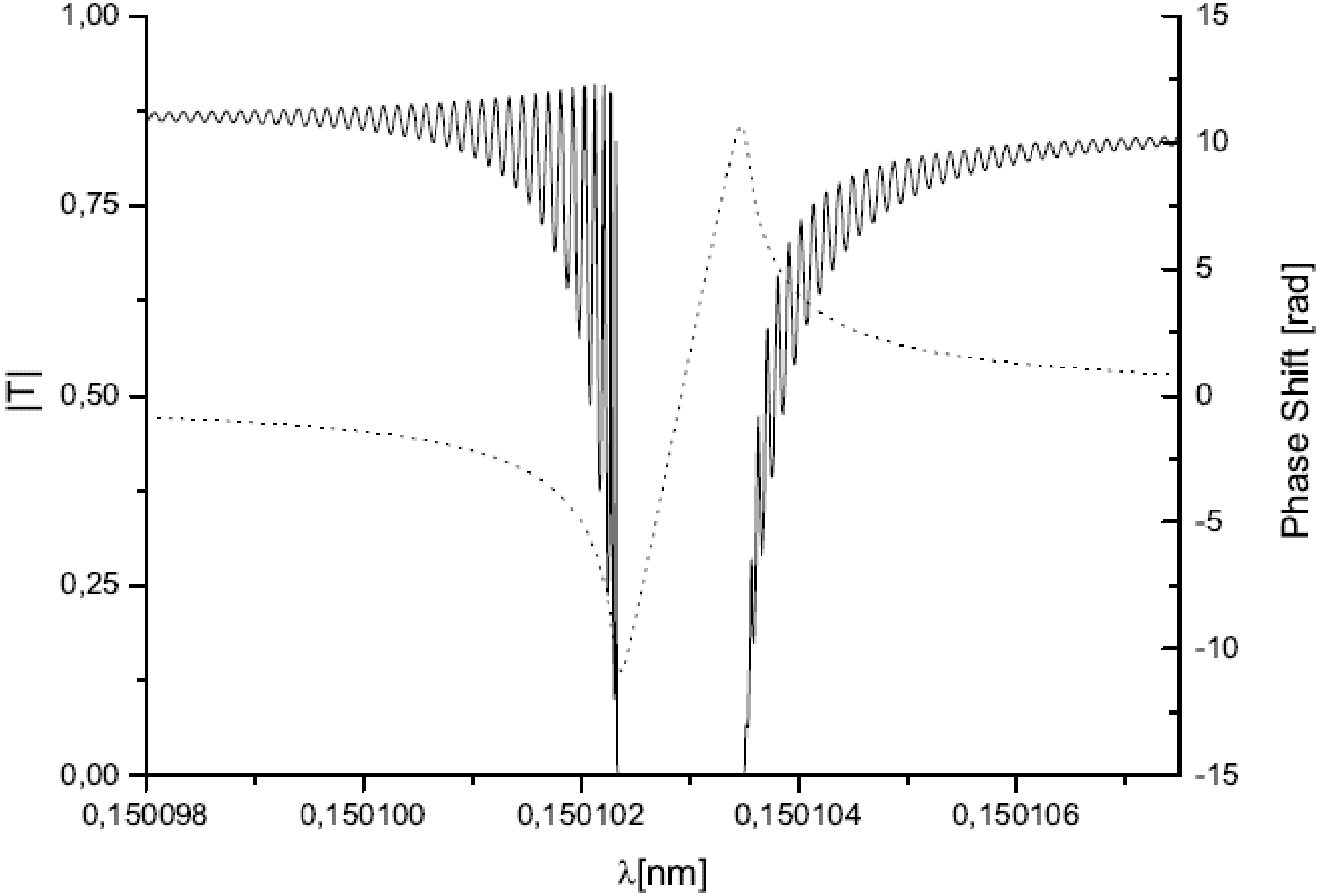
Has no zeros on the upper complex plane (so that ln[|T|] is not singular and we can recover the phase).

So, knowning |T| from e.g. XOP or other easily available programs we use

$$\Phi(\omega) = -\frac{2\omega}{\pi}\mathcal{P}\int_0^\infty \frac{\ln[|T(\omega')|]}{\omega'^2-\omega^2}\,d\omega'$$

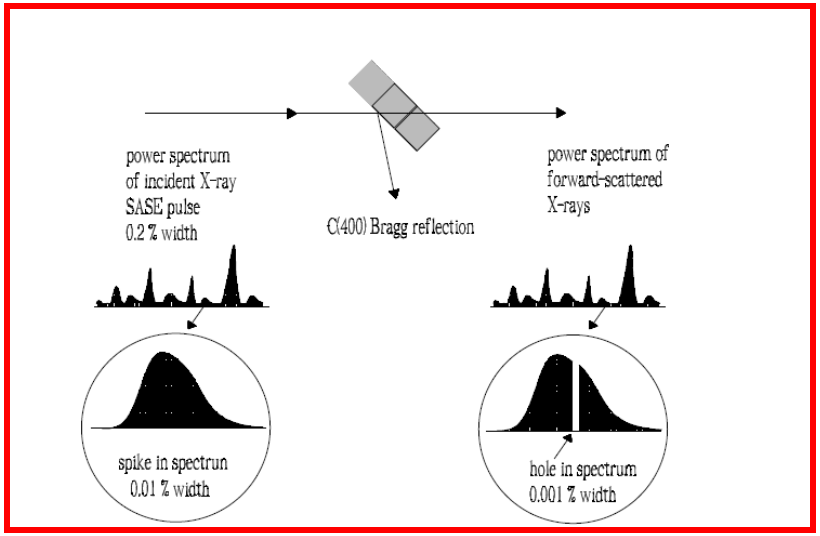


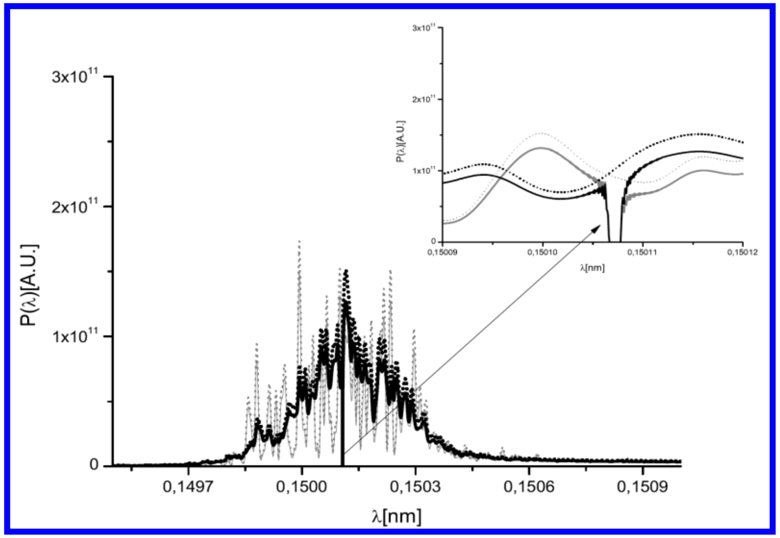
Working principle - Intermezzo

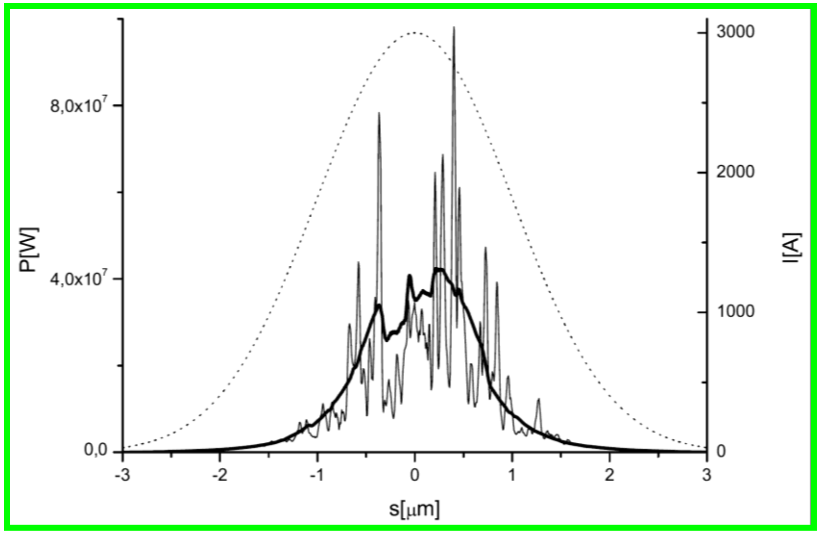


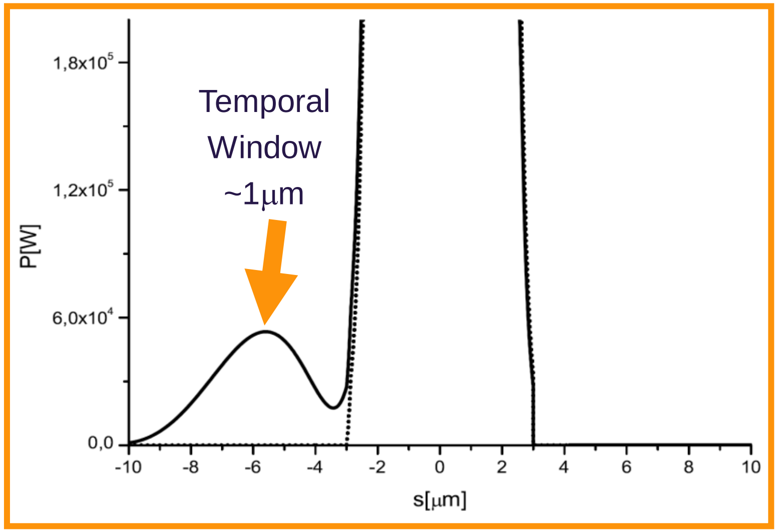
Working principle (III)

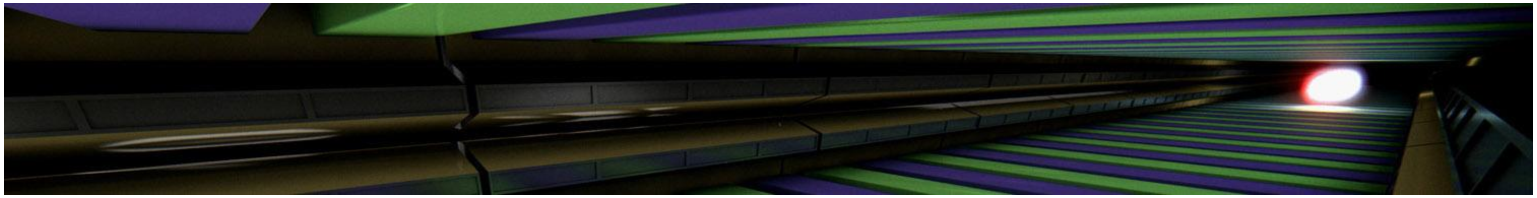
The single-crystal monochromator principle: frequency vs. time








Temporal Window ~1μm

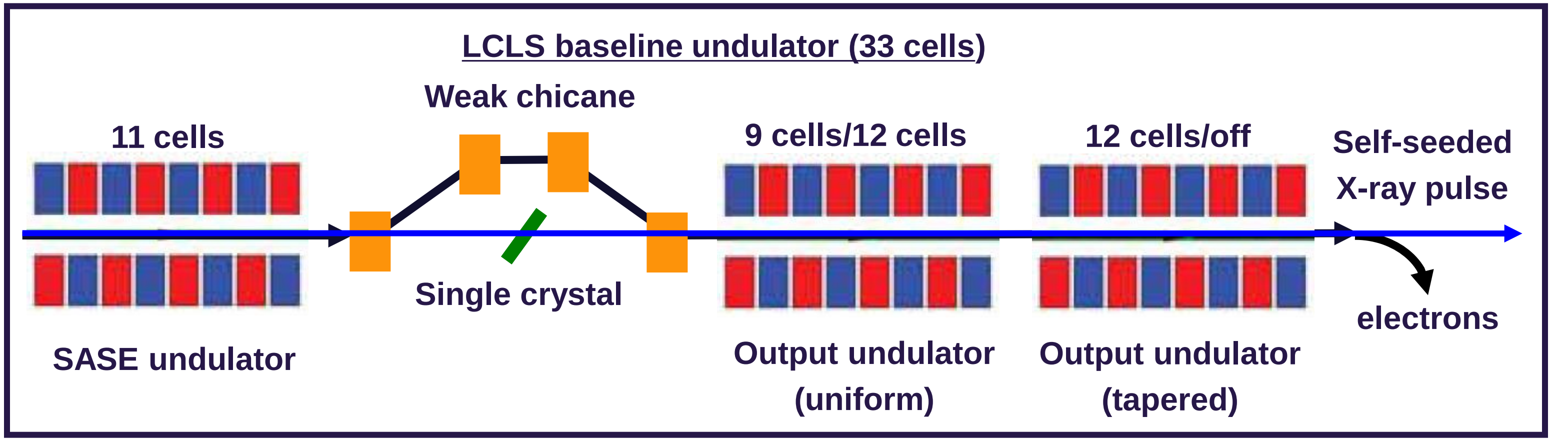


Self-seeding techniques with a single-crystal monochromator:

Feasibility study for the LCLS

-short bunch mode of operation-

Feasibility study for LCLS (I)

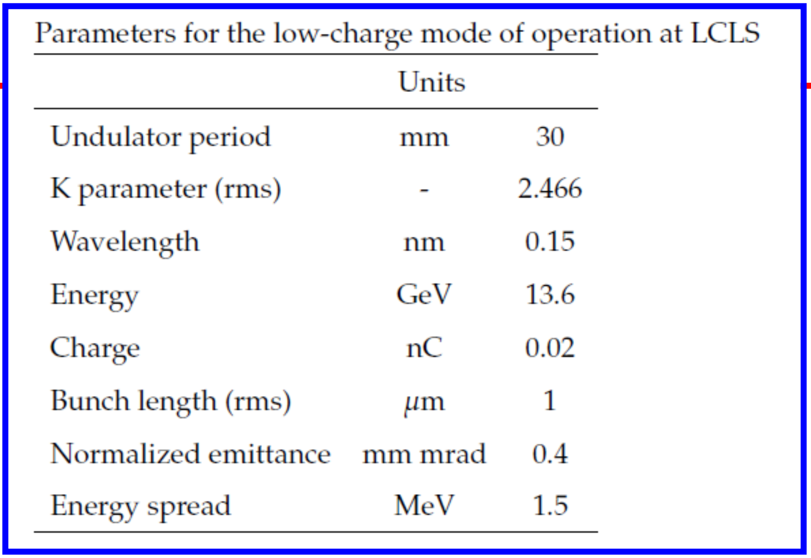


Single mode hard X-ray FEL

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

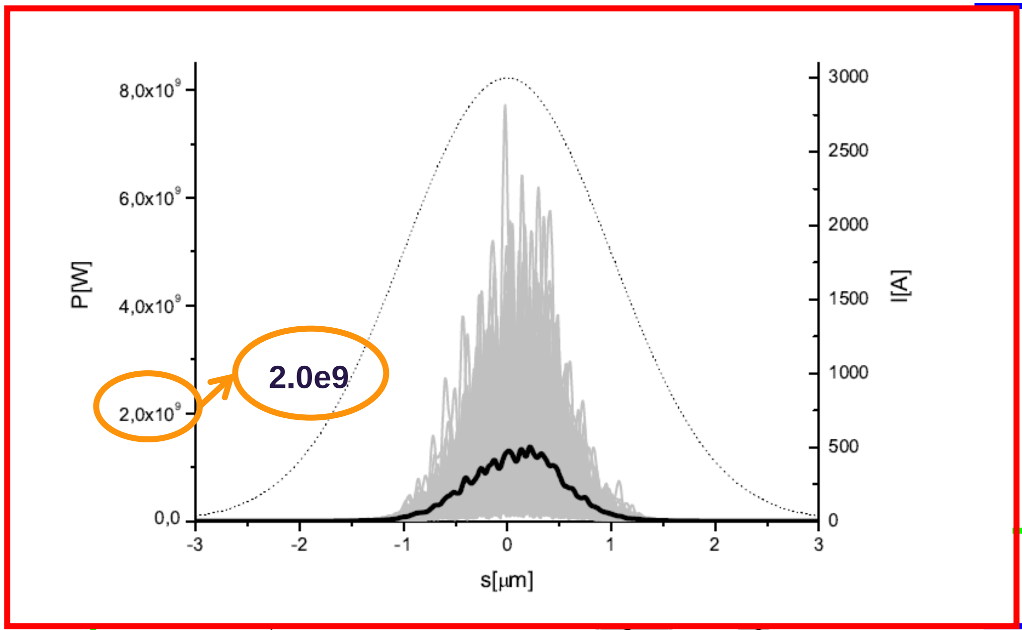


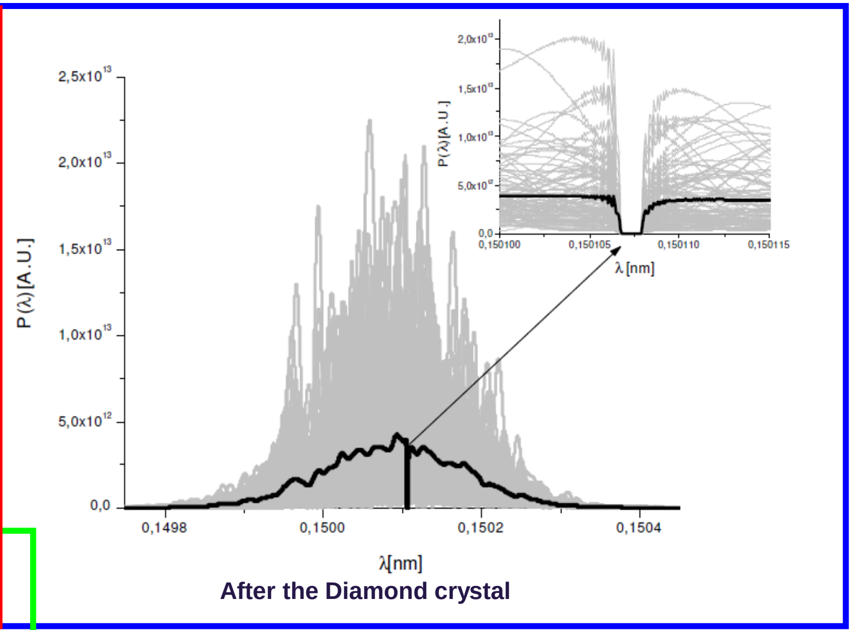
Parameters for the low-charge mode of operation at LCLS

	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

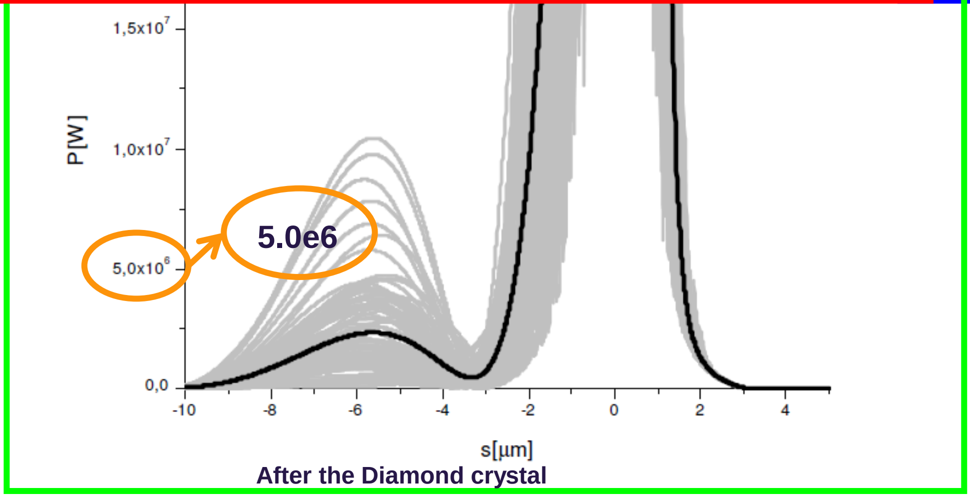
- 4m-long magnetic chicane
- R_{56}=12μm

Feasibility study for LCLS (II)





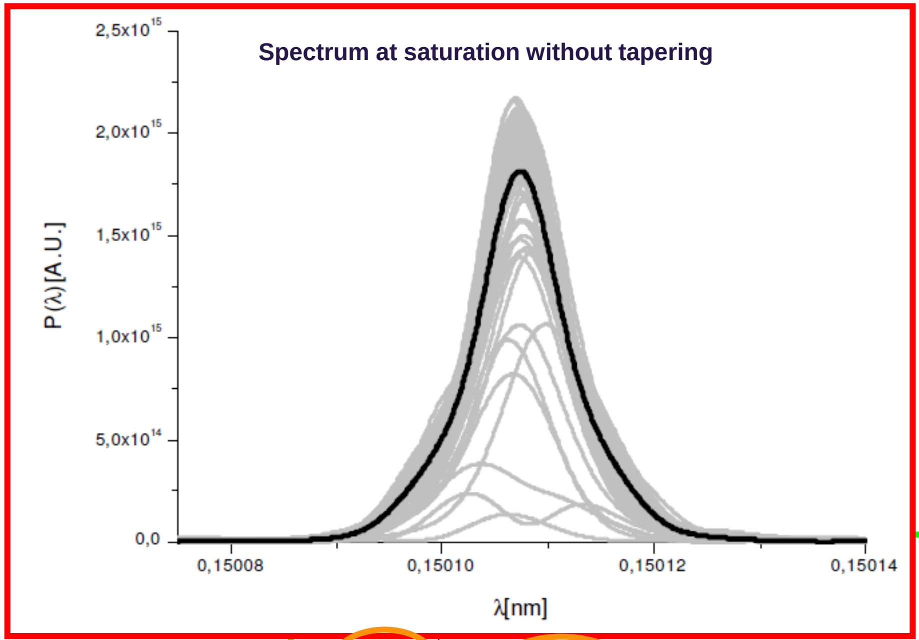
After the Diamond crystal



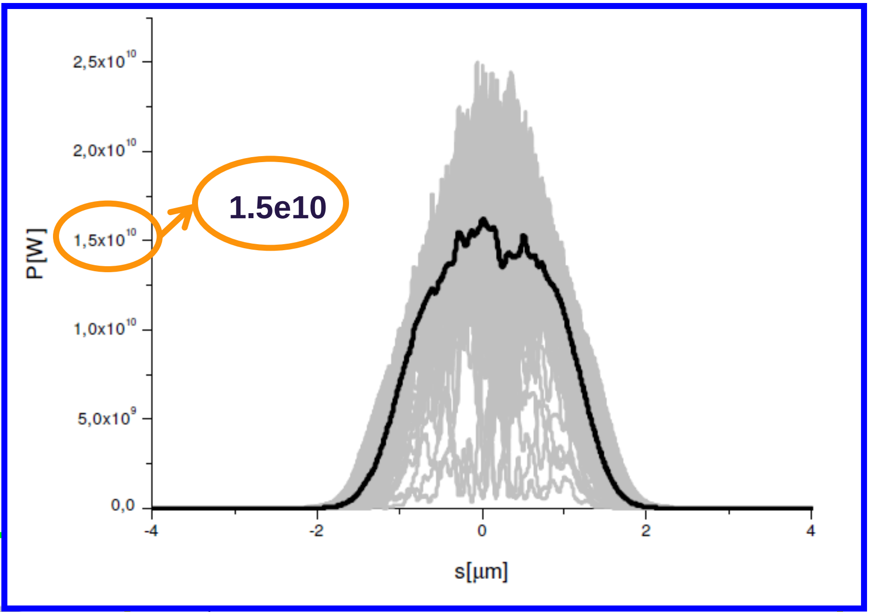
After the Diamond crystal

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

Feasibility study for LCLS (III)



Spectrum at saturation without tapering



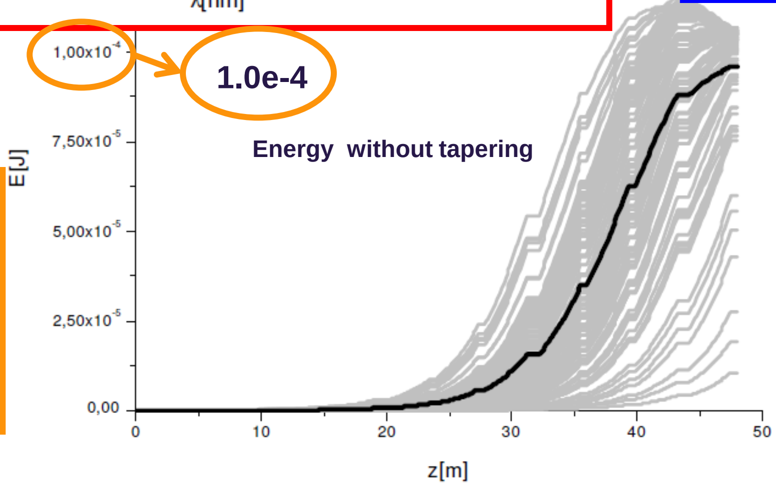
1.5e10

12 cells

Output

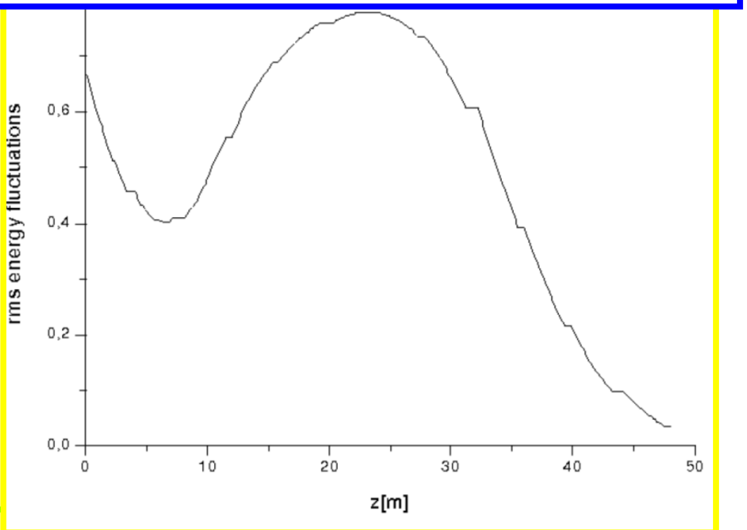
Undulator

(no tapering)

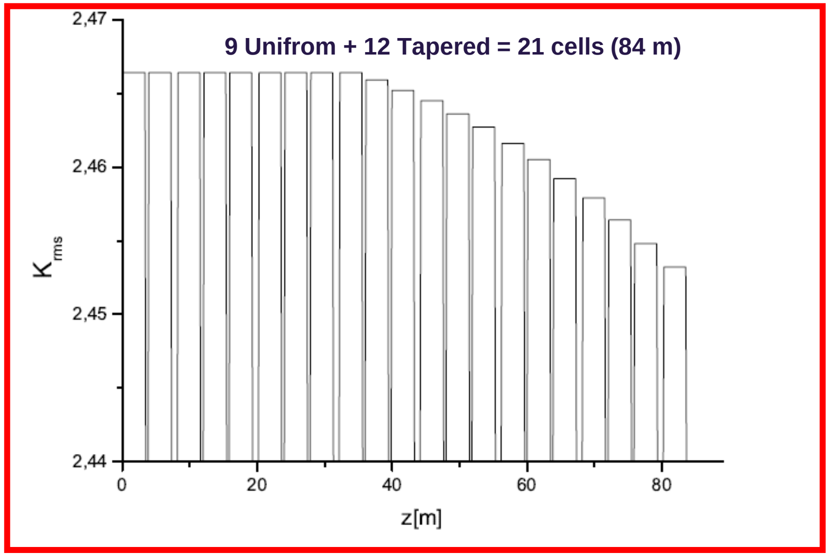


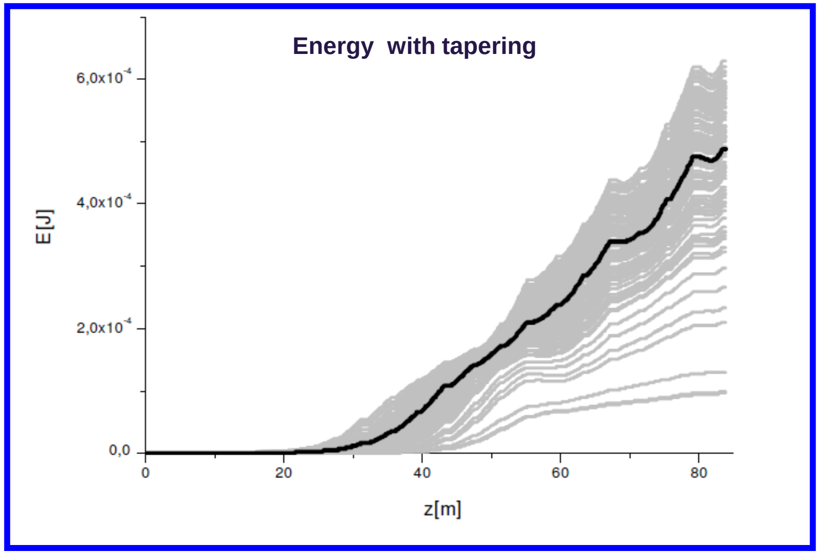
1.0e-4

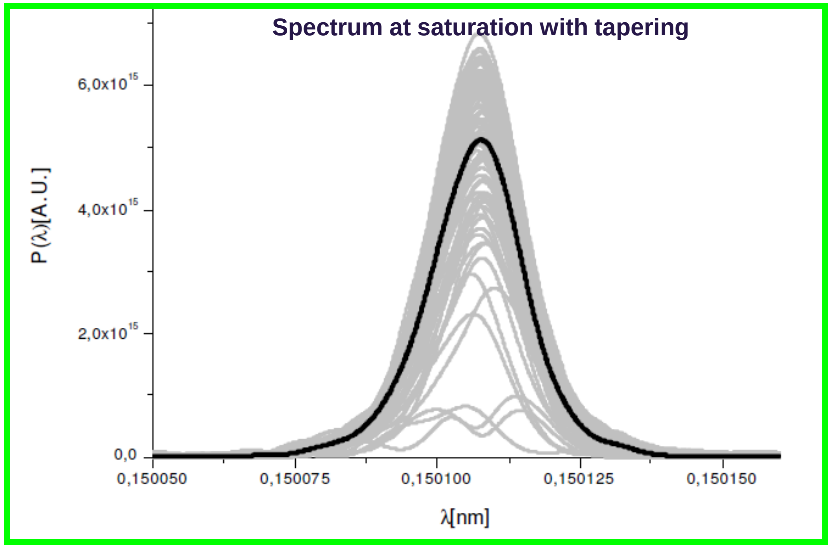
Energy without tapering

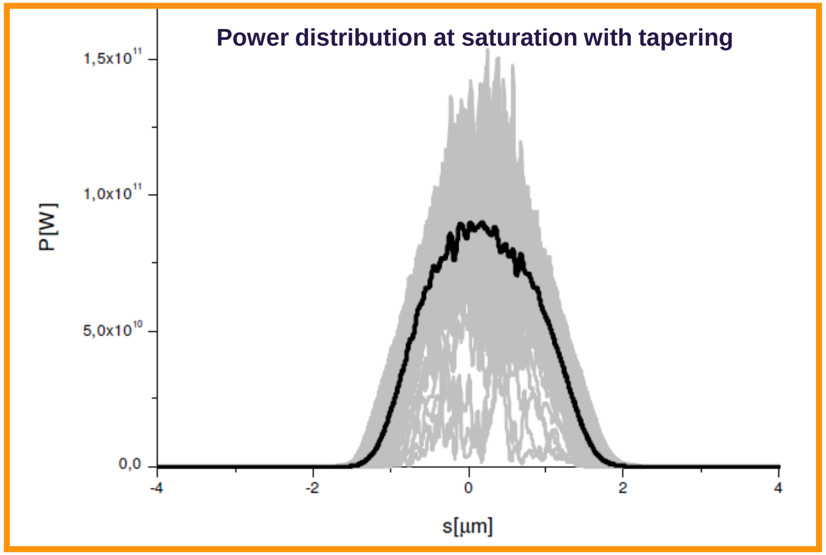


Feasibility study for LCLS (IV)


9 Unifrom + 12 Tapered = 21 cells (84 m)


Energy with tapering

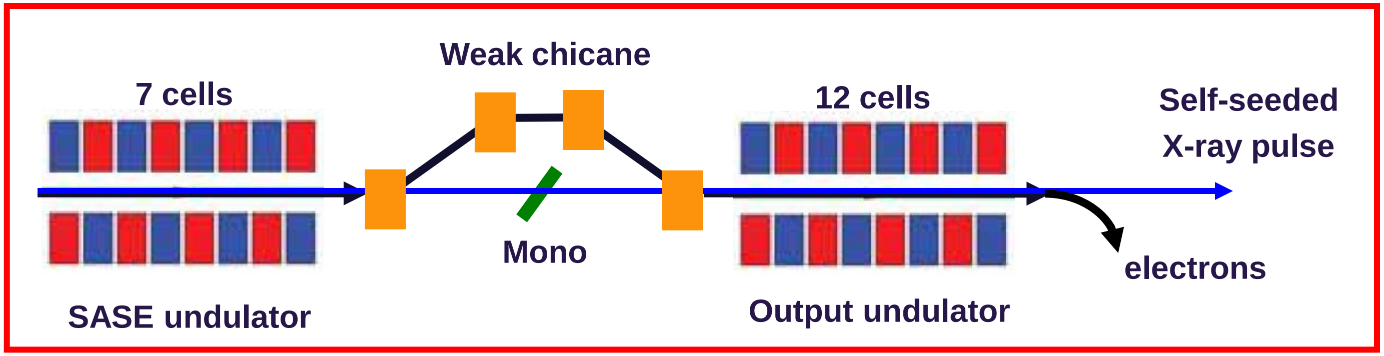

Spectrum at saturation with tapering


Power distribution at saturation with tapering

Self-seeding techniques with a single-crystal monochromator:

Feasibility study for the European XFEL
-short bunch mode of operation-

Feasibility study for the European XFEL (I)



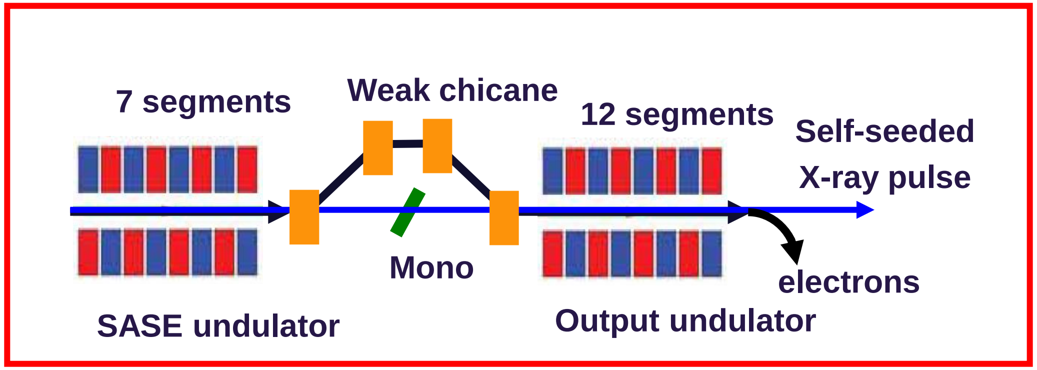
Parameters for the short pulse mode of operation

	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**

Heat loading issues

European XFEL pulse repetition rate ~ 27000 Hz → compromise in the first undulator length (heat loading!)



7 segments

Weak chicane

12 segments

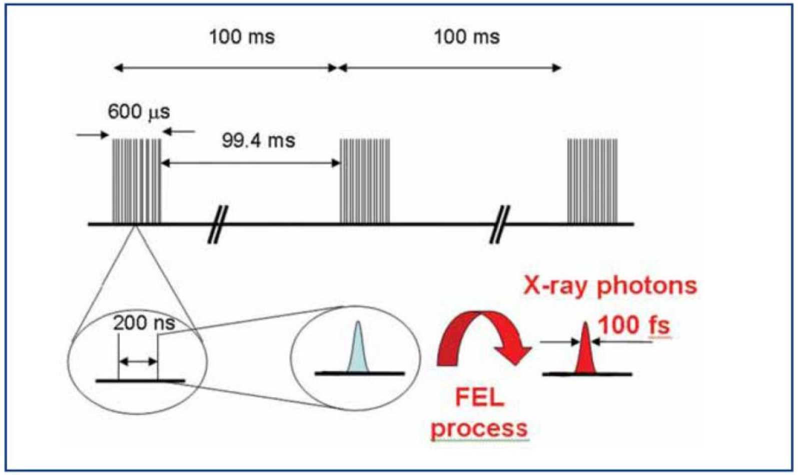
Self-seeded X-ray pulse

Mono

electrons

SASE undulator

Output undulator

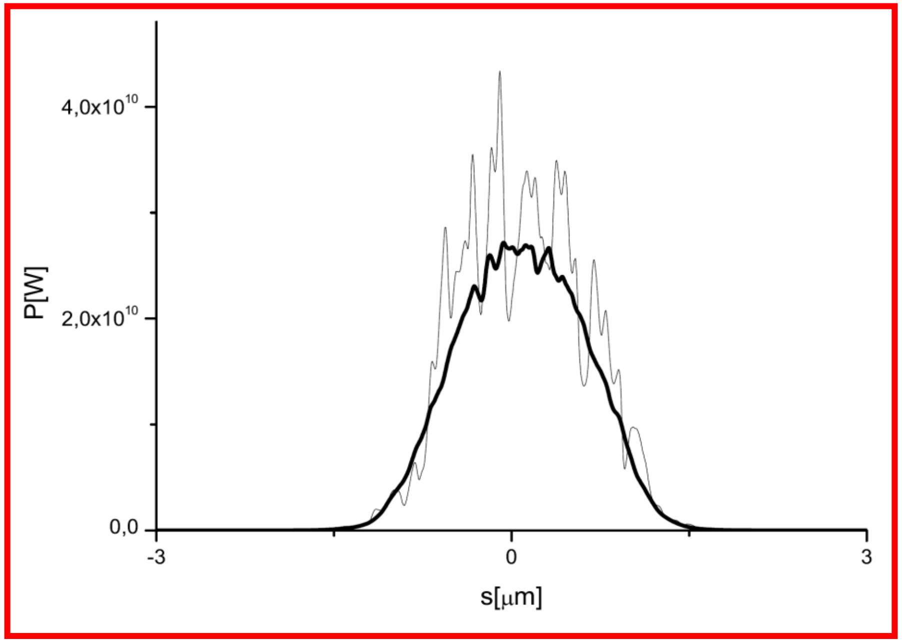


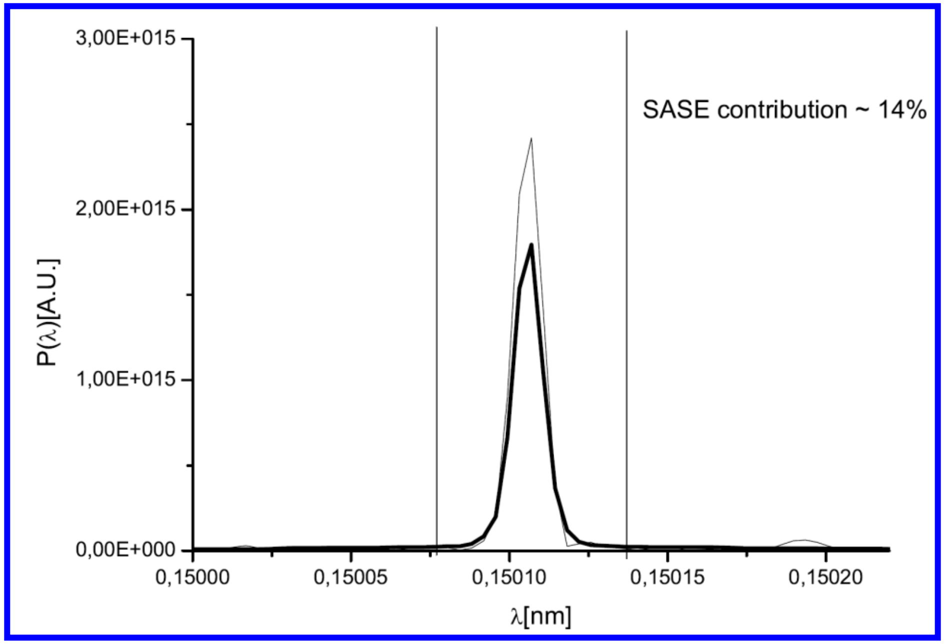
Transverse rms electron beam size	**~ 20 μm**
Longitudinal rms electron beam size 25pC/0.25nC	**~ 1-10 μm**
Energy per pulse 25pC/0.25nC bunch	**~ 150-1500 nJ/pulse**

→**Average incident power density at normal incidence within a train:**

300 W/mm^2 (25pC) – 3000 W/mm^2 (0.25nC)

Feasibility study for the European XFEL (II)





About 30000 bunches/s vs. 10 bunches/s

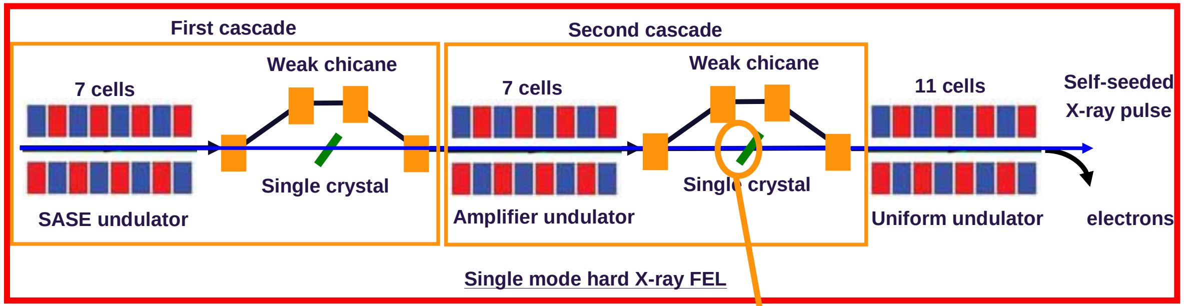
→ Heat loading much more severe for European XFEL

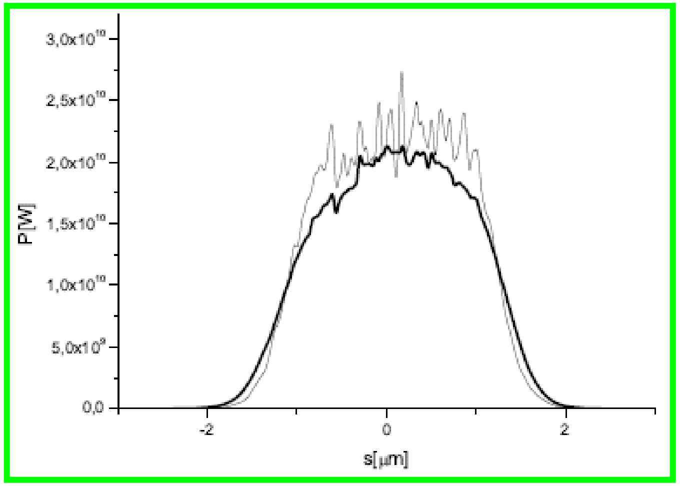
→ Cannot increase length of first undulator part

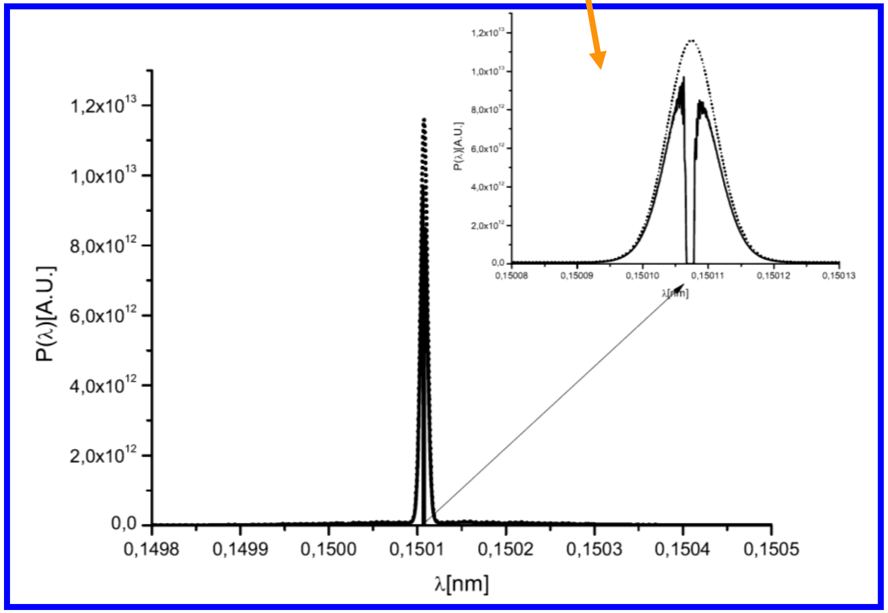
→ Relevant SASE contribution

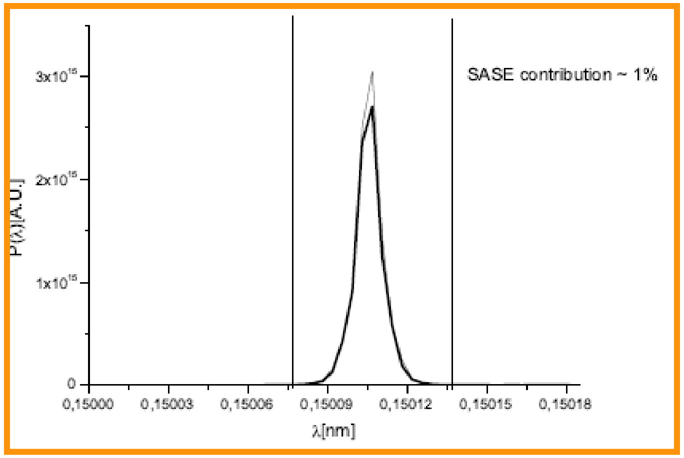
Feasibility study for the European XFEL (III)

Three-undulator setup





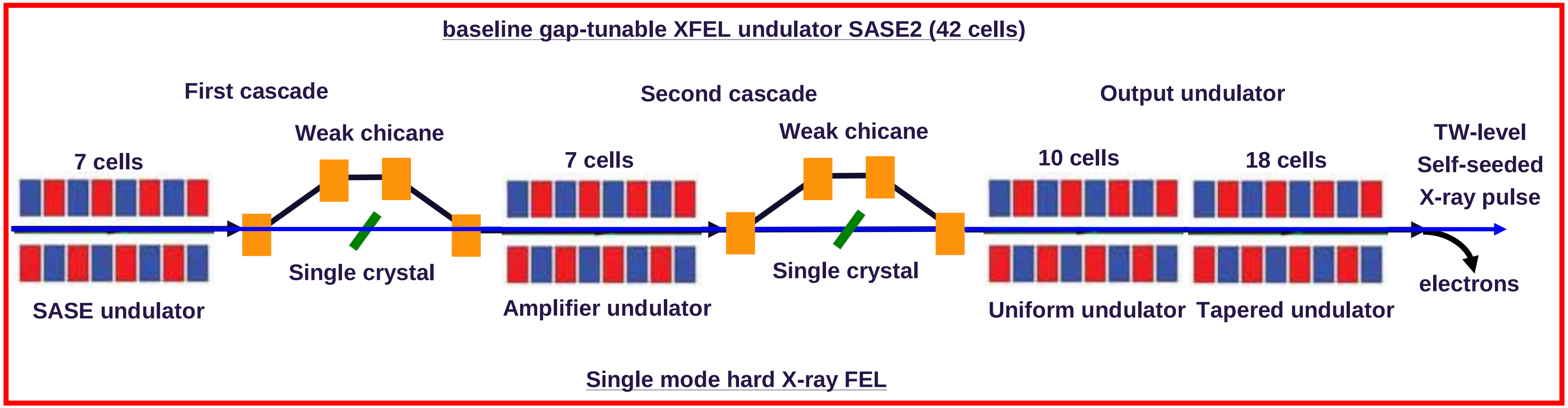




Small SASE contribution: at the second filter BW nearly Fourier limited already

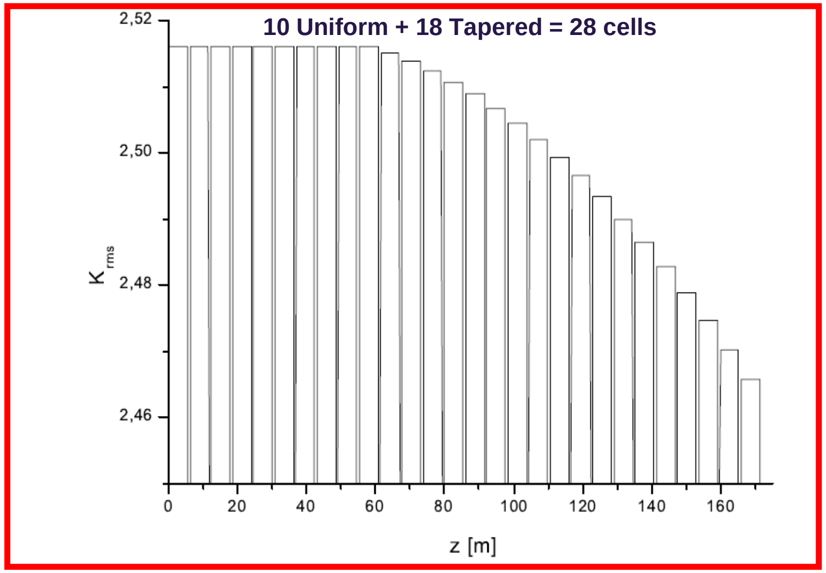
Feasibility study for the European XFEL (IV)

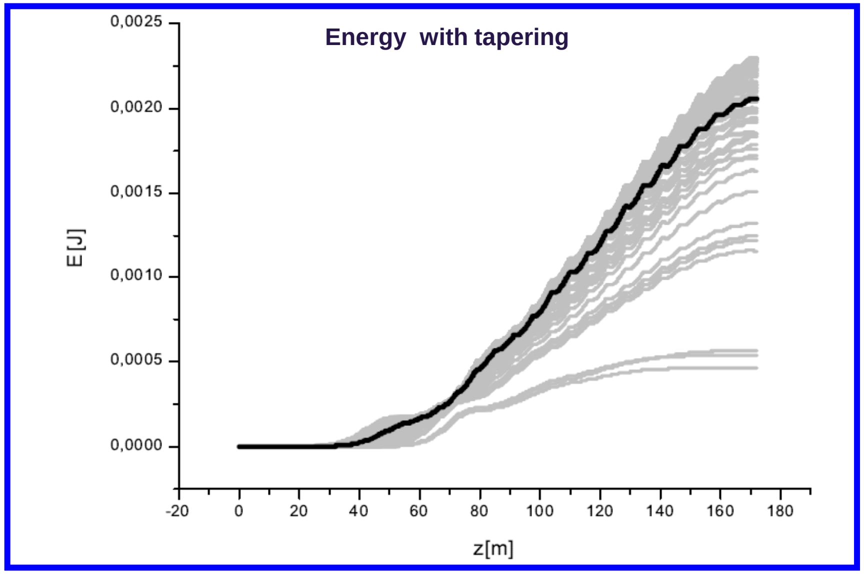
Tapering scheme

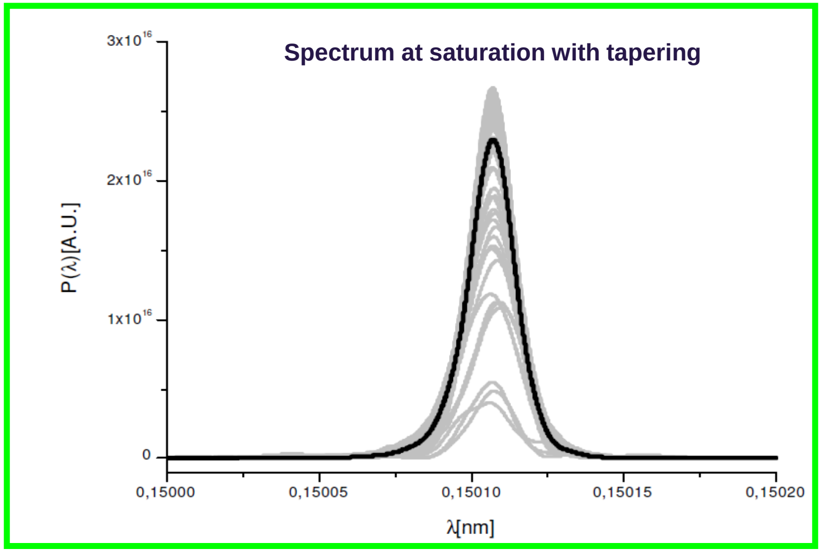


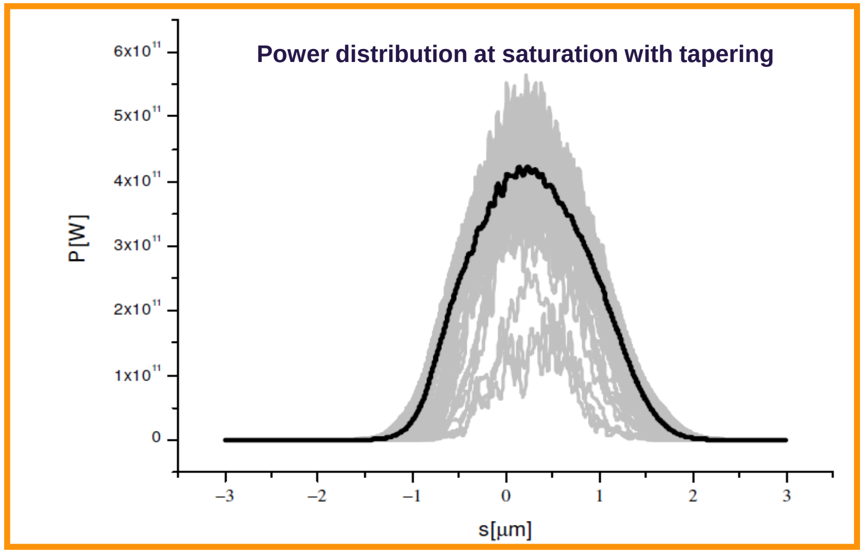
Similarly as for LCLS to increase output power/brightness

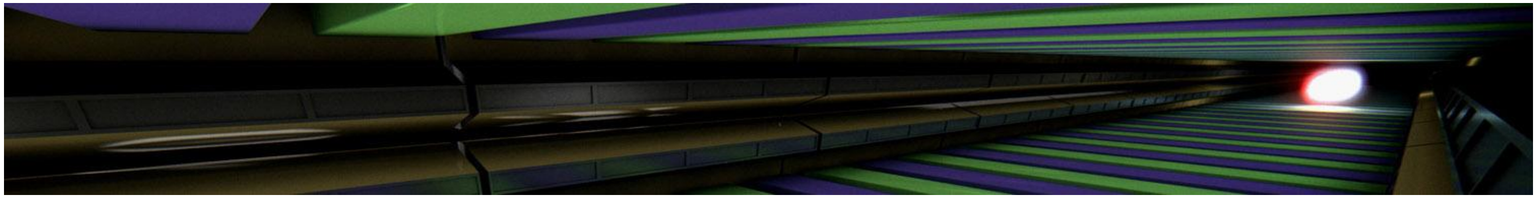
Feasibility study for the European XFEL (V)


10 Uniform + 18 Tapered = 28 cells


Energy with tapering


Spectrum at saturation with tapering

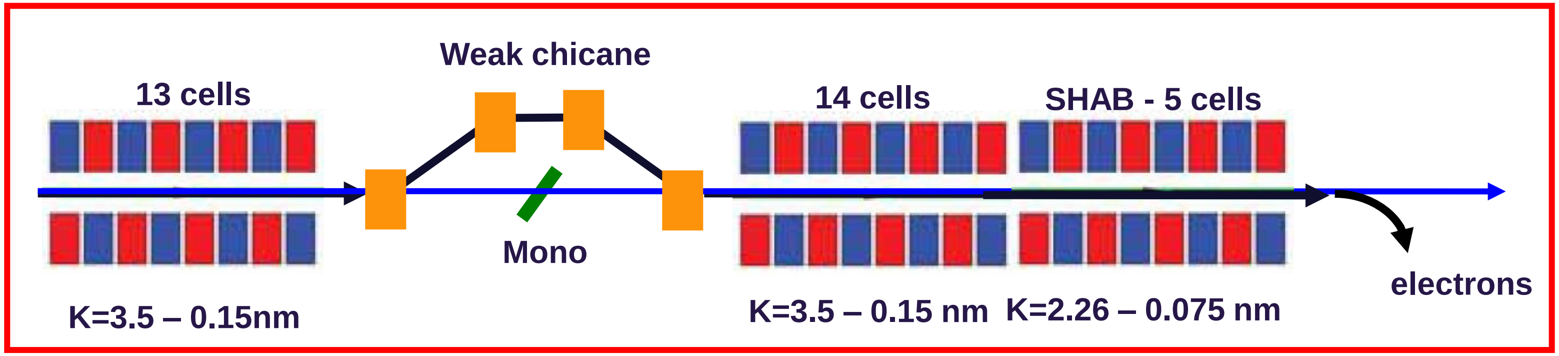

Power distribution at saturation with tapering



Self-seeding techniques with a single-crystal monochromator

Nominal mode of operation - LCLS
- Inclusion of S2E simulations -

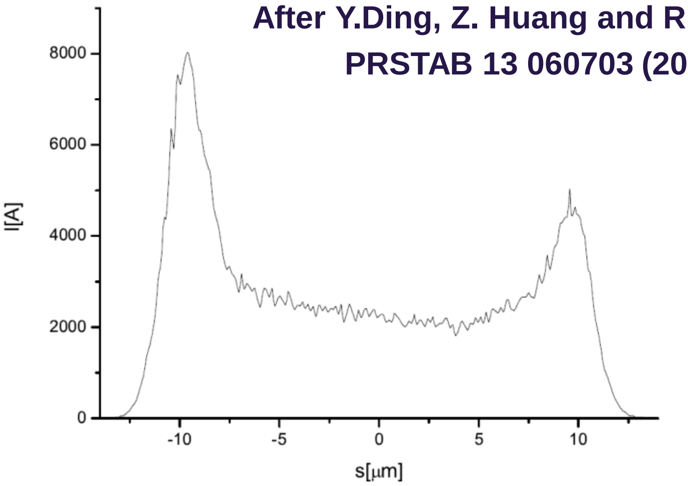
Feasibility study for the LCLS Inclusion of S2E simulations (I)

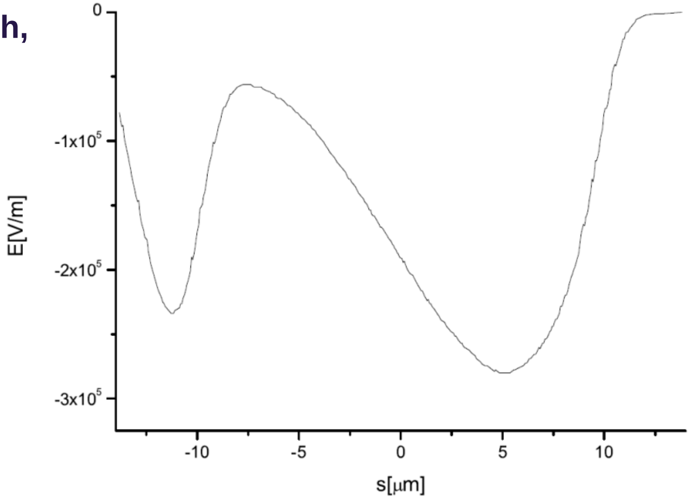


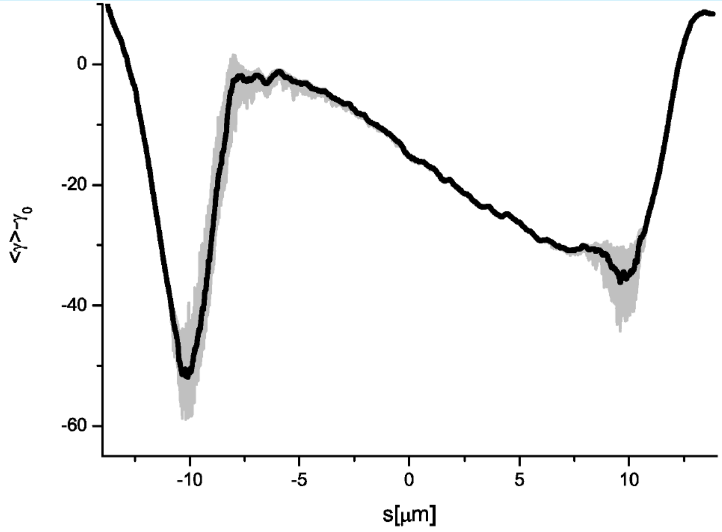
	Units	
Undulator period	mm	30
K parameter (rms)	-	2.466
Wavelength	nm	1.55
Energy	GeV	13.4
Charge	nC	0.25
Bunch length (fw)	μm	26.6
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.4

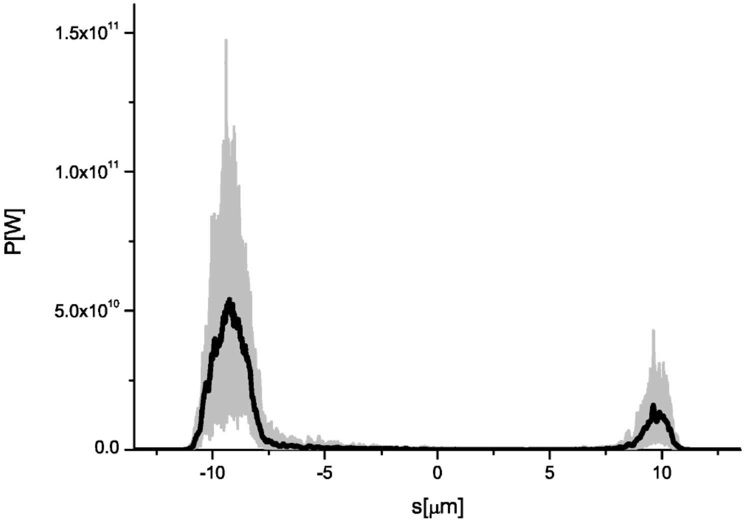
Feasibility study for the LCLS Inclusion of S2E simulations (II)

Results from S2E simulations as GENESIS input

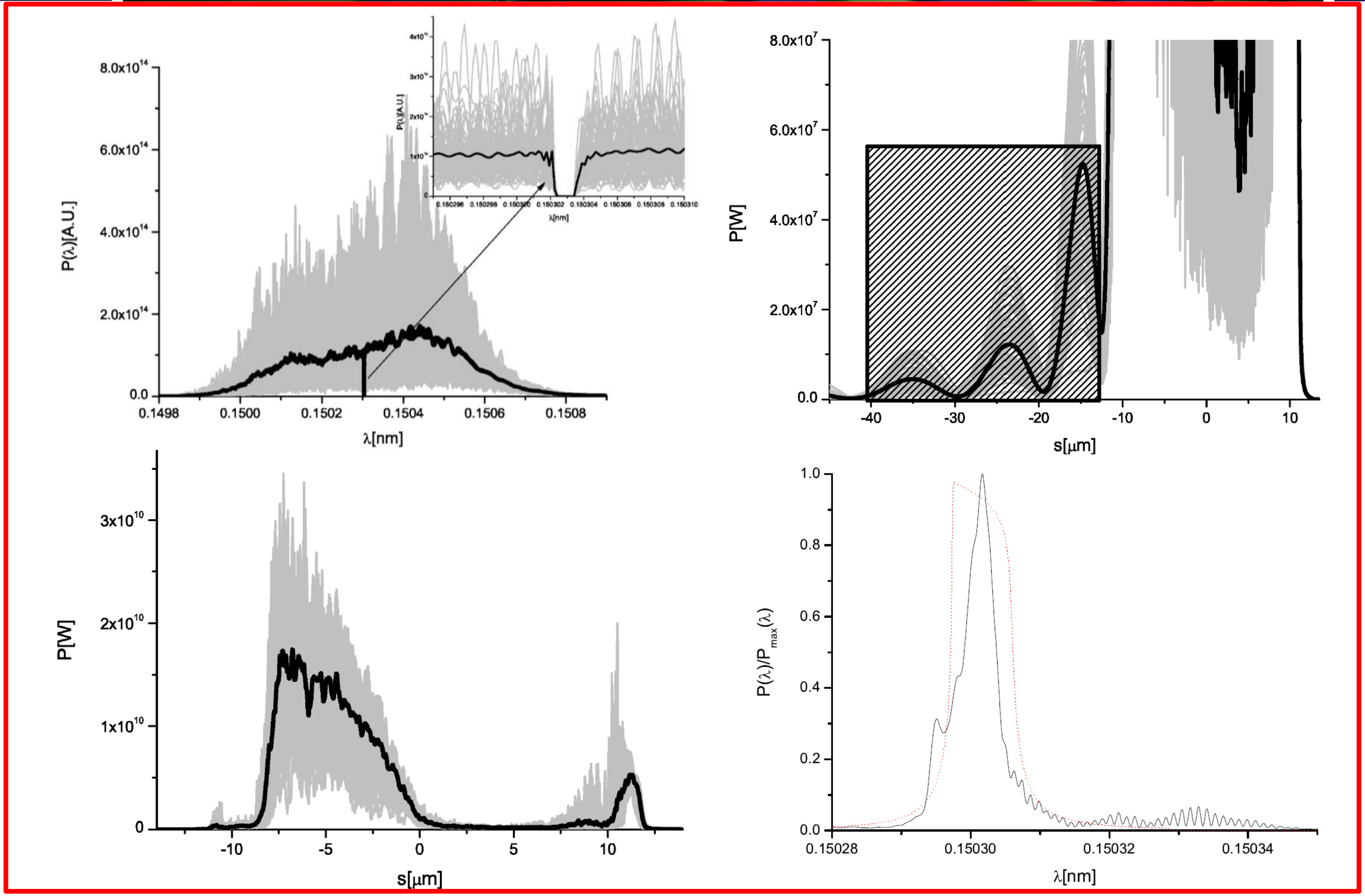

After Y.Ding, Z. Huang and R.D. Ruth, PRSTAB 13 060703 (2010)

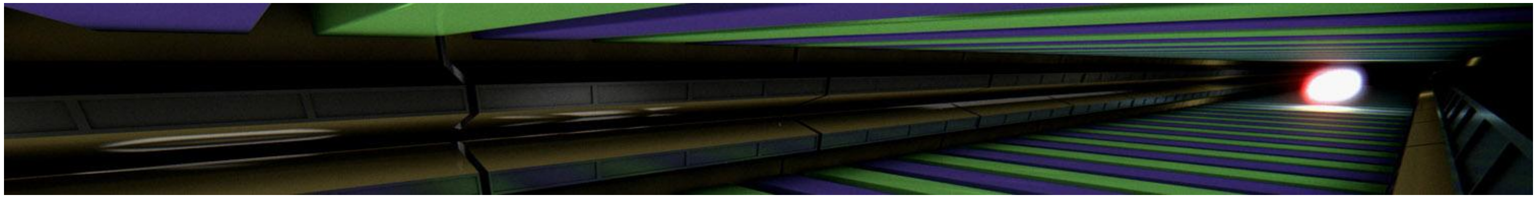






Feasibility study for the LCLS Inclusion of S2E simulations (III)

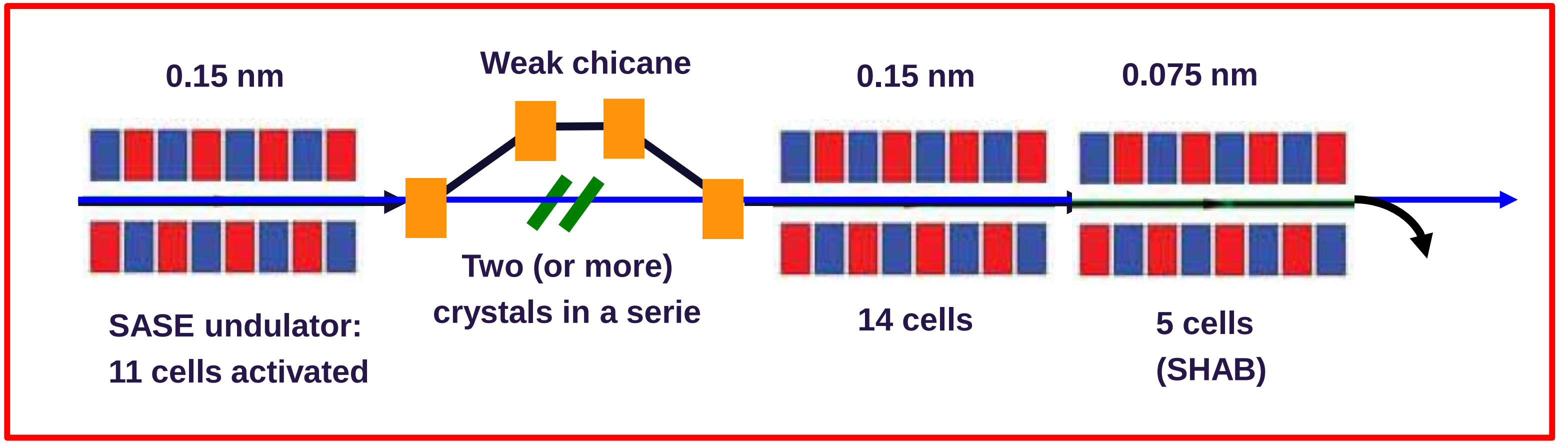




Self-seeding techniques with a single-crystal monochromator

- Doublet/multiplet generation -

Doublet generation scheme



0.15 nm

Weak chicane

0.15 nm

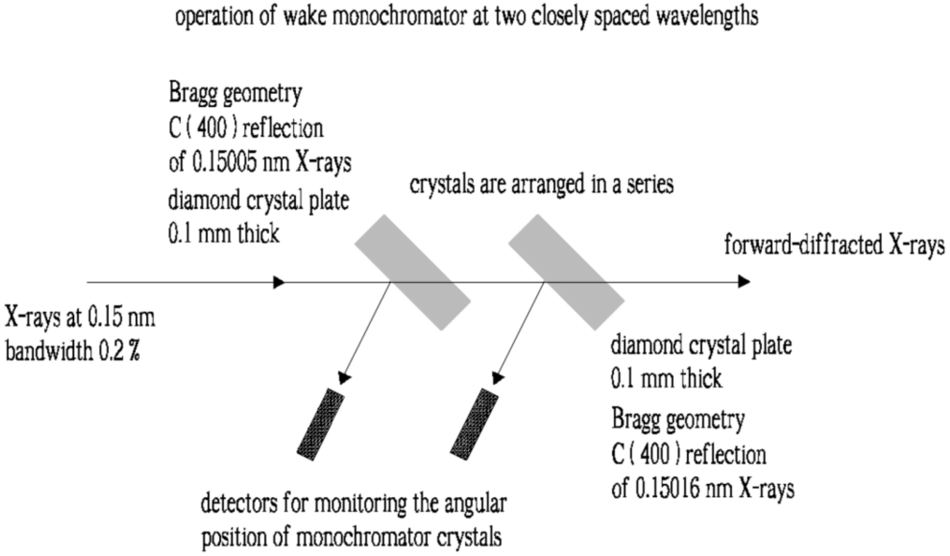
0.075 nm

Two (or more) crystals in a serie

SASE undulator:
11 cells activated

14 cells

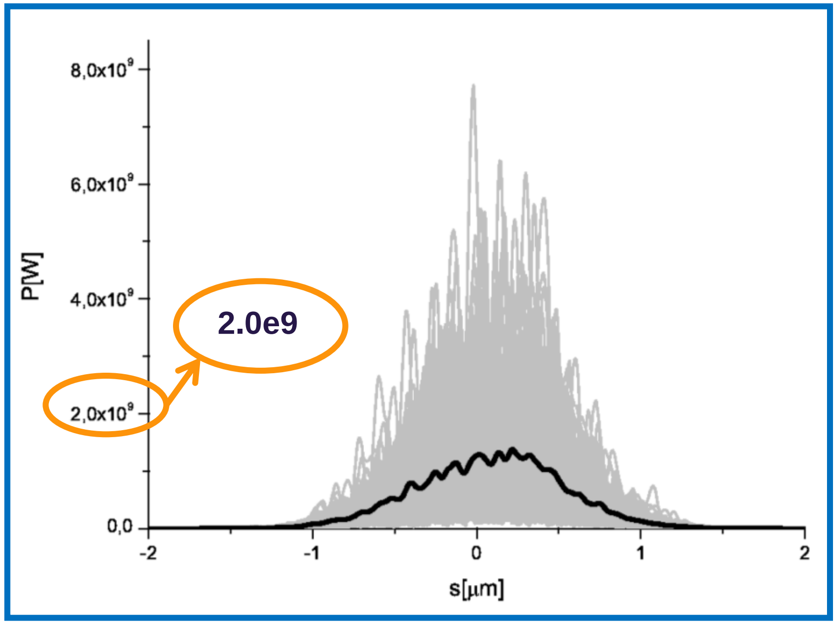
5 cells
(SHAB)

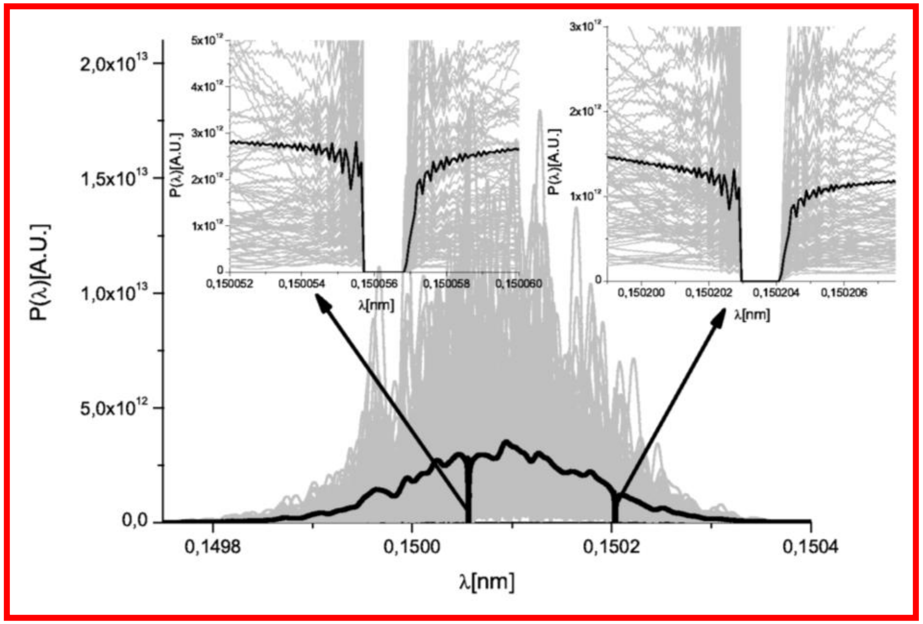


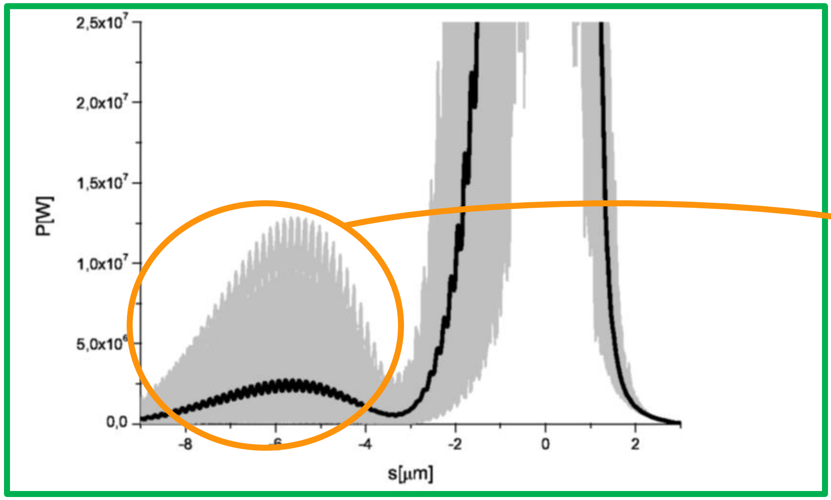
operation of wake monochromator at two closely spaced wavelengths

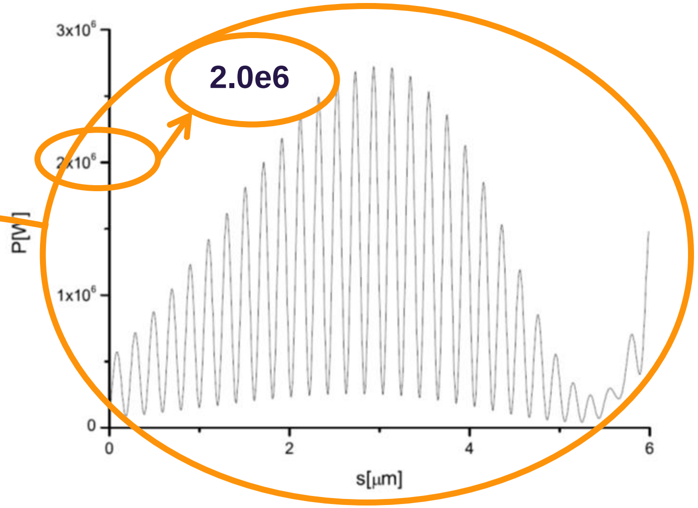
	Units	
Undulator period	mm	30
K parameter (rms)	-	2.466
Wavelength	nm	0.15
Energy	GeV	13.6
Charge	nC	0.02
Bunch length (rms)	μm	1
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

Doublet generation: crystal effect

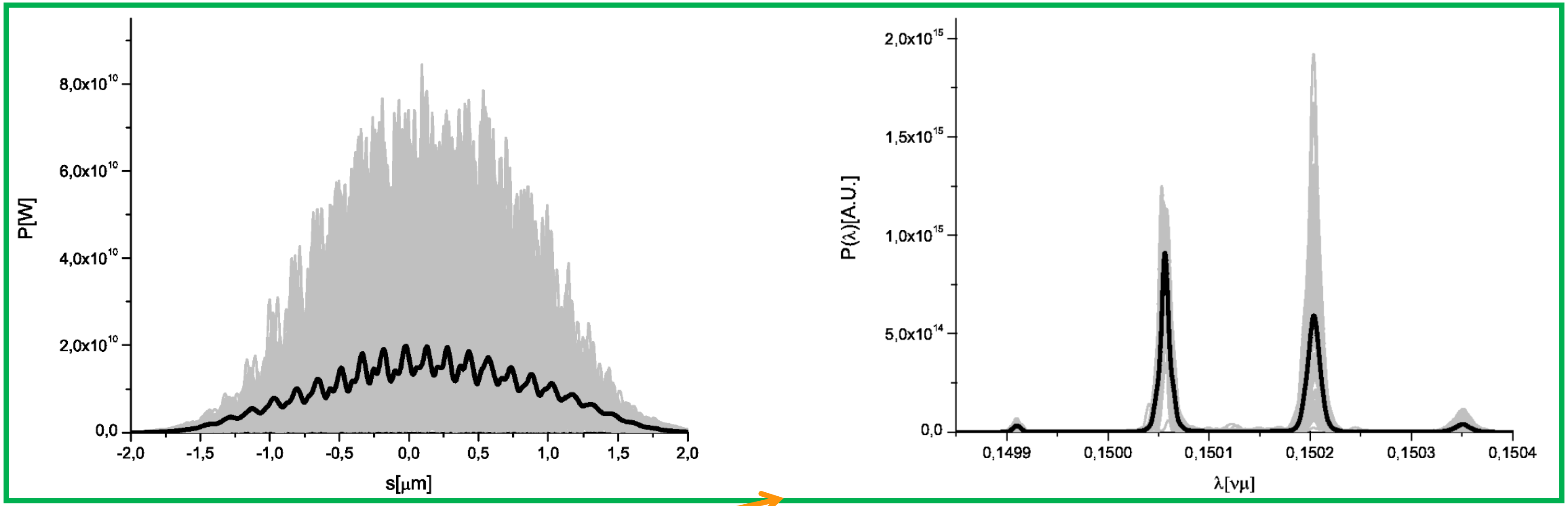






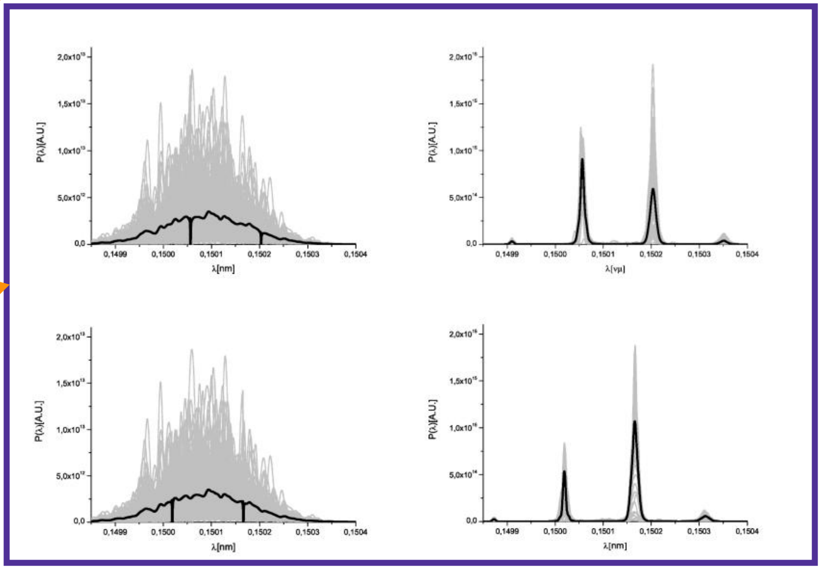


Output



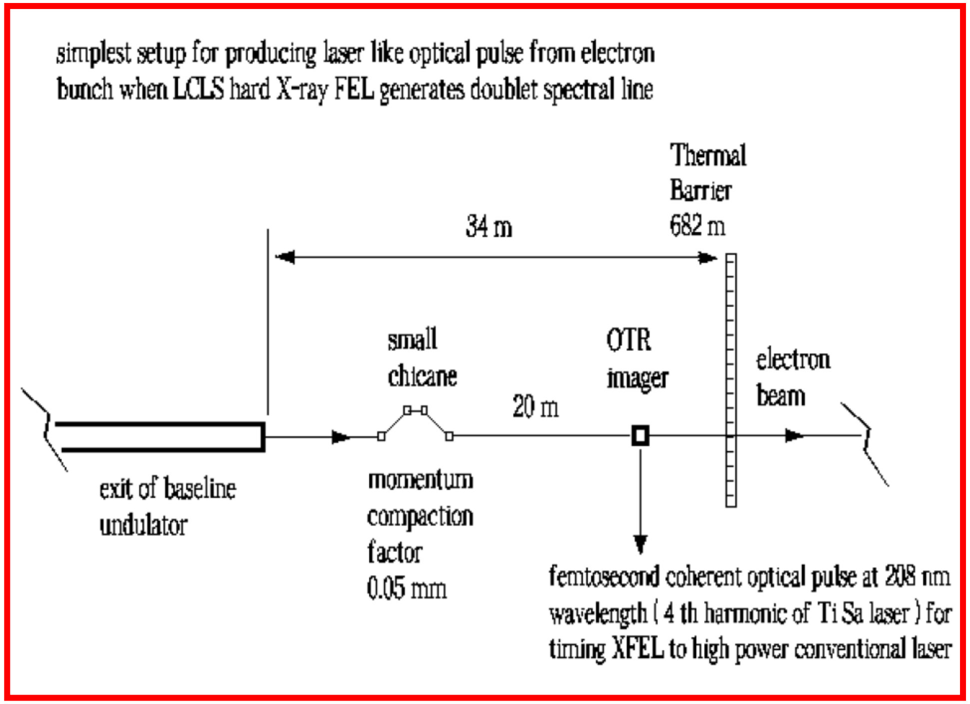
Output

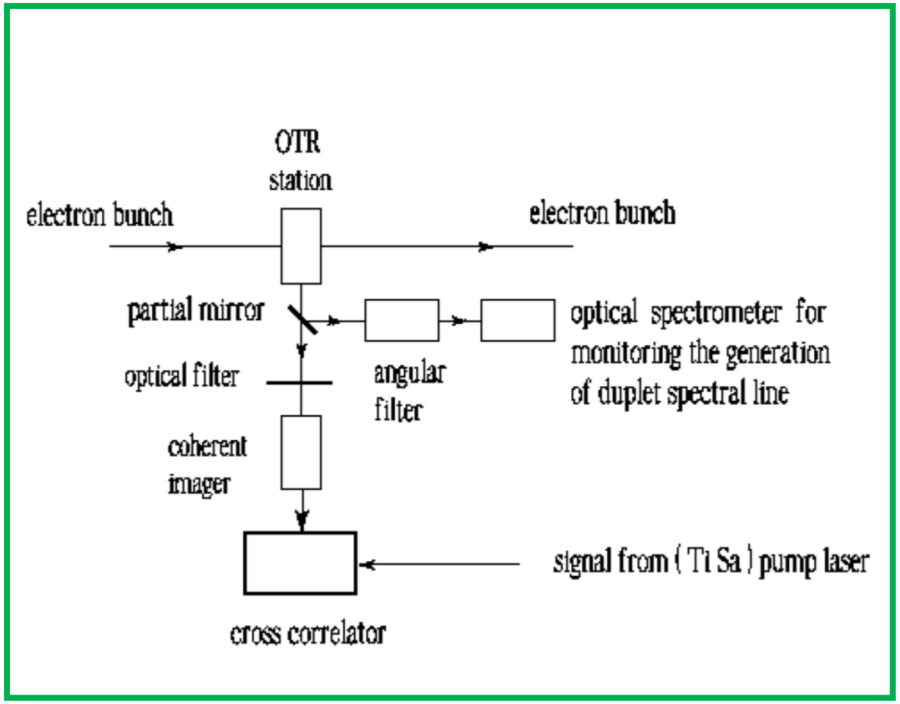
Effects of different positions within the gain length



COTR generation

The doublet setup can be used for COTR production. It can exploit the electron beam modulation naturally induced at optical wavelength


simplest setup for producing laser like optical pulse from electron bunch when LCLS hard X-ray FEL generates doublet spectral line

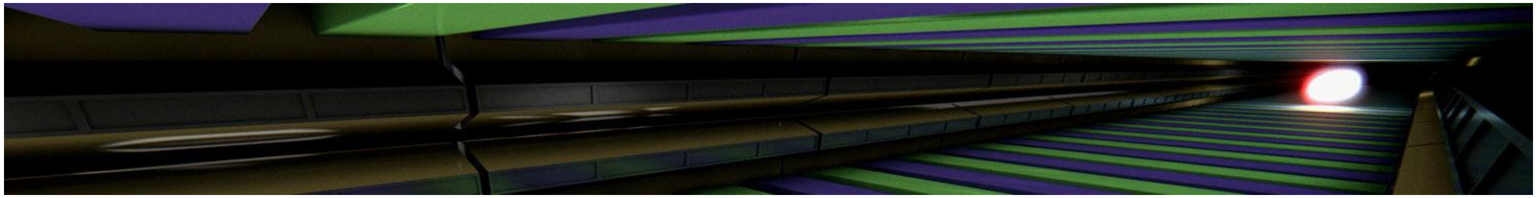


NA=0.1 → 1e11 ph/pulse

G. Geloni, V. Kocharyan, E. Saldin, 2011 Free Electron Laser Conference, Shanghai, August 23th 2011

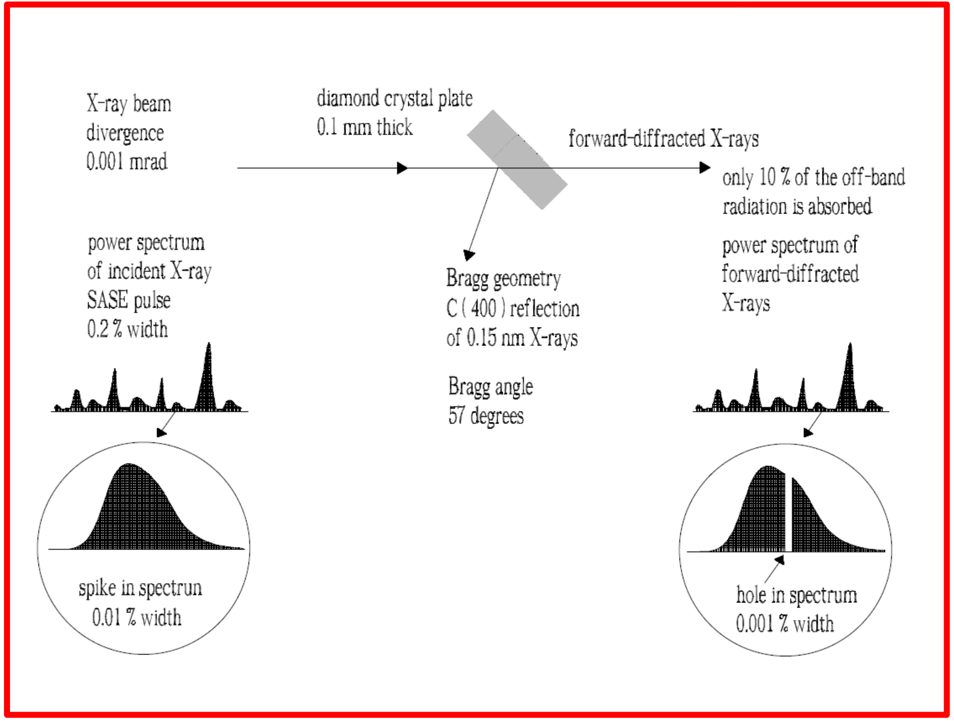
Self-seeding techniques with a single-crystal monochromator

Extension for soft X-rays

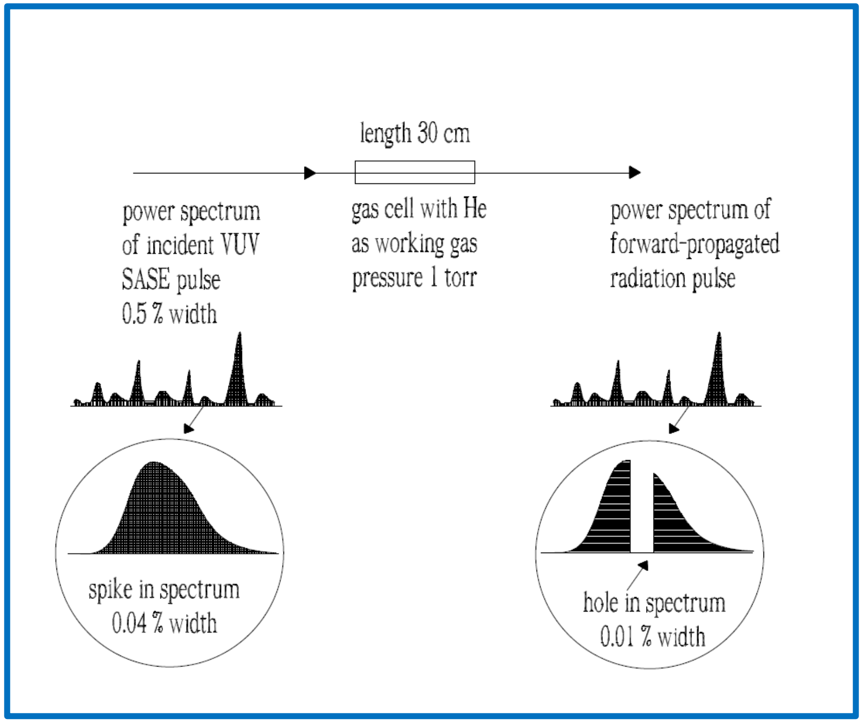


Extensions to soft X-rays – comparison (I)

The physical principle behind the self-seeding scheme can be exported to different setups



Hard X-rays



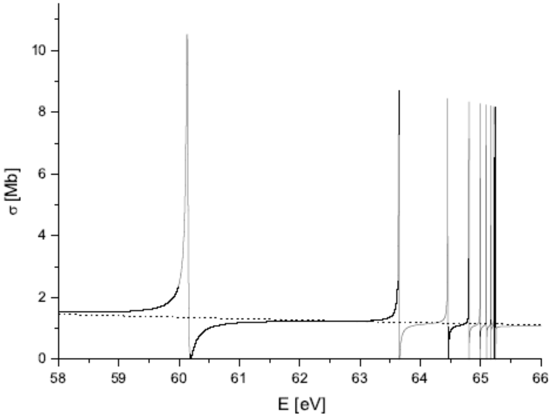
Soft X-rays

<u>Conceptually</u> we are playing the same game!

<u>Practically</u> we will need to implement some changes in the setup

Photoabsorption cross-sections; He: 60-65 eV

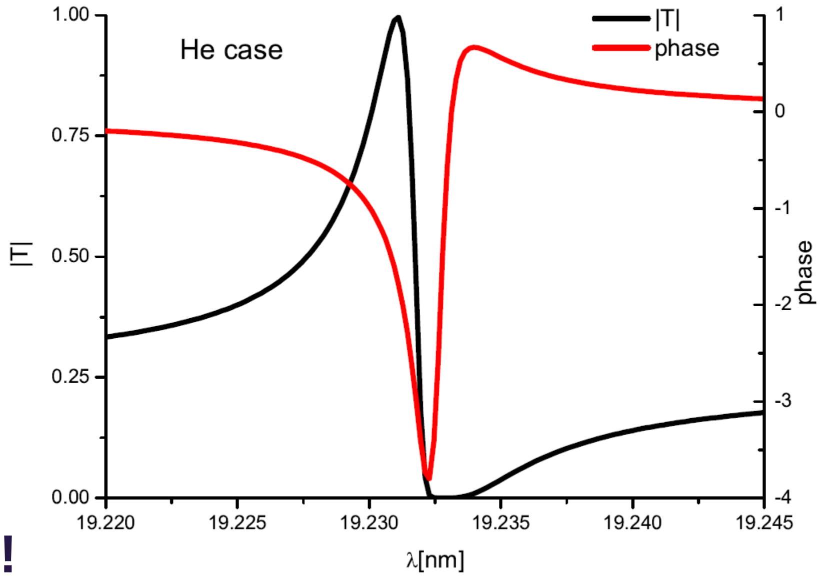
$$\boxed{I(\omega) = I_0 exp[-n_0 l \sigma(\omega)]} \rightarrow |T| = \exp[-n_0 l \sigma/2]$$



$$\ln[T(\omega)] = \ln[|T(\omega)|] + i\Phi(\omega) = -nl\sigma/2 + i\Phi(\omega)$$

σ~Im[n] → K.K. :

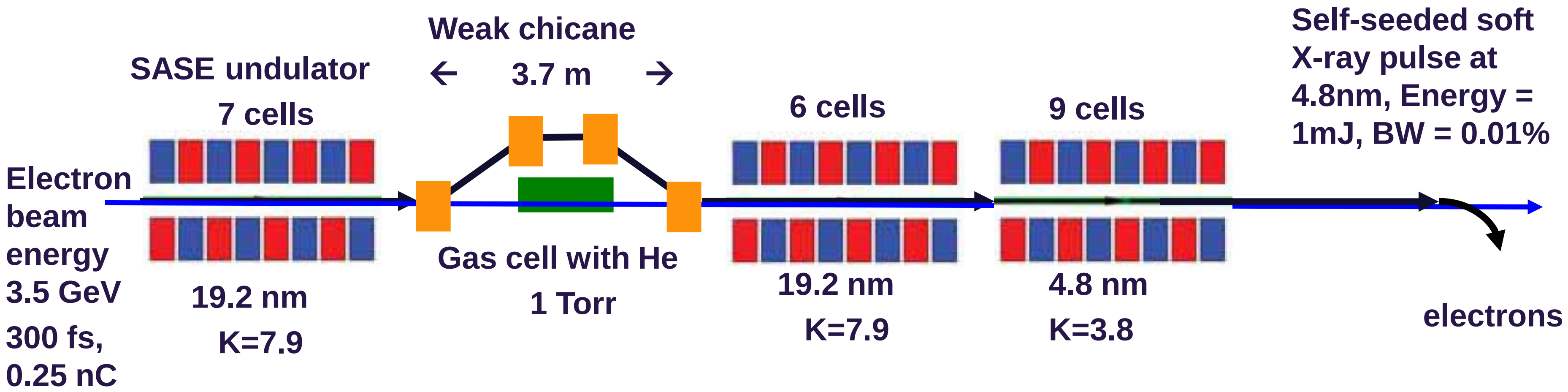
$$\Phi(\omega) = -\frac{2\omega}{\pi}\mathcal{P}\int_0^\infty \frac{\ln[|T(\omega')|]}{\omega'^2 - \omega^2} d\omega'$$



Same reasoning as for hard X-rays!

Extensions to soft X-rays – feasibility (I)

1. Not all resonances can be used
2. The wavelength is too long (~20 nm) → Practical changes →Harmonics



Electron beam energy 3.5 GeV
300 fs,
0.25 nC

SASE undulator
7 cells
19.2 nm
K=7.9

Weak chicane
← 3.7 m →

Gas cell with He
1 Torr

6 cells
19.2 nm
K=7.9

9 cells
4.8 nm
K=3.8

Self-seeded soft X-ray pulse at 4.8nm, Energy = 1mJ, BW = 0.01%

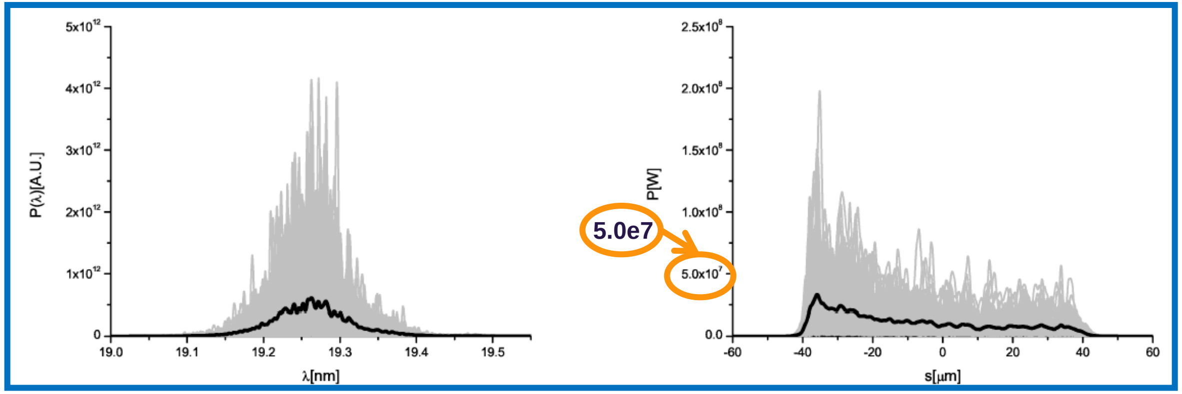
electrons

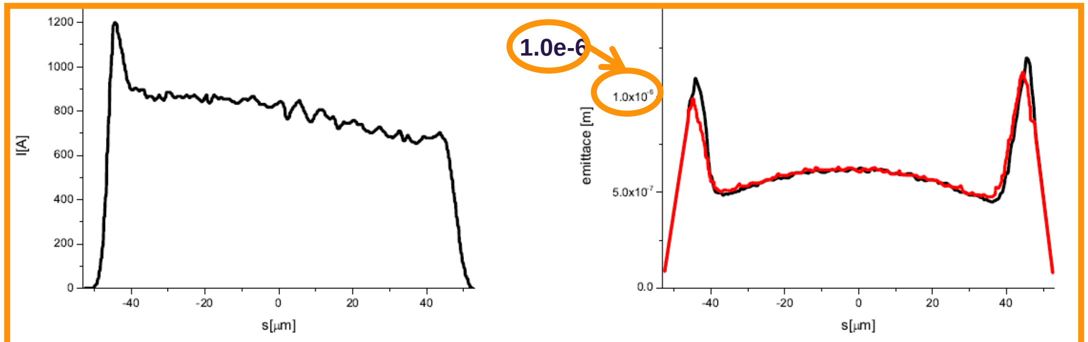
LCLS-II baseline tunable gap undulator with 60mm period, K = 1.3-12

Beta function 10m
Cell length 3.7m
Undulator segment length = 3m

Extensions to soft X-rays – feasibility (II)

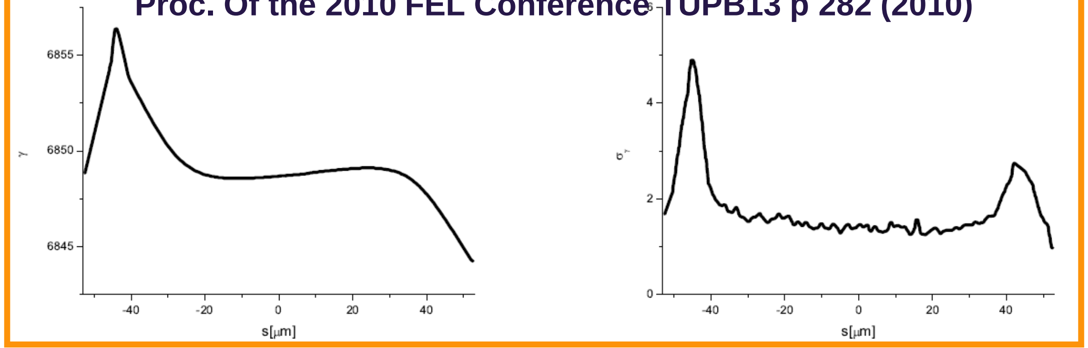
	Units	
Undulator period	mm	60
K parameter	-	1.3-12
Wavelength (fundamental)	nm	19.2
Energy	GeV	3.5
Charge	nC	0.25

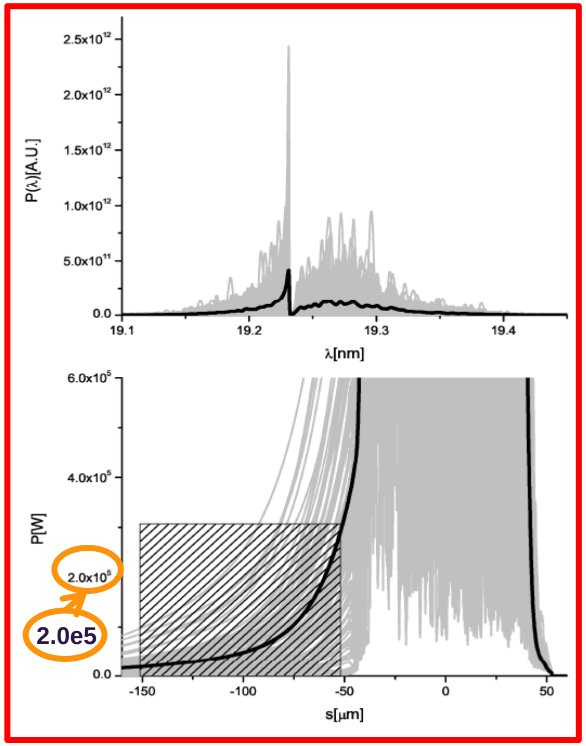




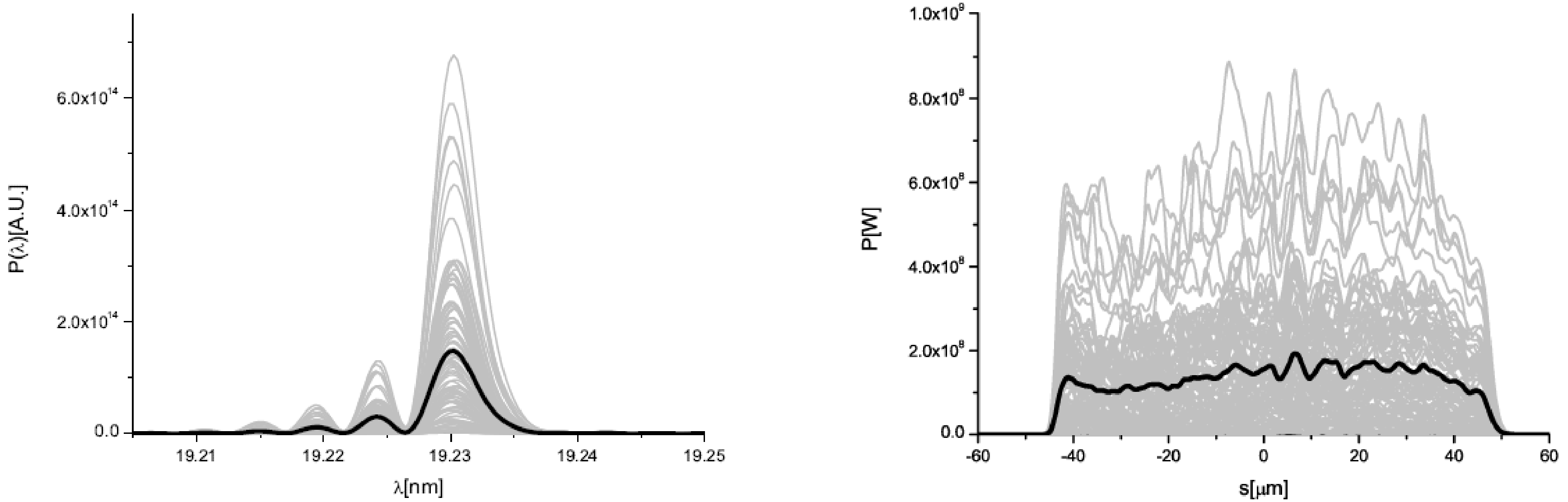
After D. Xiang and G. STupakov,

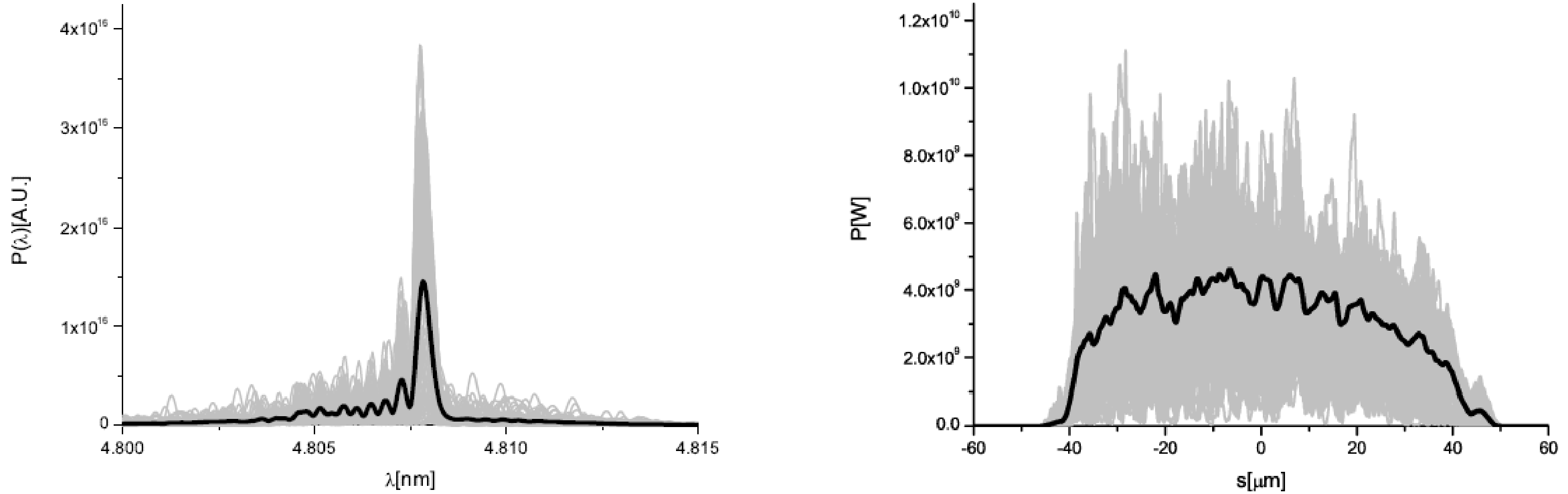
Proc. Of the 2010 FEL Conference TUPB13 p 282 (2010)





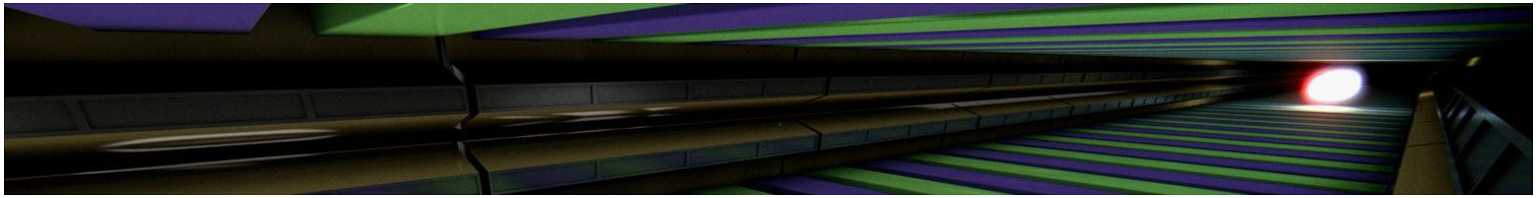
Extensions to soft X-rays – feasibility (III)





Conclusions

- Solves the problem of poor longitudinal coherence for hard x-ray FELs
  - Bandwidth down to 10^{-4} for Q=0.02 nC (depends on mode of operation)
- Robust
  - Baseline mode of operation is easily recovered
- Minimal modifications to the baseline setup
  - No need for long electron bypass
  - No need for special photo-injector setup
  - Only needs: 1 weak chicane + 1 crystal (or gas cell) within a single segment
- Low cost



Thank You!