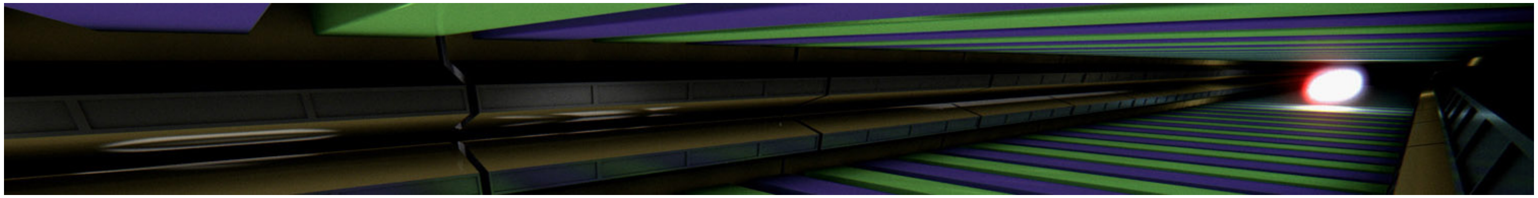


Self-seeding methods at the European XFEL

Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin

Contents

- Self-seeding - Motivations & principle for HXRSS
- Plans for HXRSS implementation at European XFEL
- Ideas beyond the baseline (under discussion)
- Conclusions

Motivations for Self-seeding & working principle

Motivations for self-seeding

SASE pulses, baseline mode of operation: poor longitudinal coherence

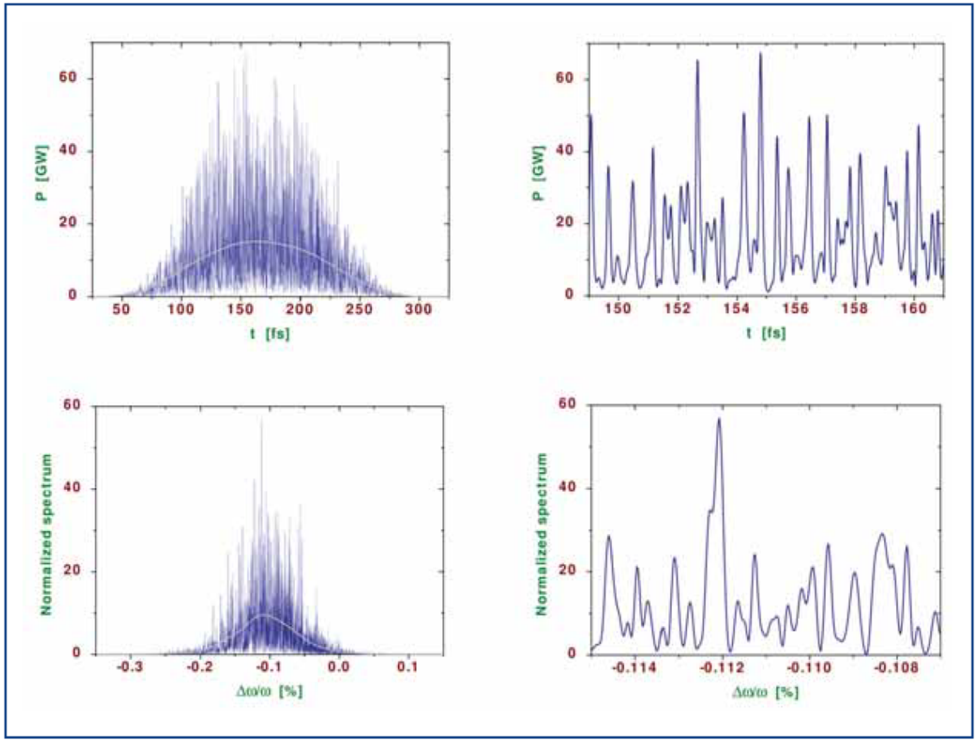


Figure 5.2.4 *Temporal (top) and spectral (bottom) structure for 12.4 keV XFEL radiation from SASE 1. Smooth lines indicate averaged profiles. Right side plots show enlarged view of the left plots. The magnetic undulator length is 130 m.*

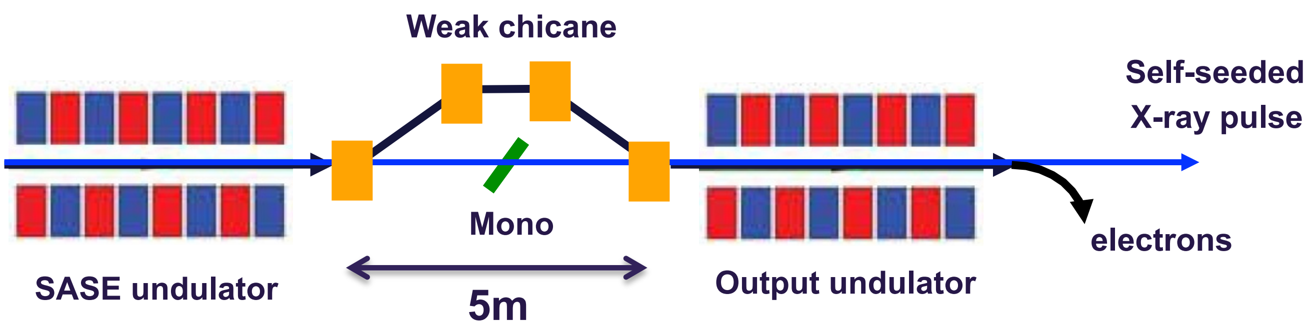
Source: The European XFEL TDR – DESY 2006-097 (2006)

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

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

- **Hundreds of longitudinal modes**
- **A lot of room for improvement**
- **Self-seeding schemes [Method historically introduced for soft x-rays in: J. Feldhaus et al., Optics Comm. 140, 341 (1997)] answer the call for increasing longitudinal coherence, but needed major baseline changes**

Working principle for HXRSS

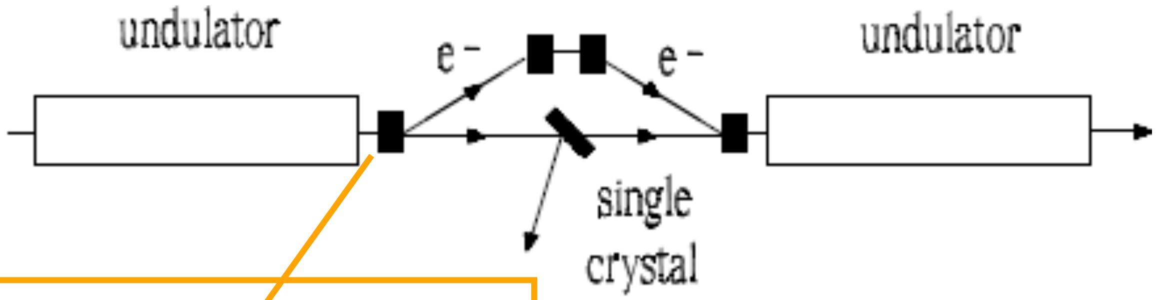


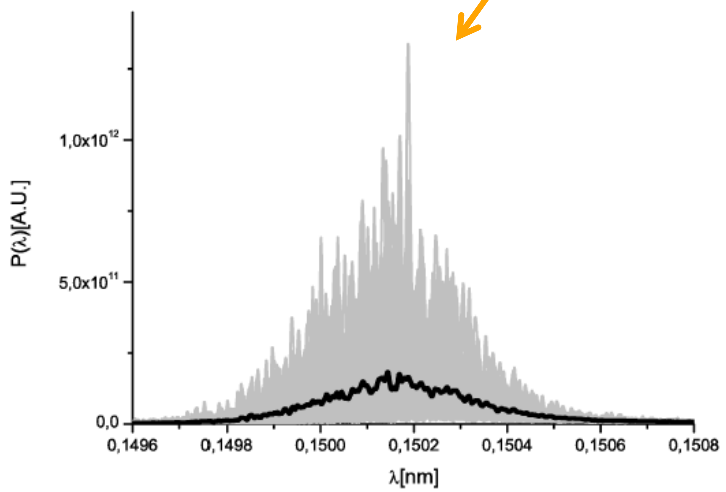
- First part: usual SASE FEL process
- Weak chicane acts as a tunable delay line, washes out microbunching, creates transverse offset
- The photon pulse from SASE goes through the monochromator
- Photon and electron pulses are recombined

G. Geloni, V. Kocharyan and E. Saldin, J. of Modern Optics 58, 1391 (2011).

Working principle for HXRSS

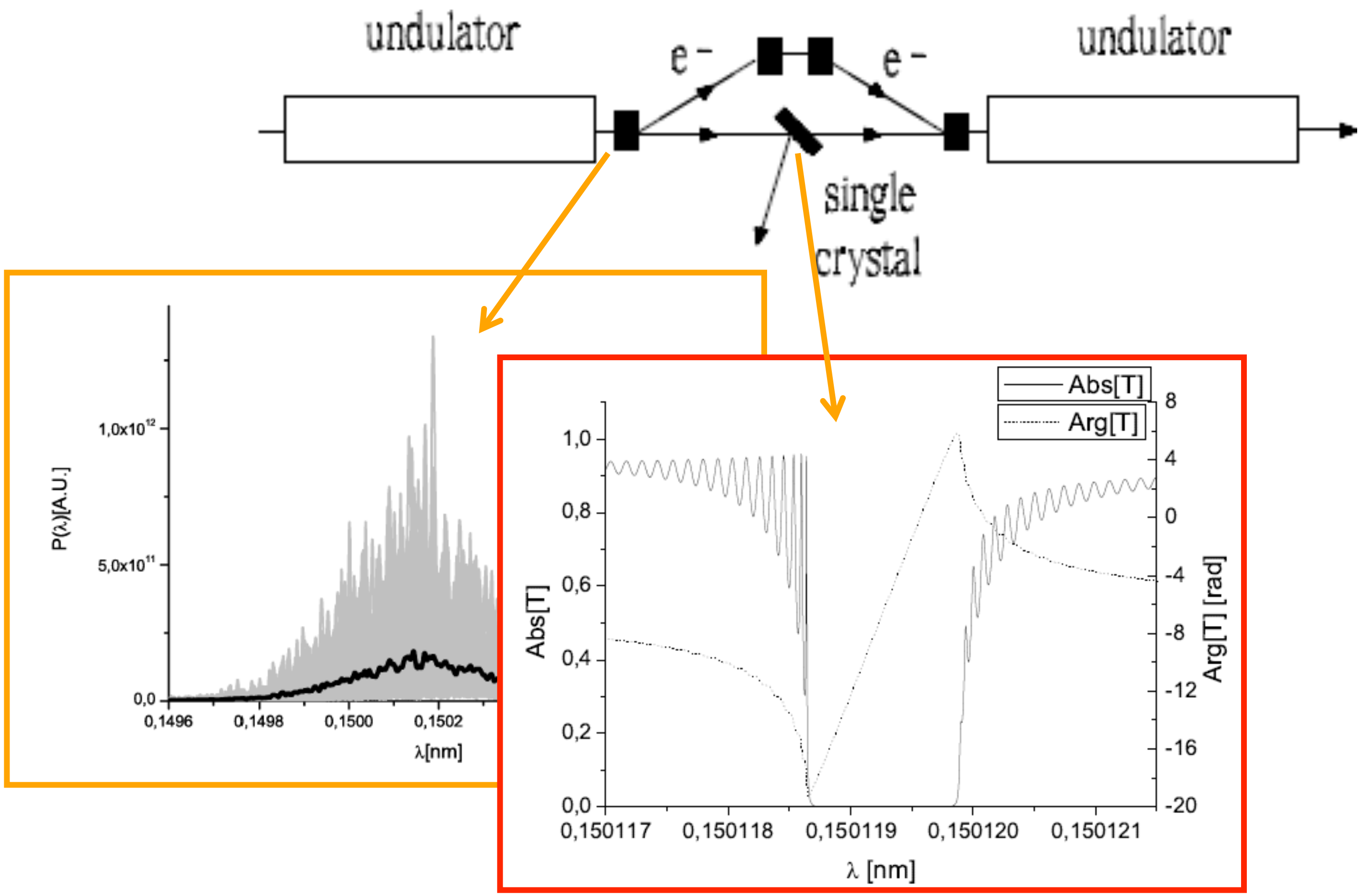
The single-crystal monochromator principle: frequency domain





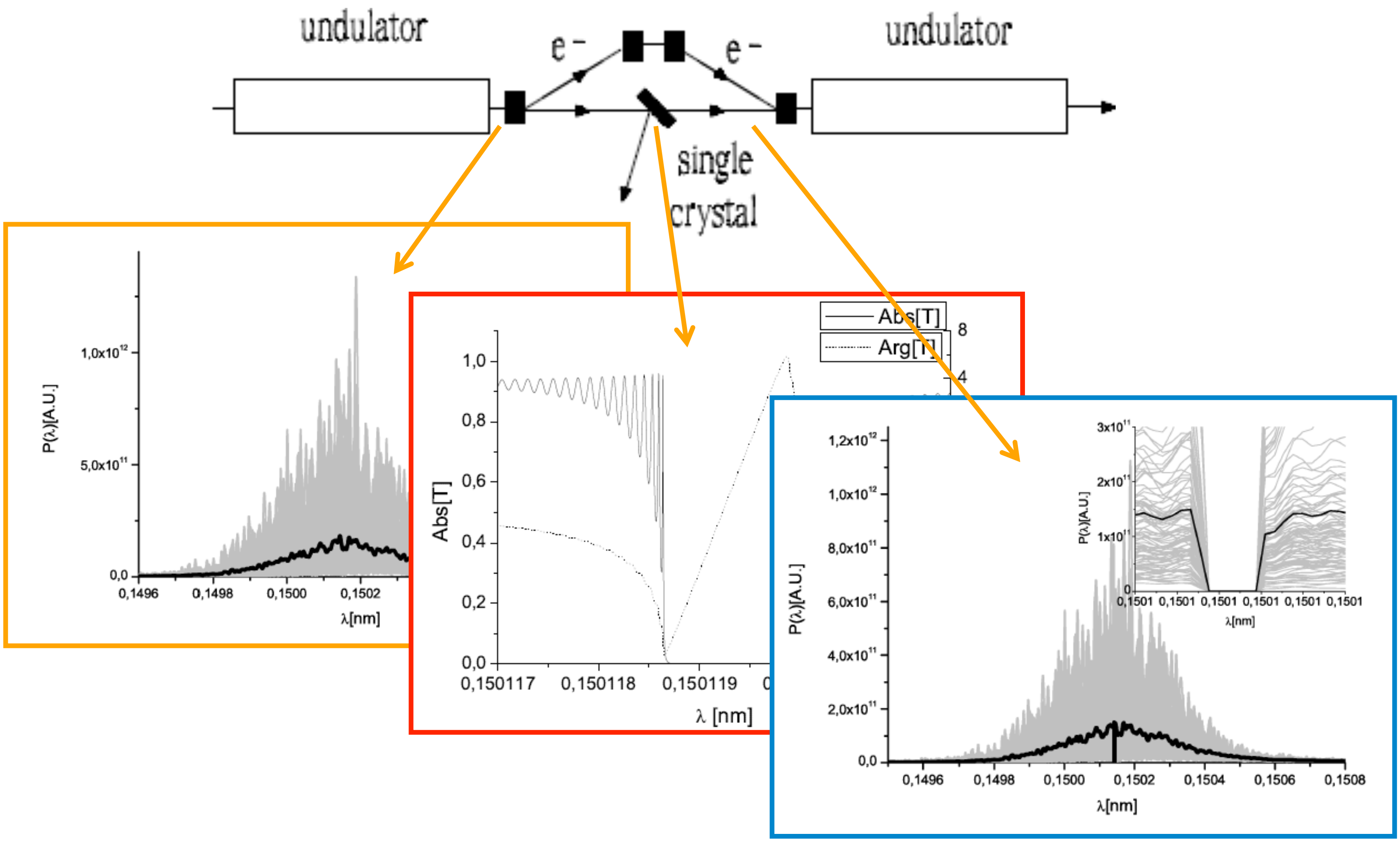
Working principle for HXRSS

The single-crystal monochromator principle: frequency domain



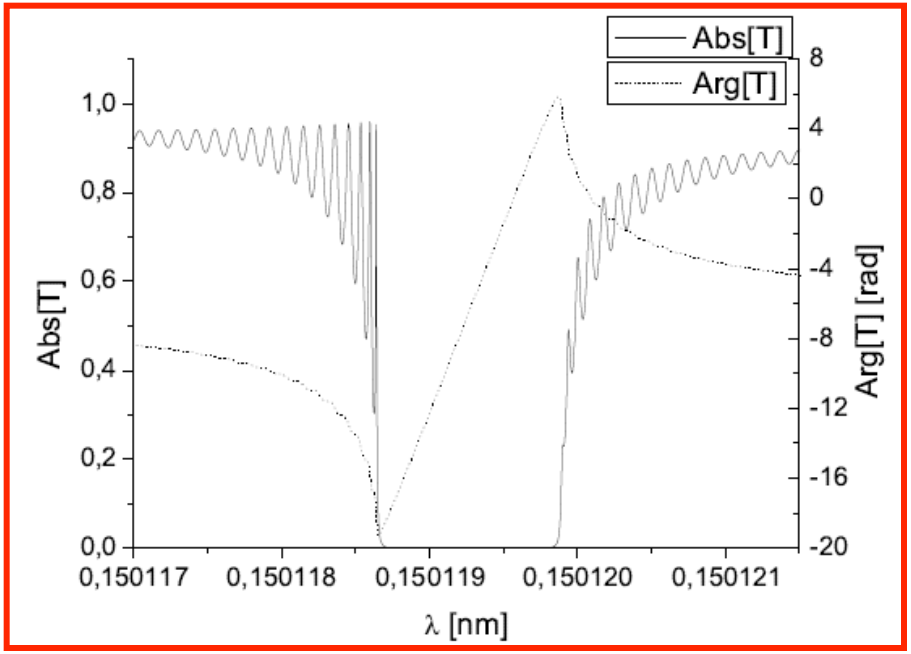
Working principle for HXRSS

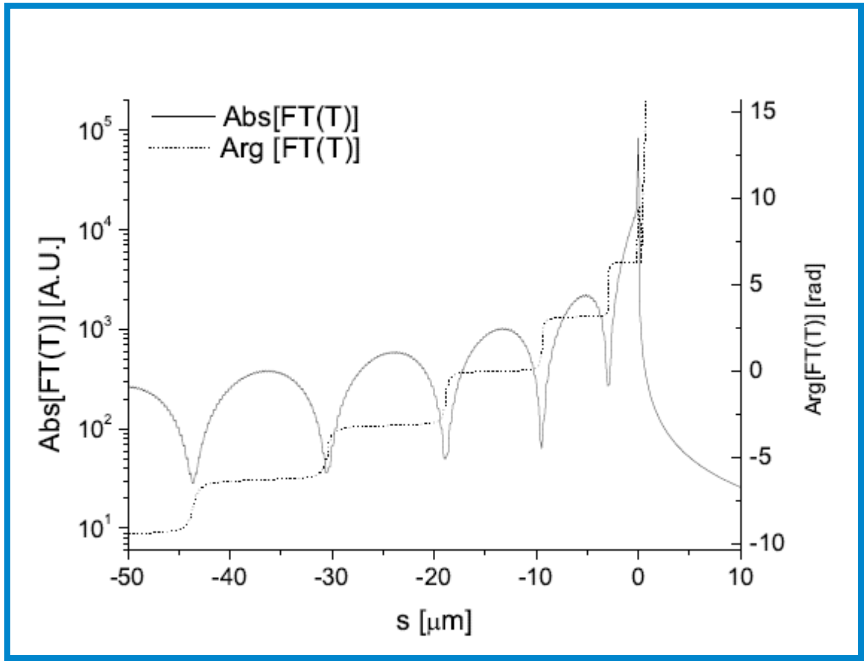
The single-crystal monochromator principle: frequency domain



Working principle for HXRSS

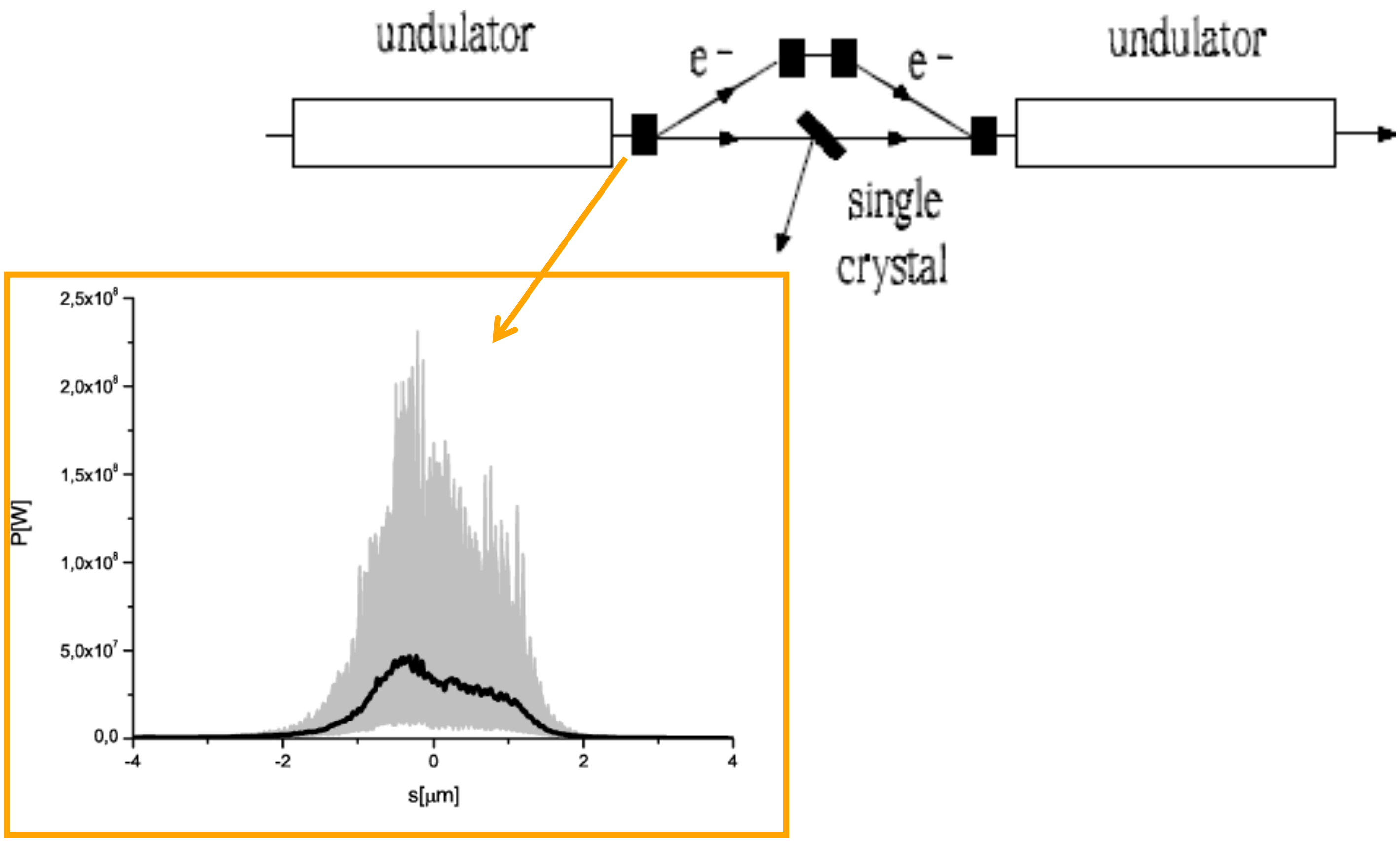
The single-crystal monochromator principle: what happens in the time domain?





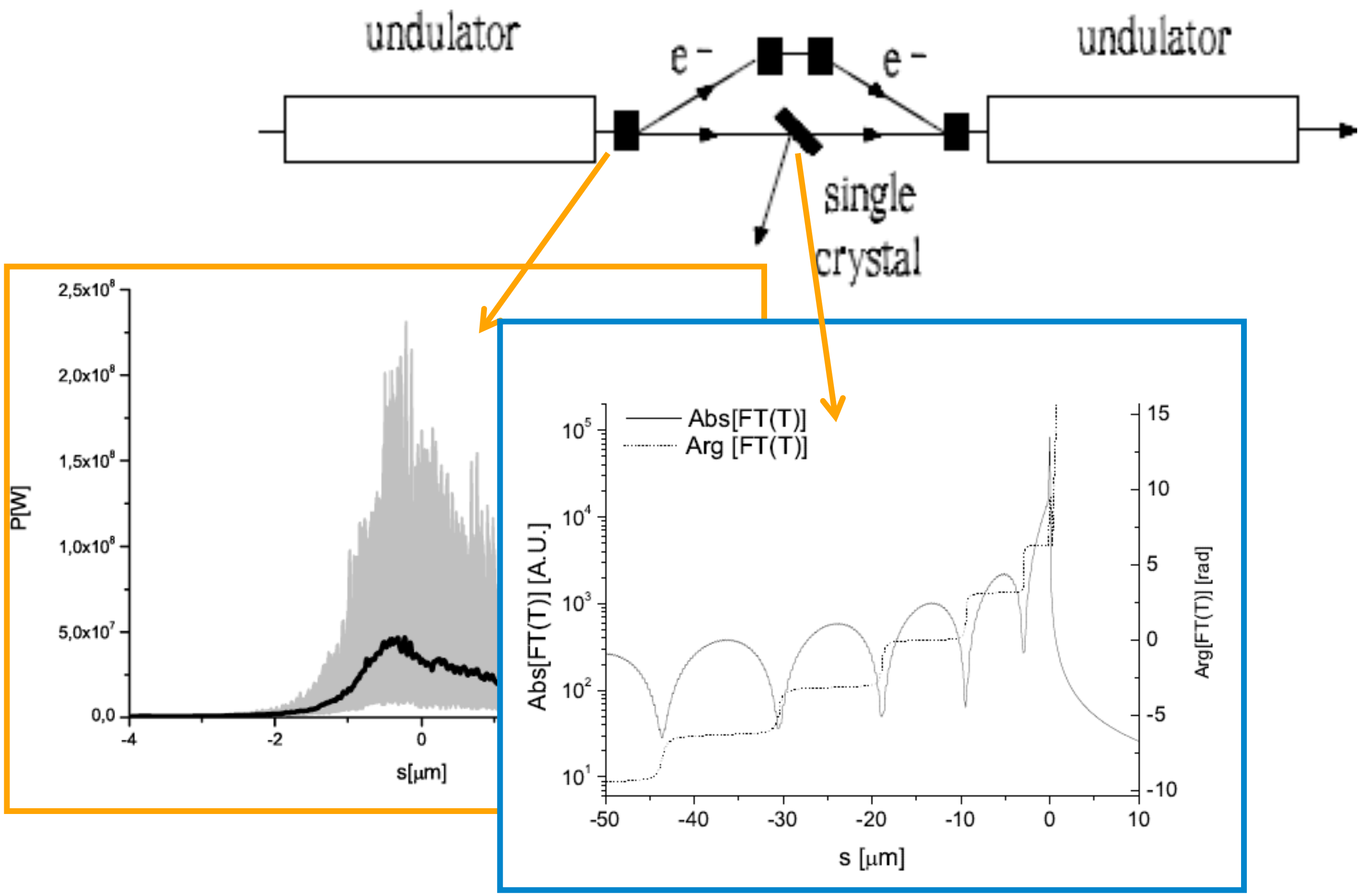
Working principle for HXRSS

The single-crystal monochromator principle: time domain



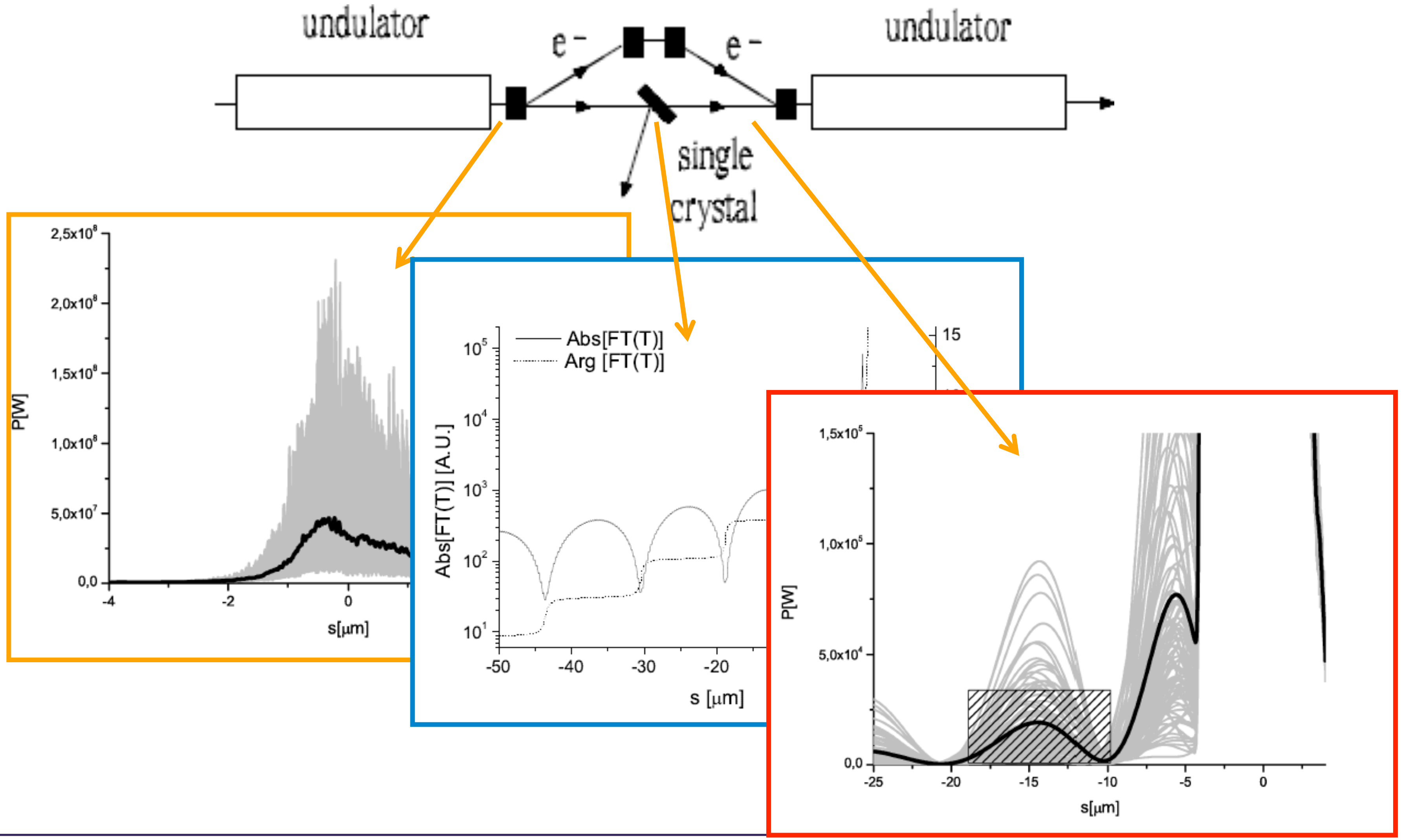
Working principle for HXRSS

The single-crystal monochromator principle: time domain



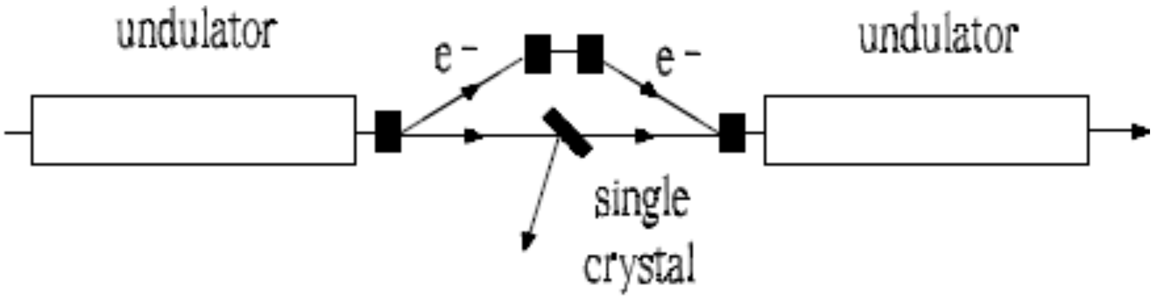
Working principle for HXRSS

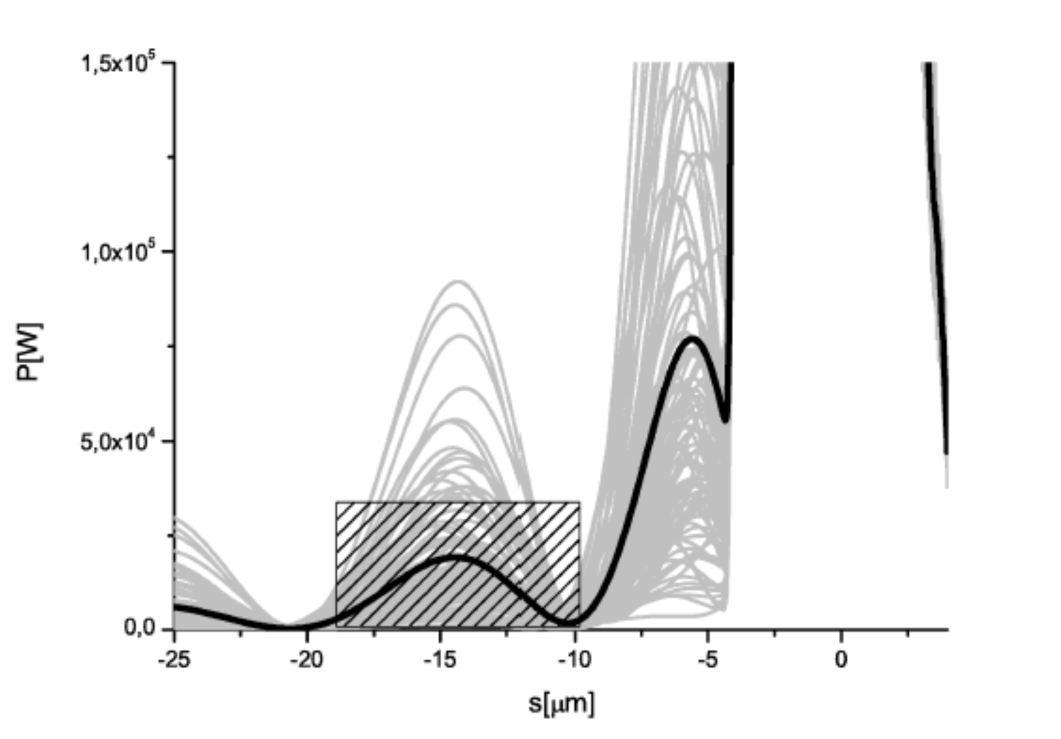
The single-crystal monochromator principle: time domain



Working principle for HXRSS

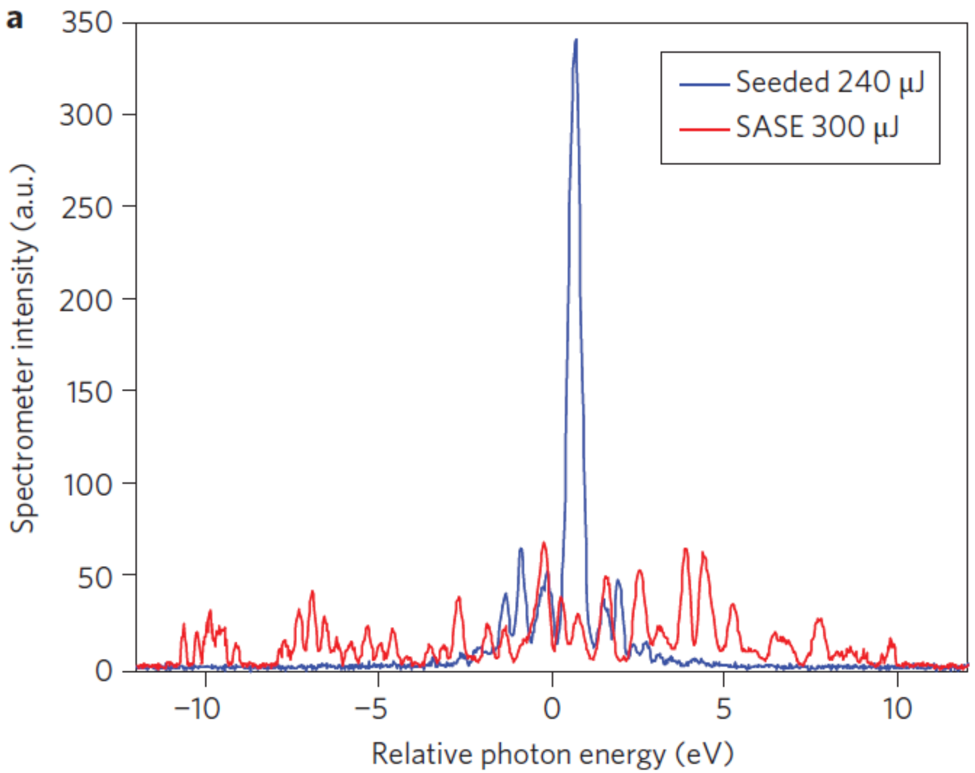
The single-crystal monochromator principle: time domain





Working principle for HXRSS

Experimental verification at the LCLS (Jan 2012)

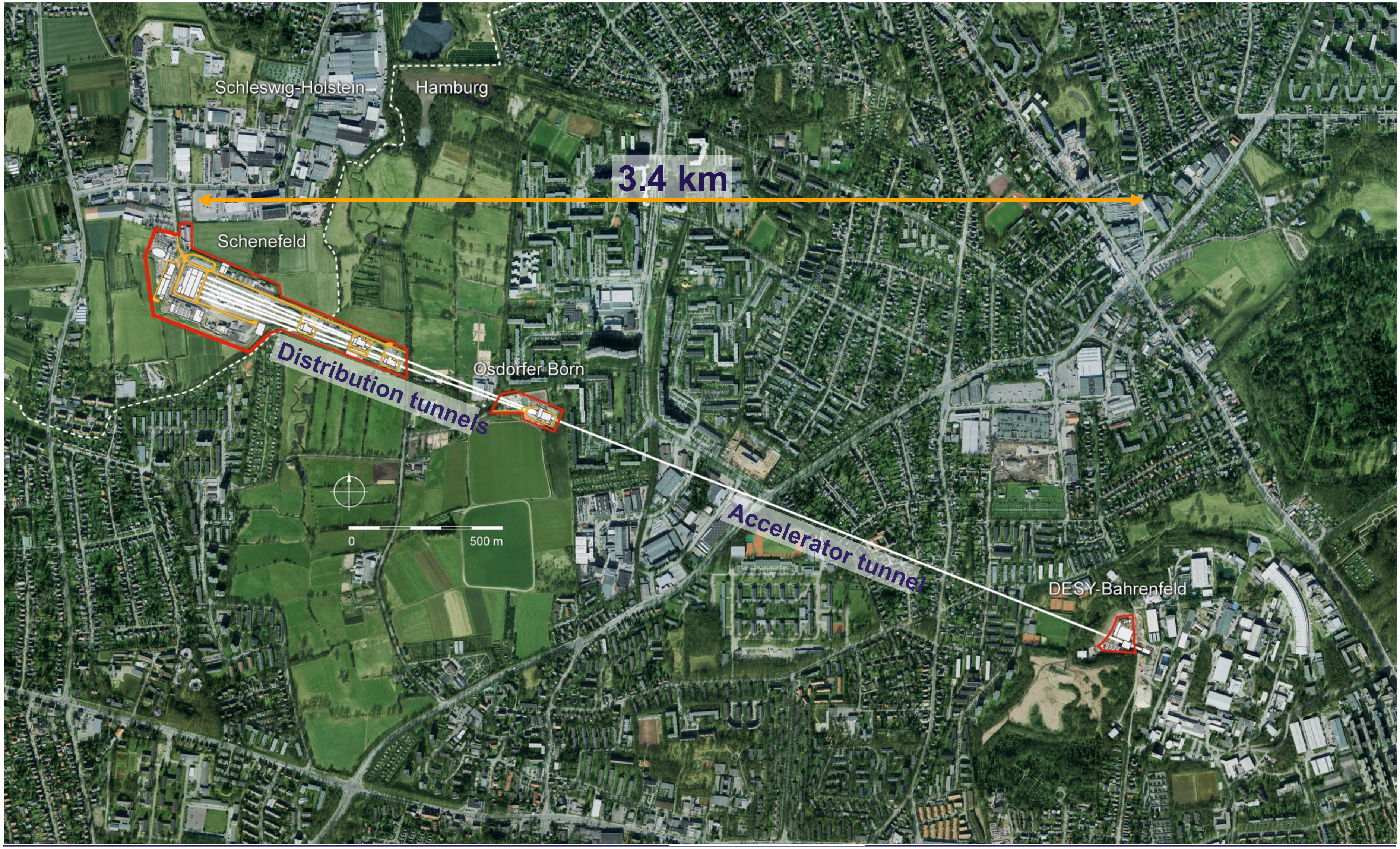


- **Single-shot X-ray SASE spectrum compared with single-shot seeded spectrum at 0.15 nm for a 40pC electron bunch**
- **SASE spectrum is with all 28 undulators in**
- **The seeding increases the spectral density of the FEL pulse.**

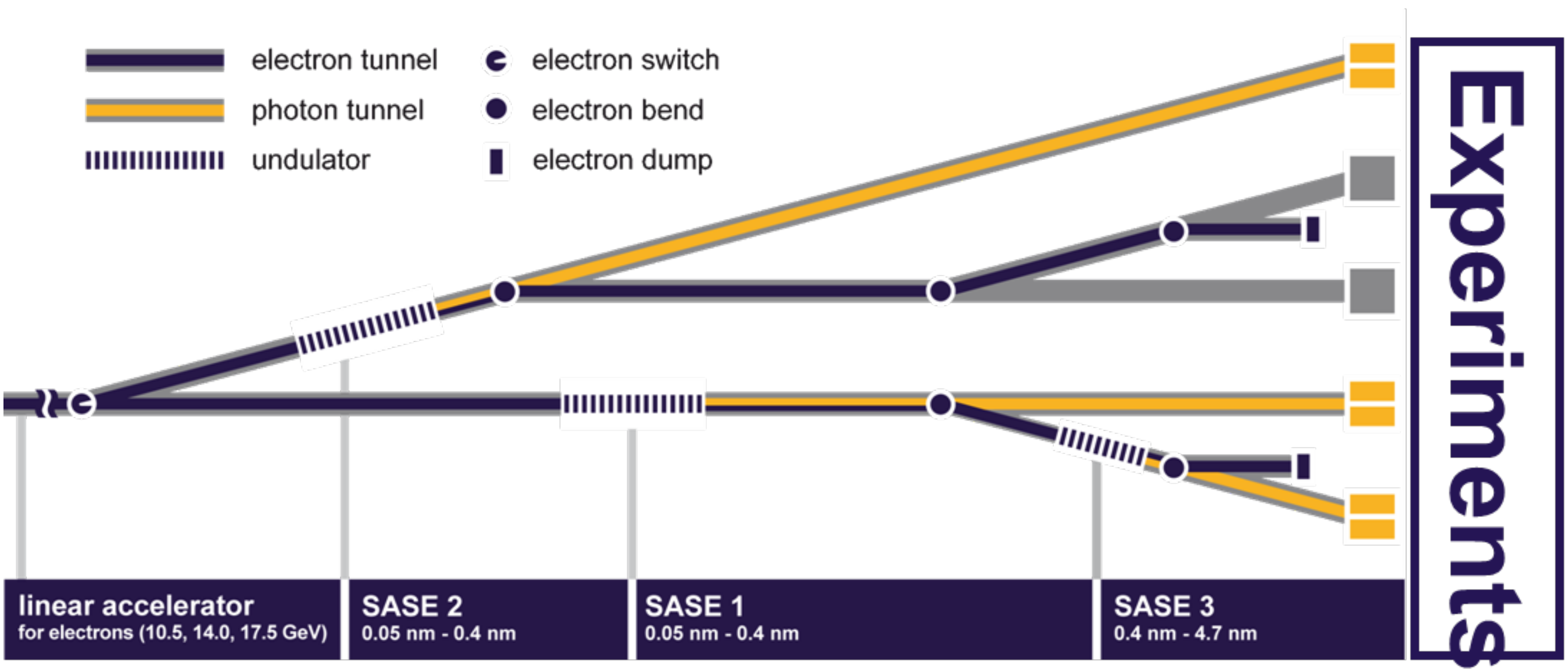
J. Amann et al., Demonstration of self-seeding in a hard-X-ray free-electron laser, NATURE PHOTONICS DOI: 10.1038/NPHOTON.2012.180 (2012)

Plans for HXRSS implementation at the European XFEL

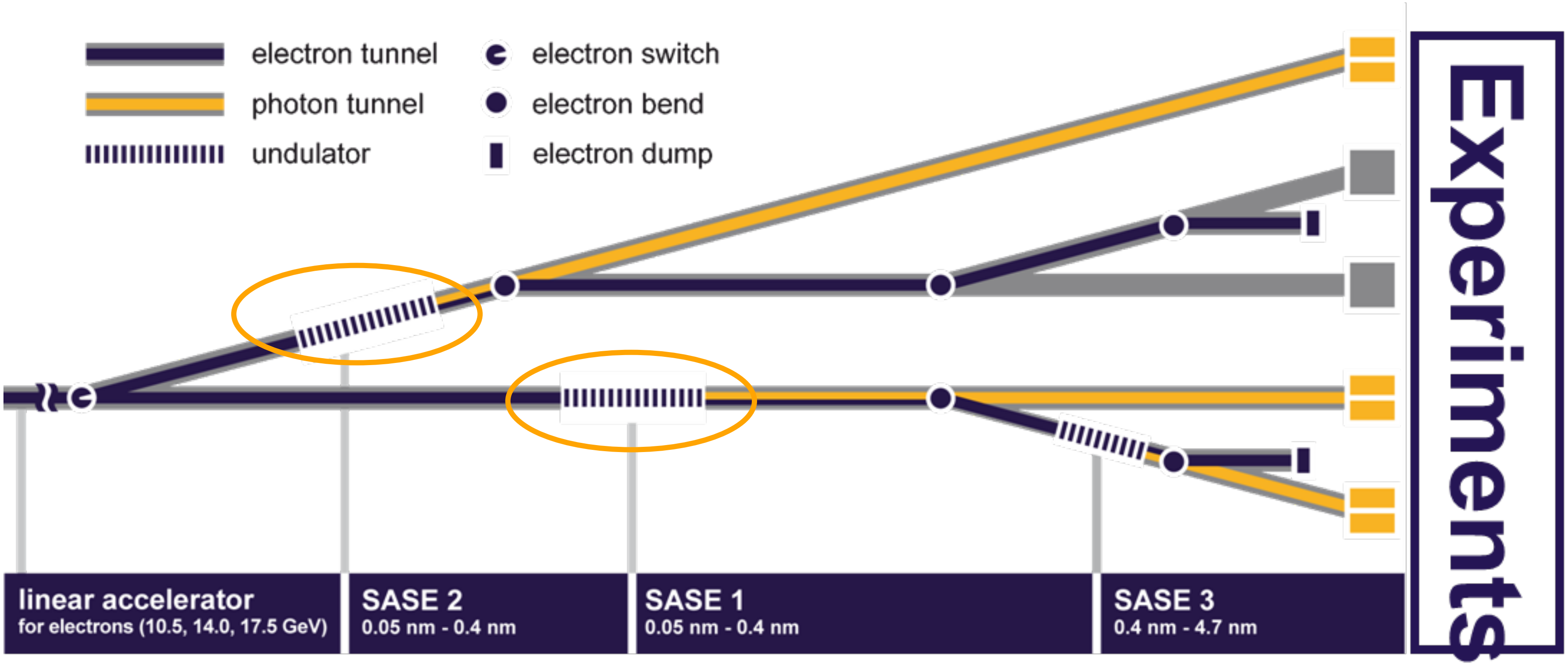
Plans for HXRSS at the European XFEL



Plans for HXRSS at the European XFEL

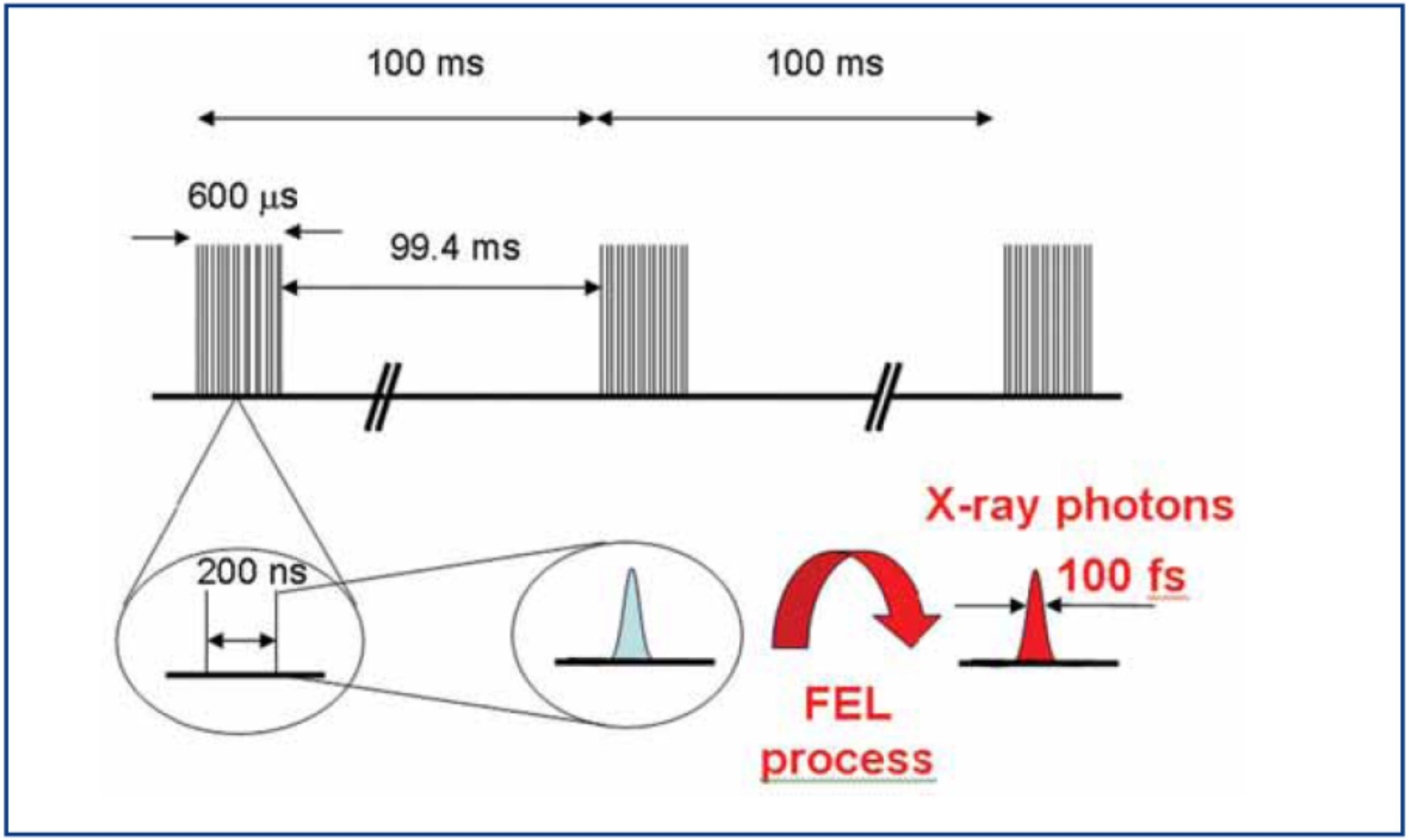


Plans for HXRSS at the European XFEL



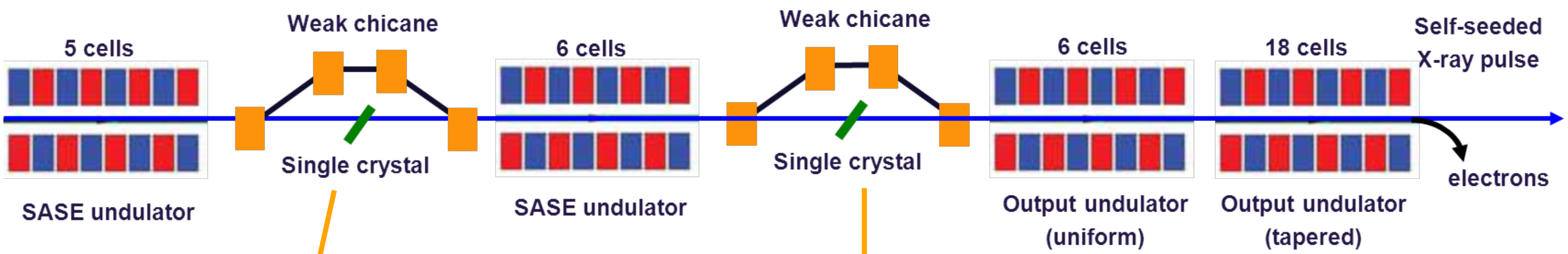
Plans for HXRSS at the European XFEL

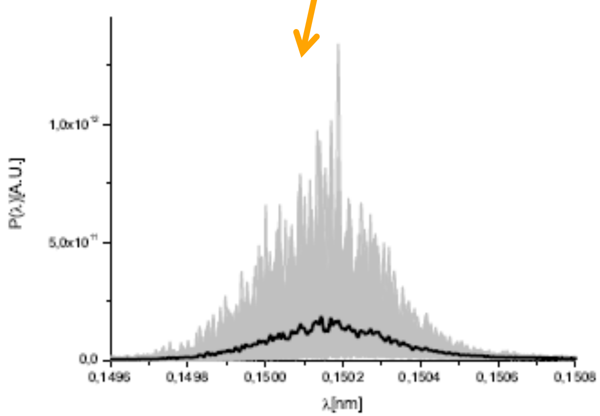
European XFEL pulse repetition rate ~ 27000 Hz → compromise in the first undulator length (heat loading!)

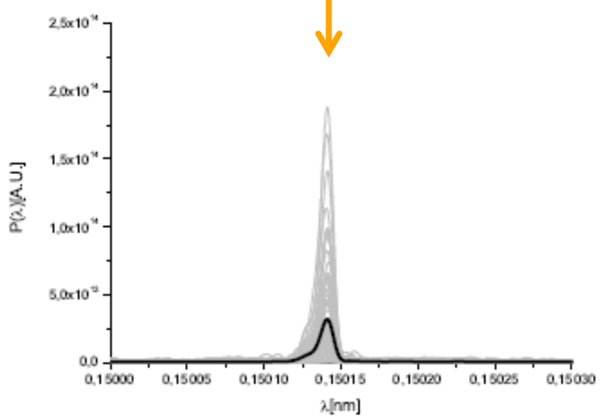


14.0 GeV – 30 pC Working point for HXRSS @ SASE1/2

2 Chicanes





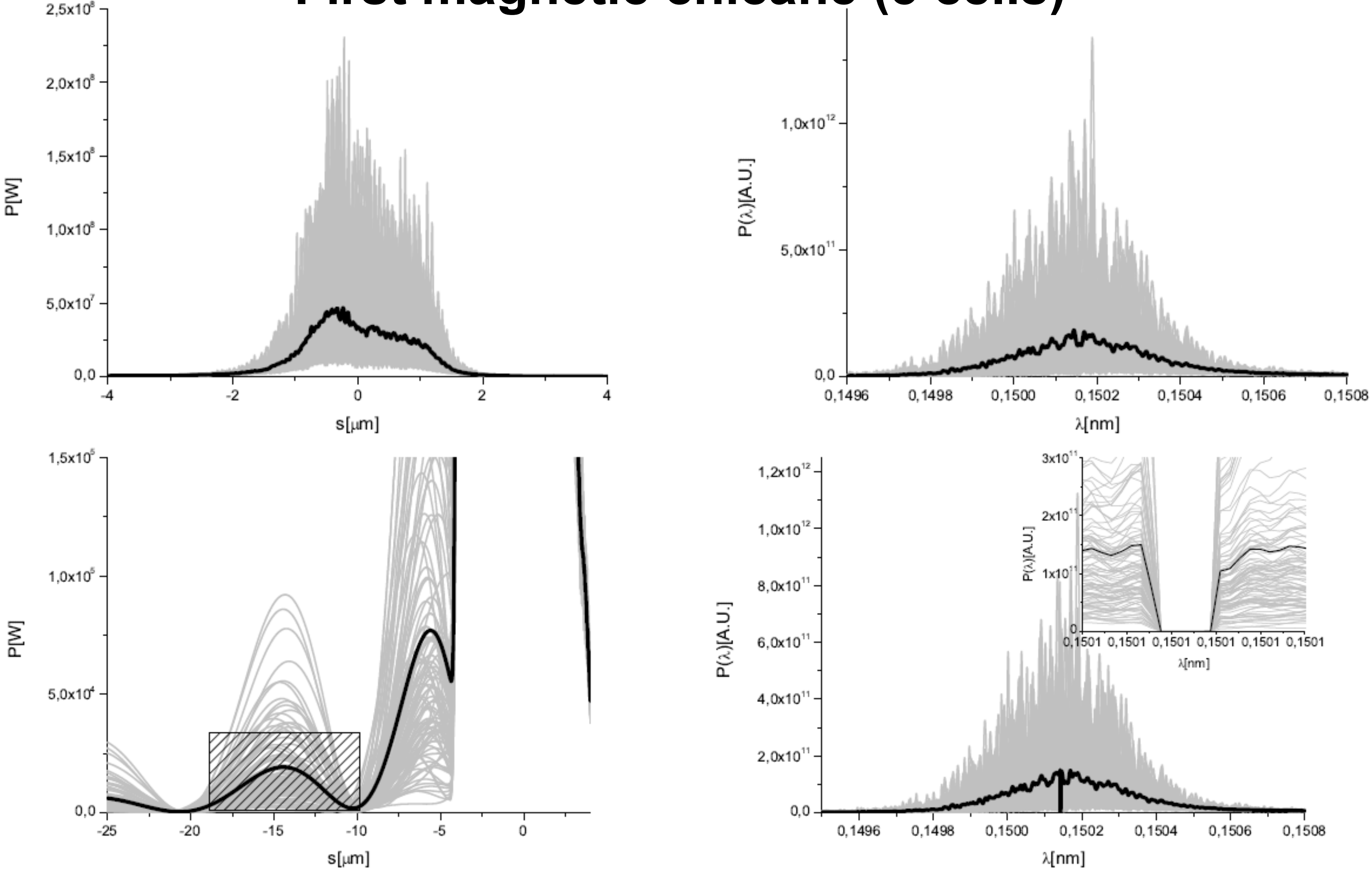


2-Chicanes increase the S/N ratio

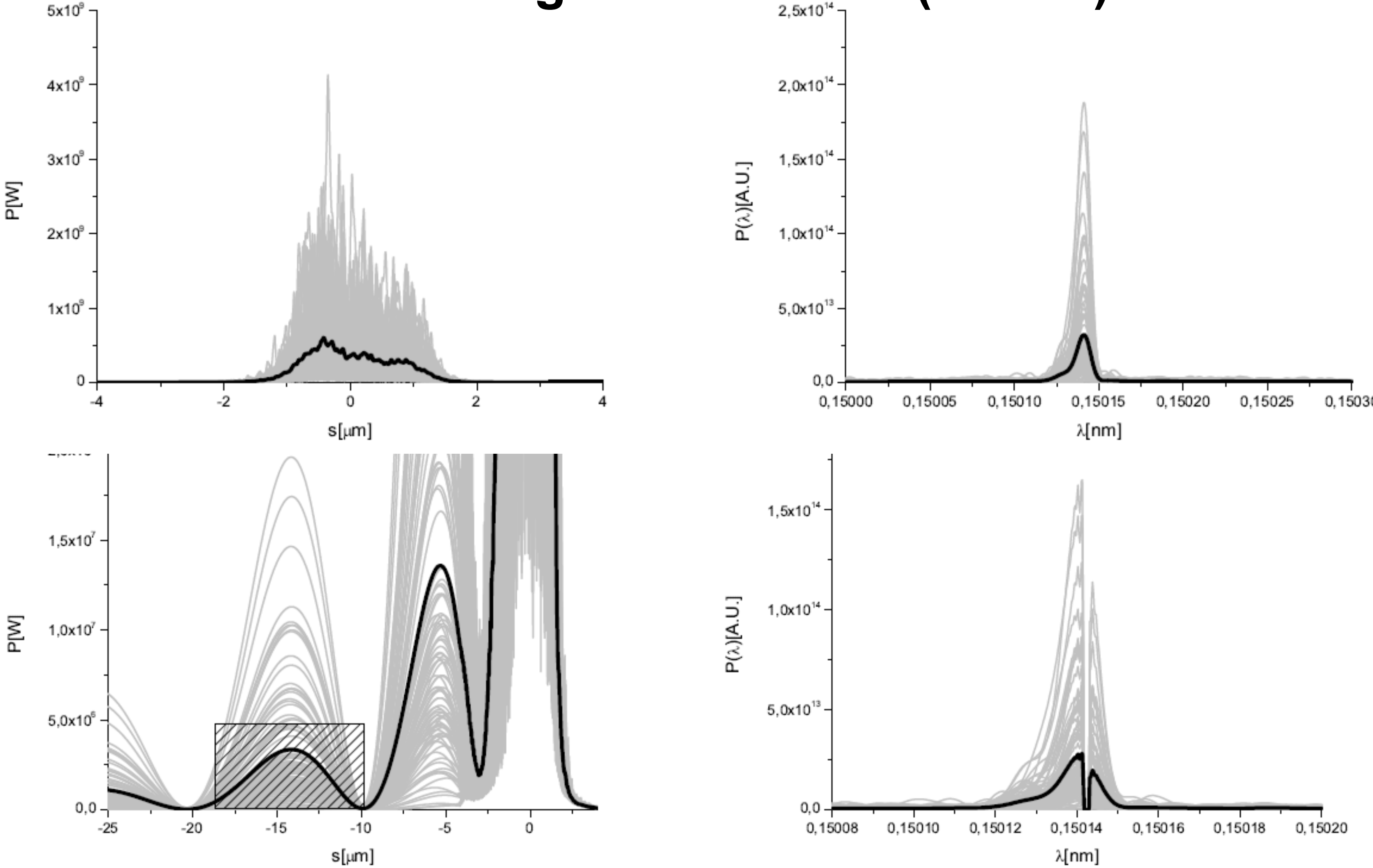
Same power level but different spectra

→ Larger seed on the second crystal

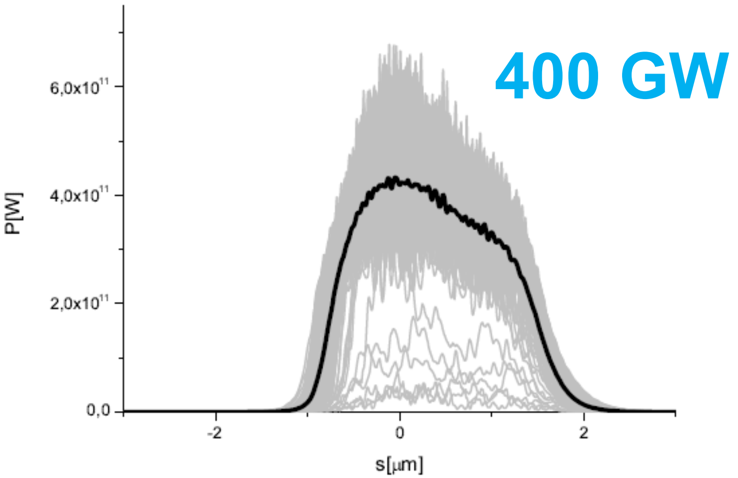
First magnetic chicane (5 cells)

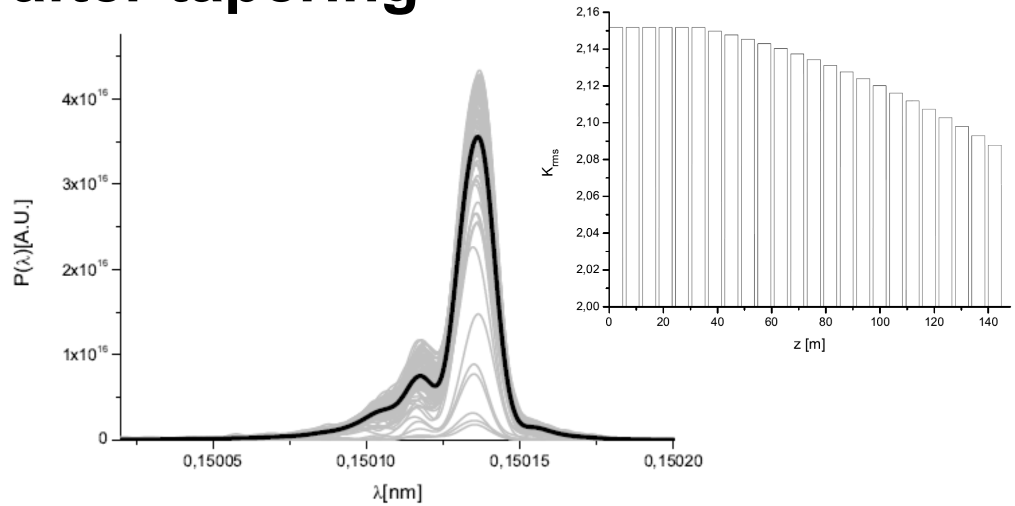


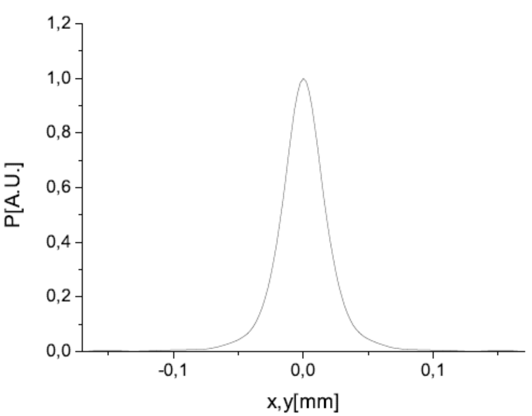
Second magnetic chicane (6 cells)

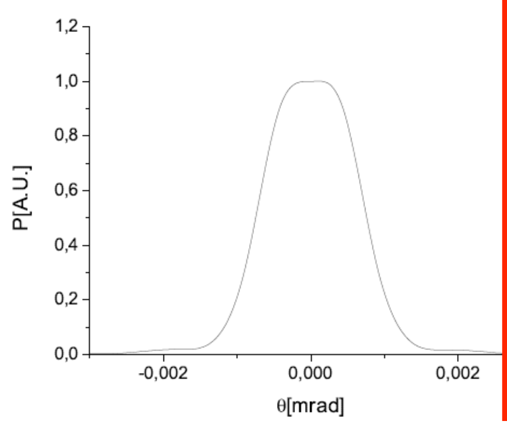


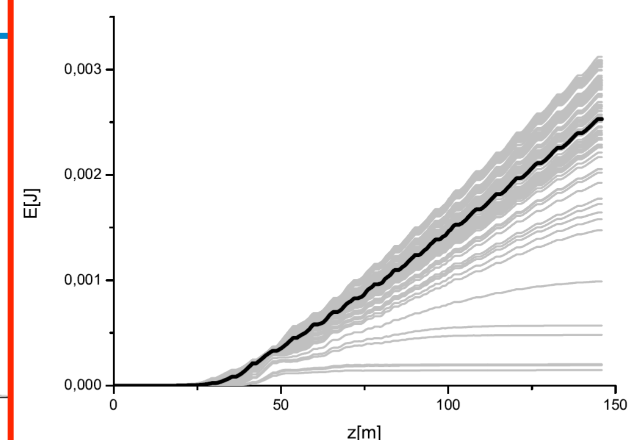
Output after tapering





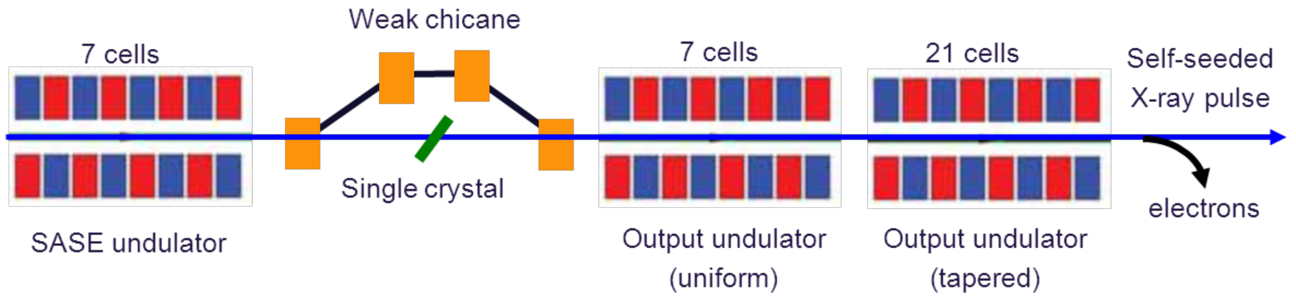




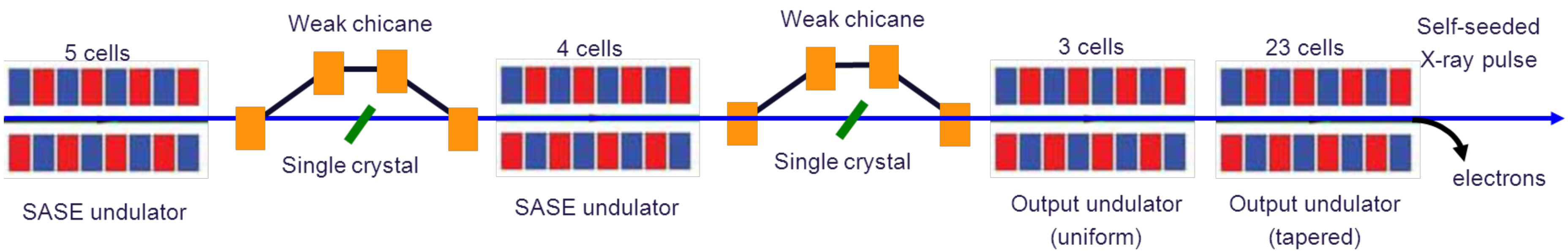


17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane

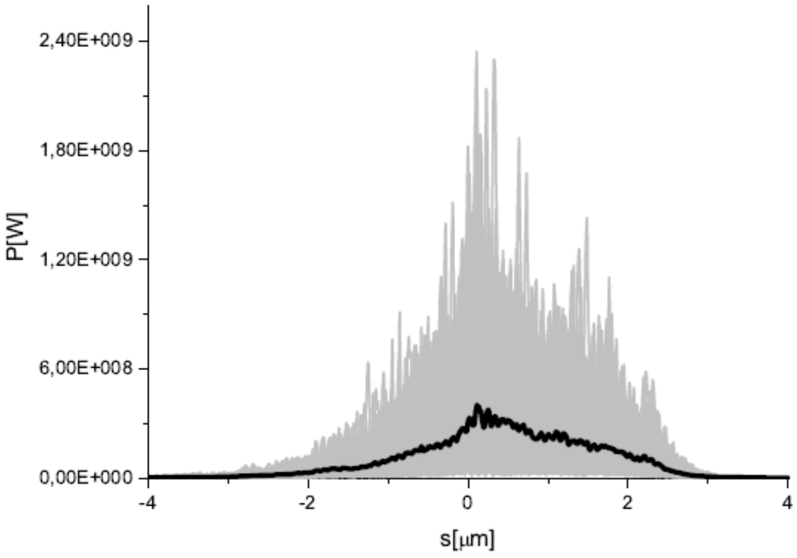


2 Chicanes



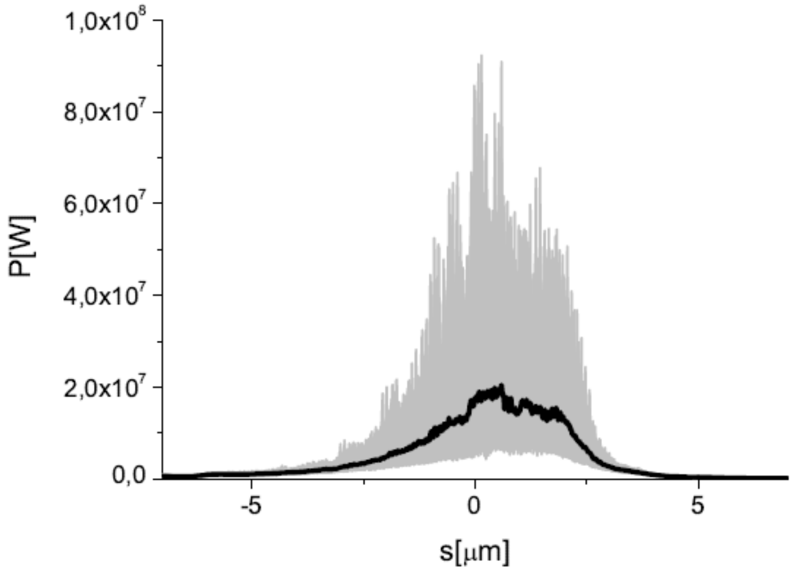
17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane



Power after 7 cells

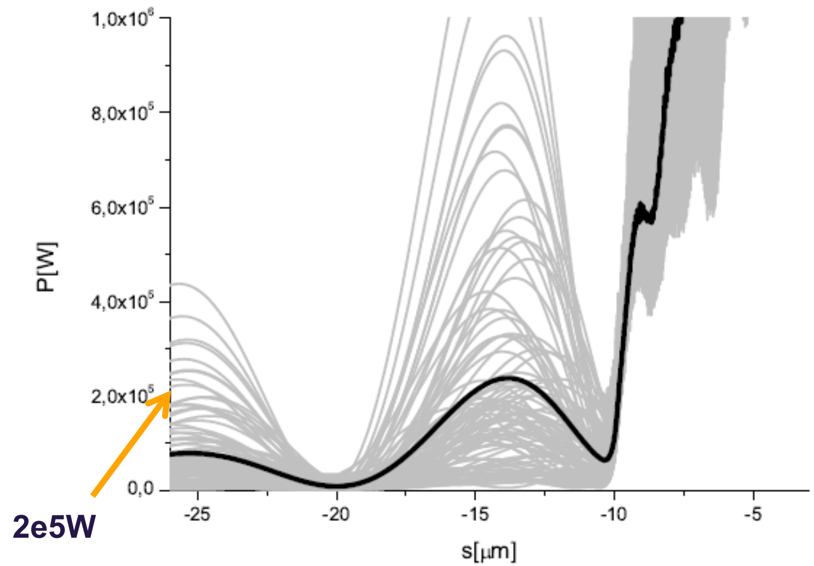
2 Chicanes



Power after 5 cells

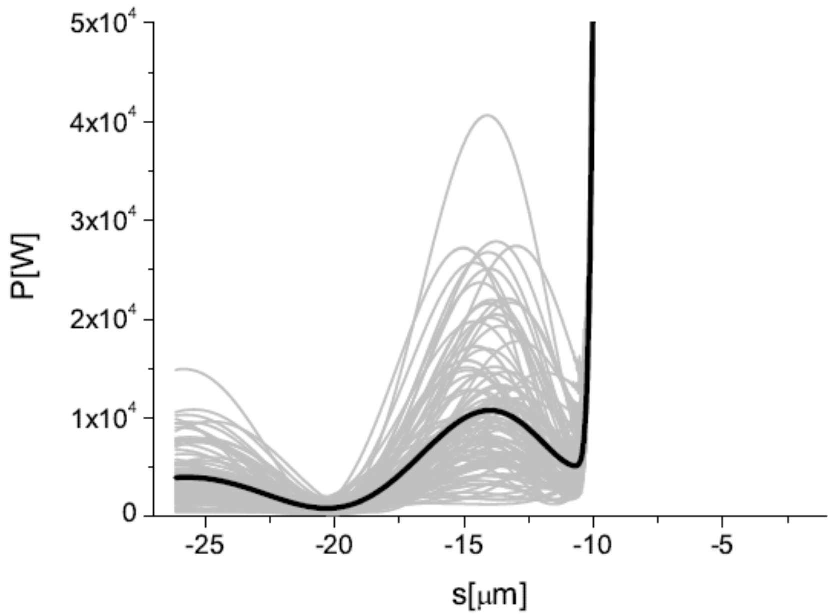
17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane



Seed after 7 cells

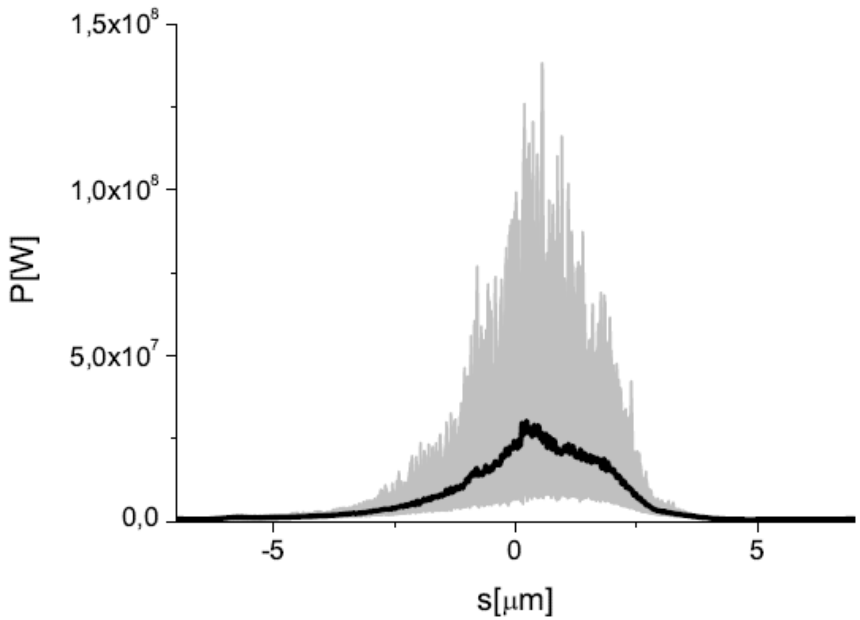
2 Chicanes

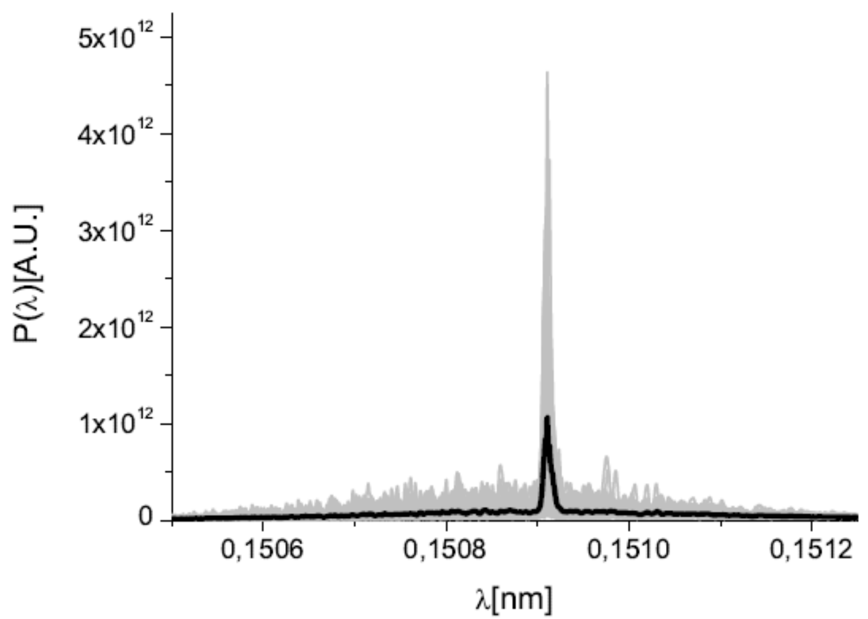


Seed after 5 cells

17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

2 Chicanes



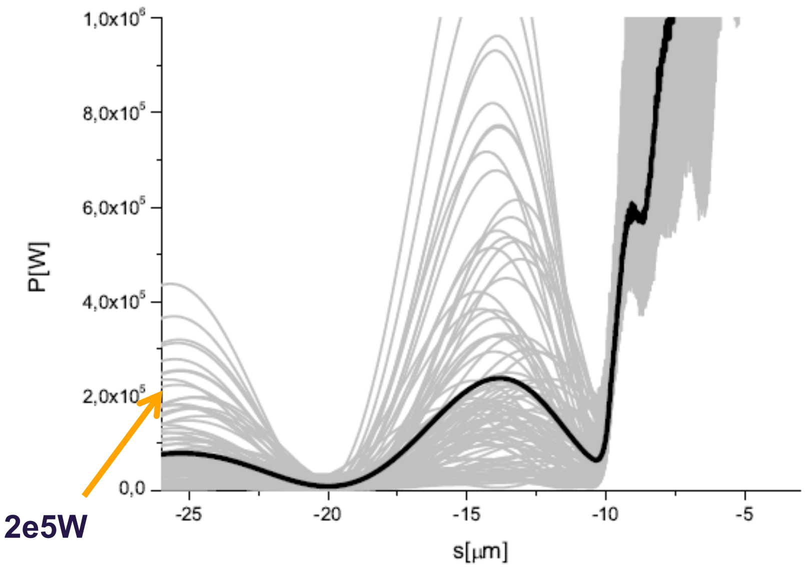


Before the second crystal Power ~ before the first

Spectrum has a monochromatic spike, with large background

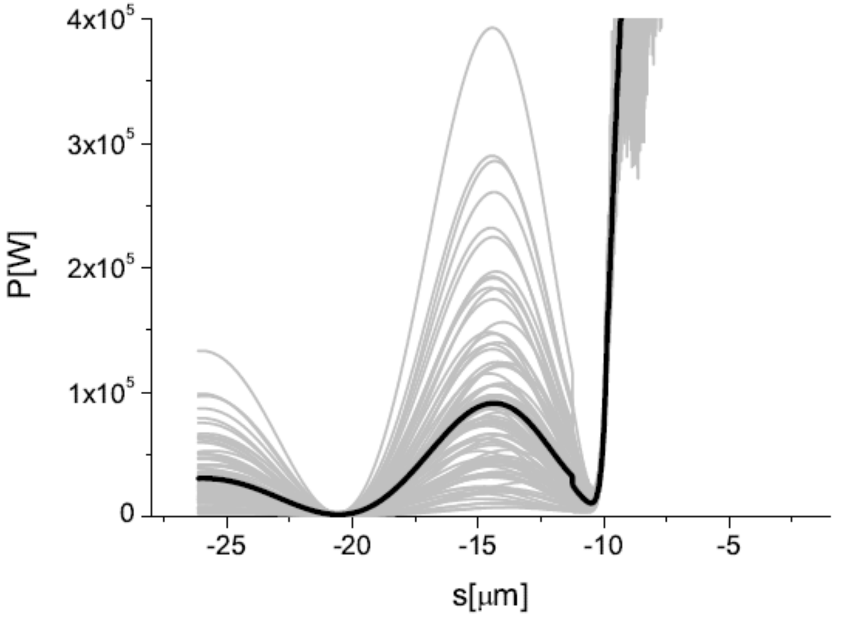
17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane



Seed after 7 cells

2 Chicanes

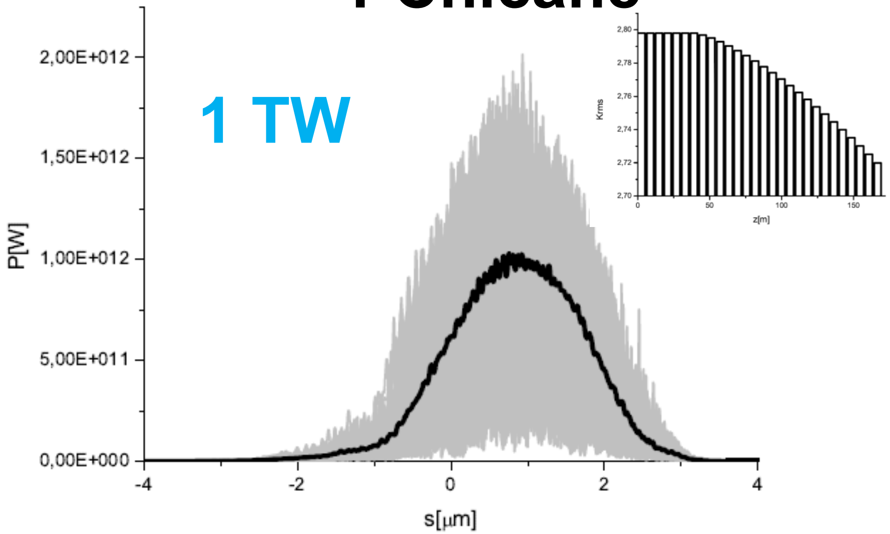


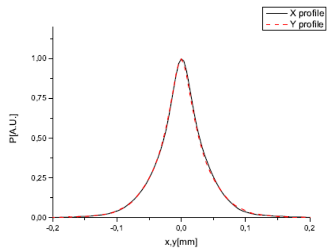
Seed after the second crystal

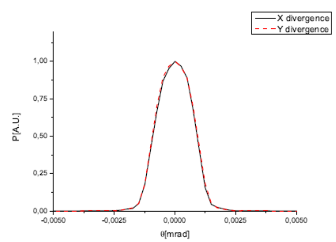
5 cells + 4 cells

17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane

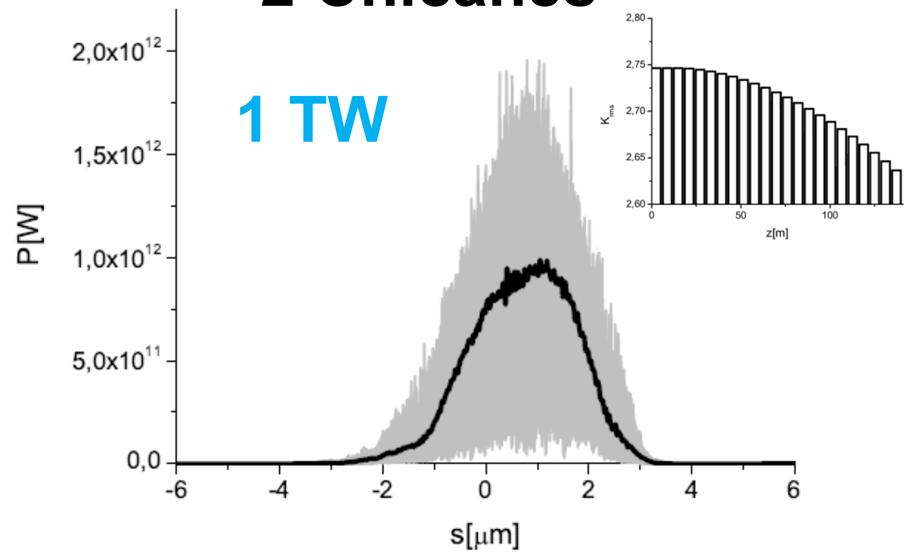


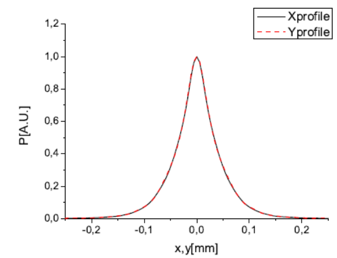


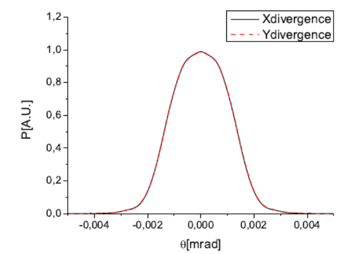


Final power

2 Chicanes





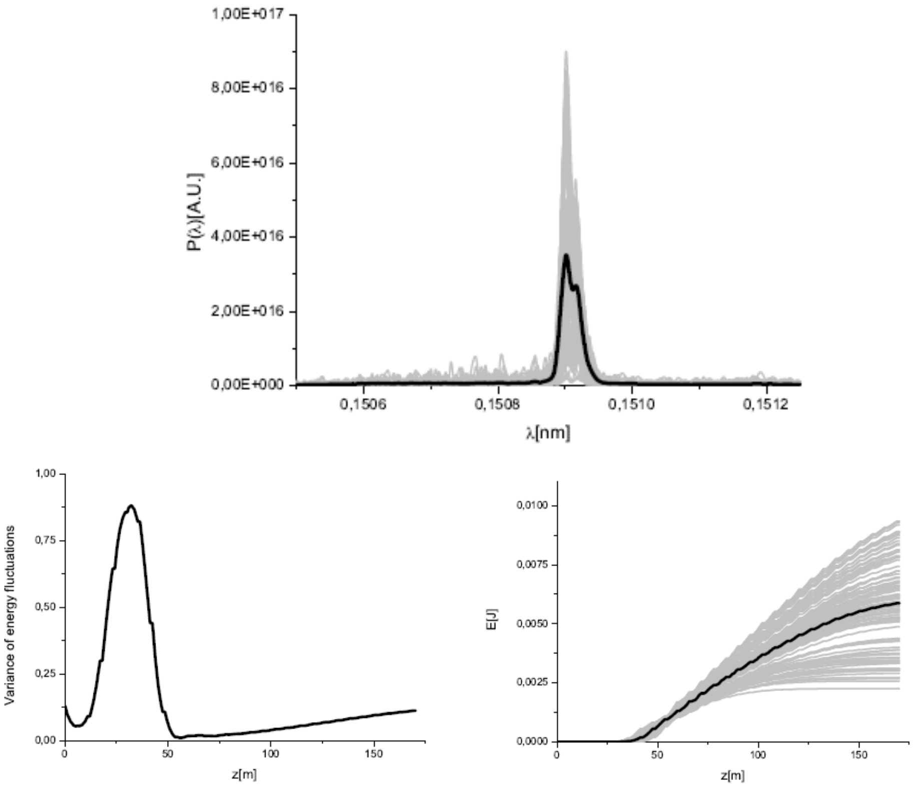


Final power

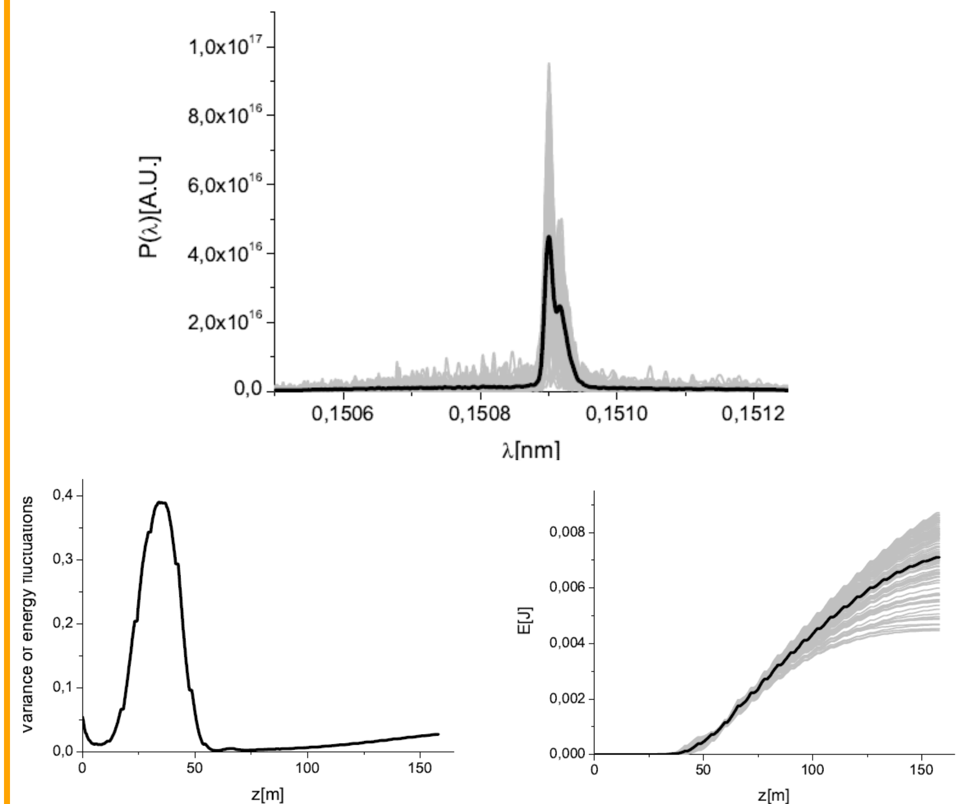
Plans for HXRSS at the European XFEL

17.5 GeV – 100 pC -Working point for HXRSS @ SASE1/2

1 Chicane



2 Chicanes



Present status:

- Supported by MB
- Supported by SAC, MAC
- Supported by Council

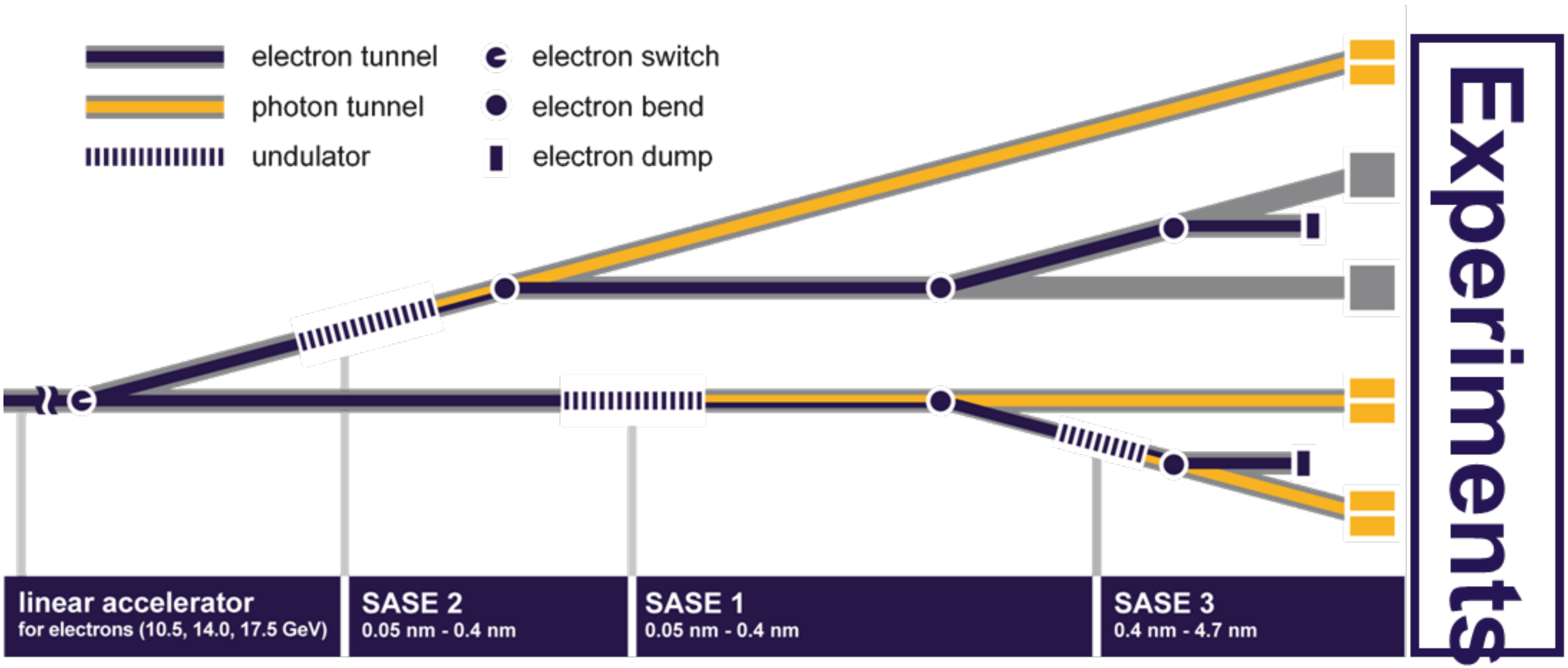
- Need to start detailed design

Ideas beyond the baseline

Present status:

- An idea by V.K., E.S., G.G.
- Discussions taking place

Ideas beyond the baseline



Ideas beyond the baseline

Motivation: imaging of interesting biological structures

	NON-VARIABLE	VARIABLE
PERIODIC	Nanocrystals	DNA, microtubules, viral capsides
NON-PERIODIC	Viruses, molecular machines	Small cells, organelles

Interesting biostructure size vary: 10nm – 1000nm
Resolution required ~ 0.3 nm
N. Biostructures < 10nm ~ 1e5
N. Biostructures 10nm-600nm ~ 1e9
→ Focal spot requirements varies with size

Source Requirements - Nanocrystallography (LCLS-II New Instruments Workshop rep.):

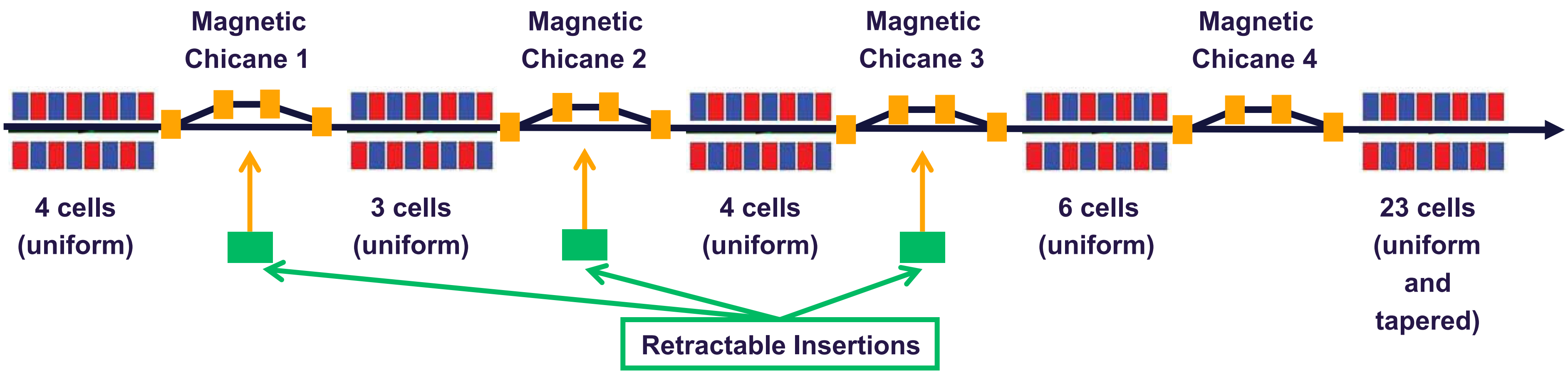
- TW-level peak power (focused down to 0.3-3 micron diameter)
- Variable energy range between 2keV and 14 keV

Source Requirements - Non-periodic samples (LCLS-II New Instruments Workshop rep.):

- 1e13 – 1e14 ph/pulse (focused down to 1-3 micron spot)
- Variable energy range between 3keV and 5keV; 0.5keV – 2keV for largest objects

A recipe for a dedicated bio-imaging undulator system

Proposed scheme:



Pulse Characteristics:

- Extremely high pulse peak power: ~1-2 TW
- Photon pulse duration tunability: 2 fs-10 fs
- Very large energy range: 0.3 keV – 13 keV

- **Sketch is not in scale: (40+4) cells x 6.1 m ~ 270 m (SASE1-2 → 35 cells)**
- **Scheme makes use of SASE3 type undulators (energy tunability)**
- **Great flexibility ←→ elaborated design: combination of self-seeding, fresh-bunch, undulator-tapering techniques**

A recipe for a dedicated bio-imaging undulator system

Full energy range can be covered with two electron beam energies (10.5 GeV – 17.5 GeV ; 100 pC):

A) e-beam in the 10.5 GeV operation mode:

i. Water window (C K-edge @ 0.28 keV – O K-edge @ 0.54 keV)

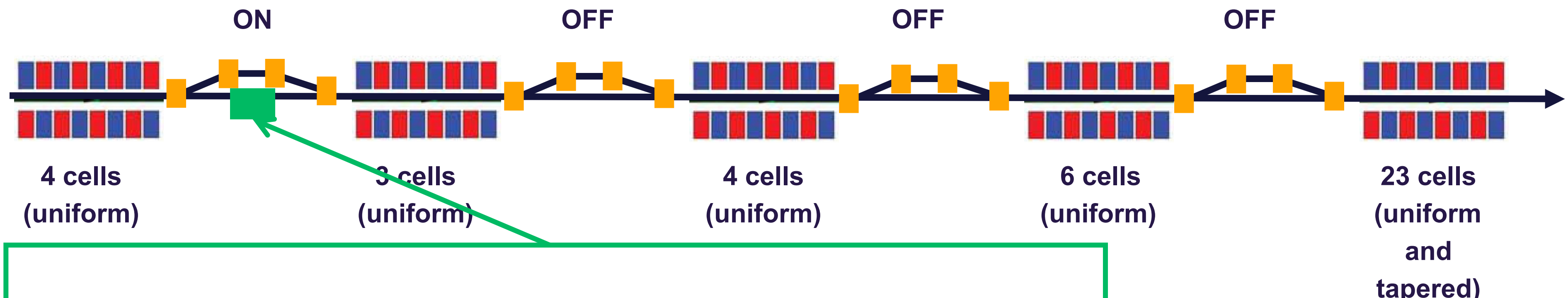
B) e-beam in the 17.5 GeV operation mode:

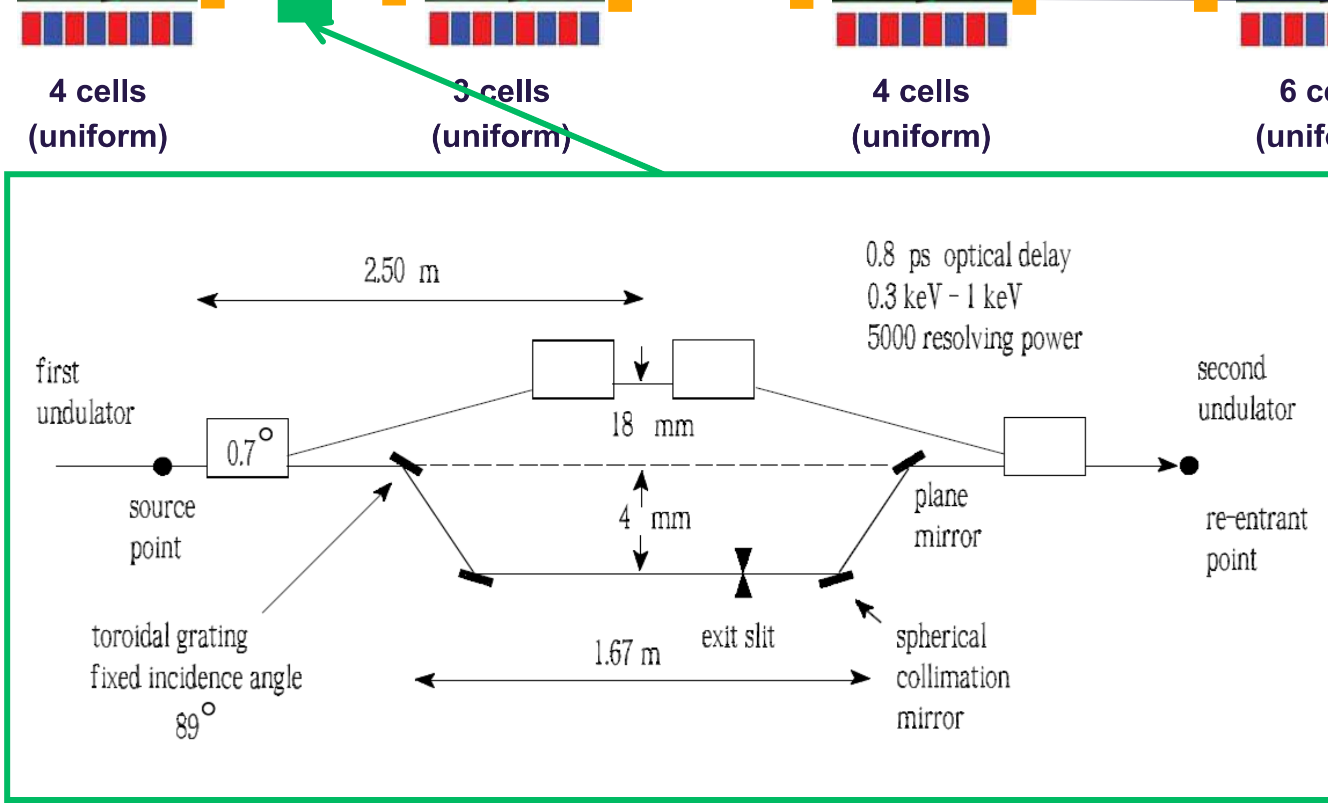
i. 2 keV – 3 keV (Sulfur K-edge @ 2.472 keV)
ii. 3 keV – 5 keV
iii. 5 keV – 7 keV
iv. 7 keV – 9 keV
v. 9 keV – 13 keV (Selenium K-edge @ 12.66 keV)

→ Little or no interference with other European XFEL beamlines

→ Dedicated operation for >4000 hours/year

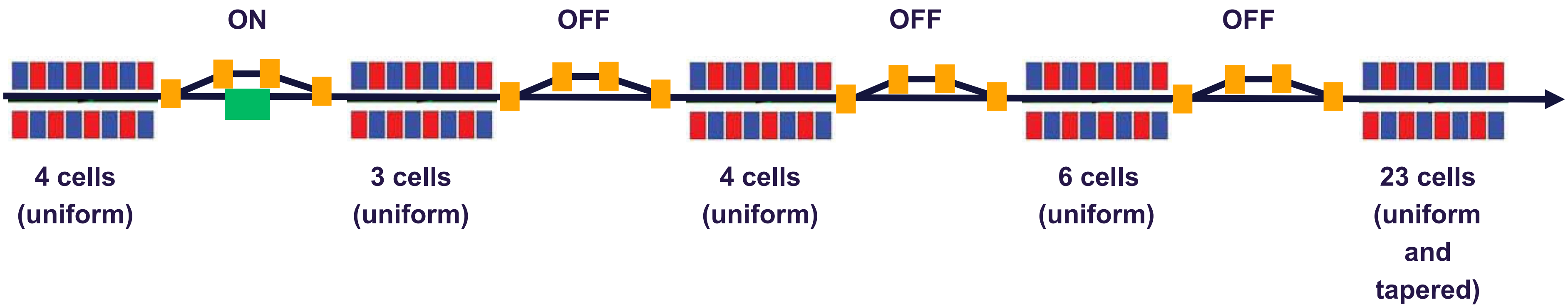
Operation in the water window and beyond (< 1keV)

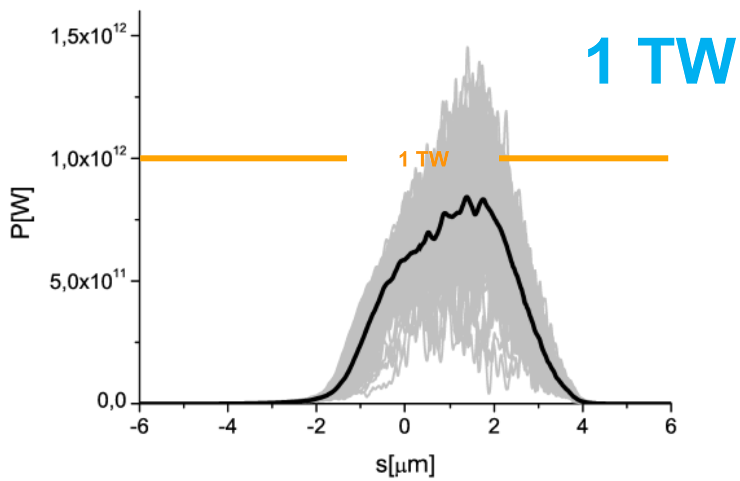


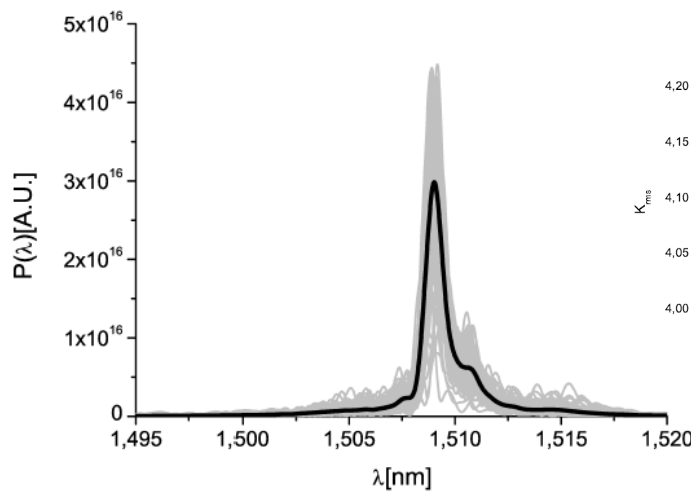


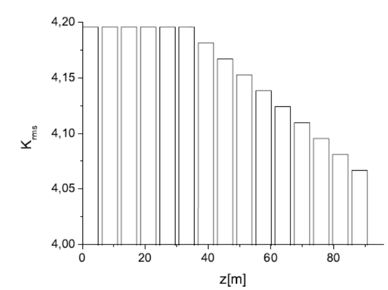
Y. Feng et al., "System design for self-seeding the LCLS at soft X-ray energies", to appear in the Proceedings of the 24th International FEL Conference, Nara, Japan (2012).

Operation in the water window and beyond (< 1keV)

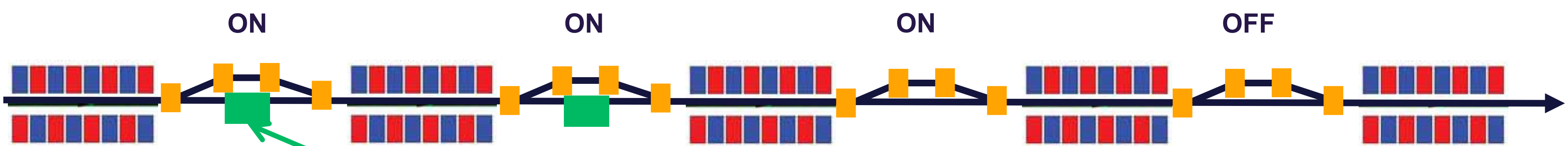




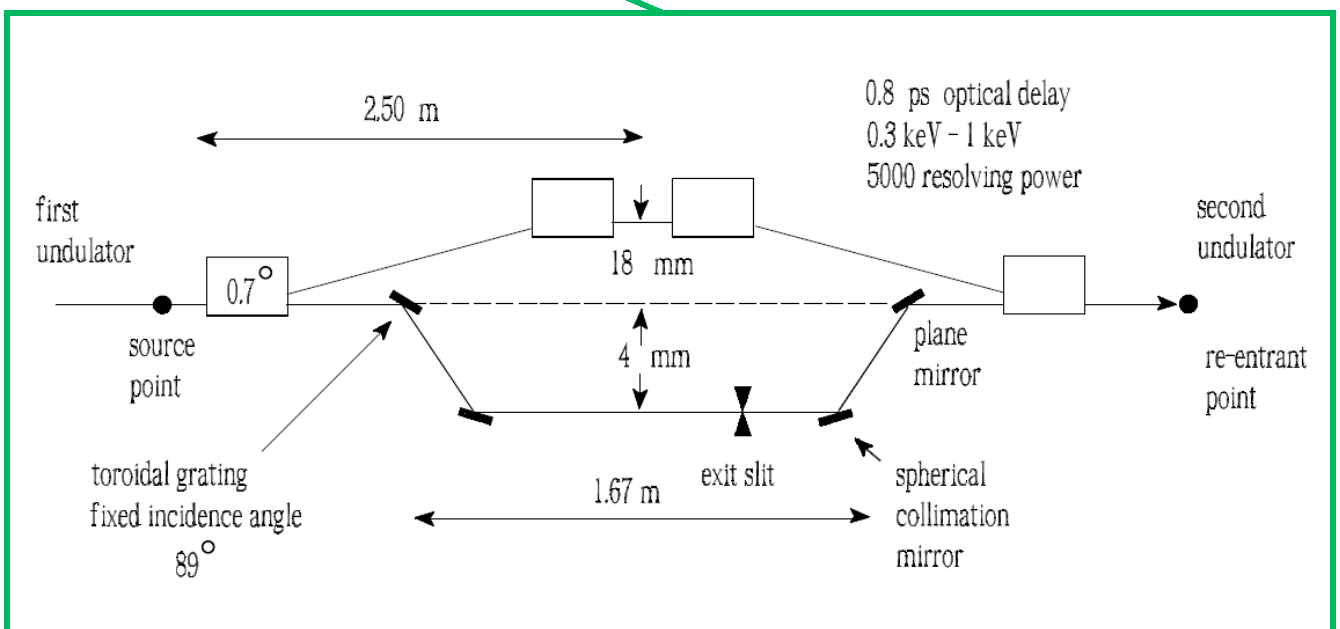




Operation around the Sulfur K-edge: 2 keV – 3 keV



4 cells (uniform) | 3 cells (uniform) | 4 cells (uniform) | 6 cells (uniform) | 23 cells (uniform and tapered)



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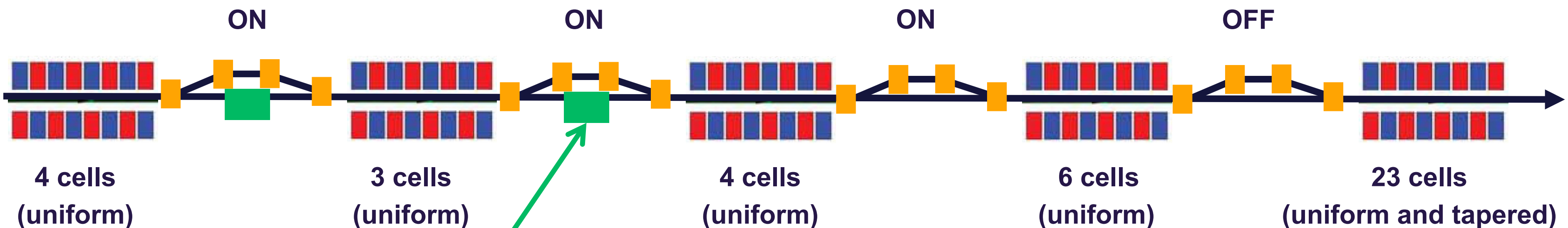
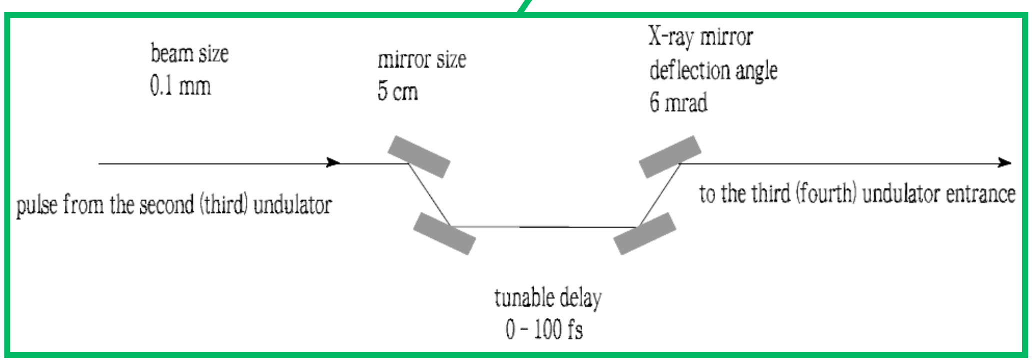
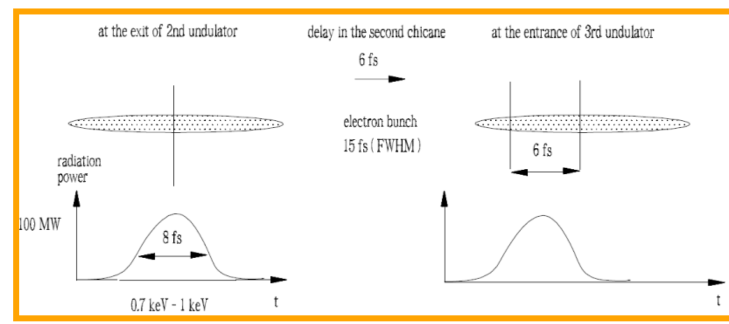
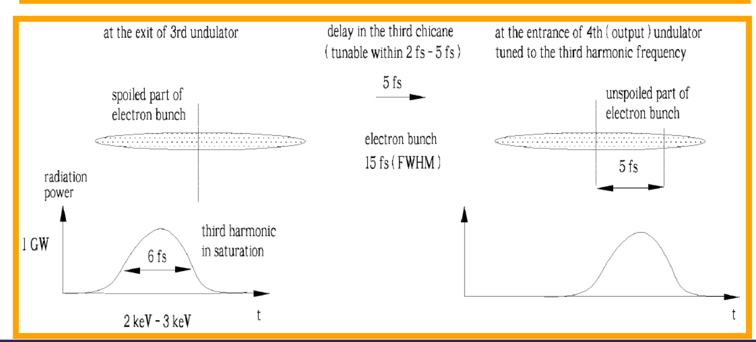
Operation around the Sulfur K-edge: 2 keV – 3 keV



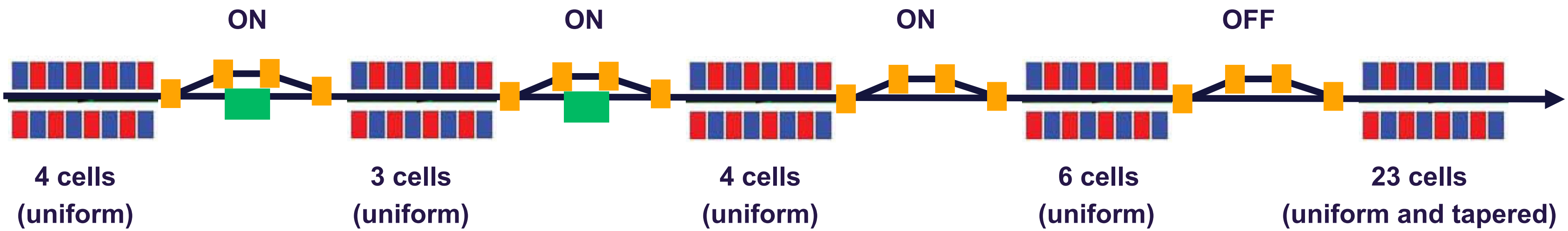


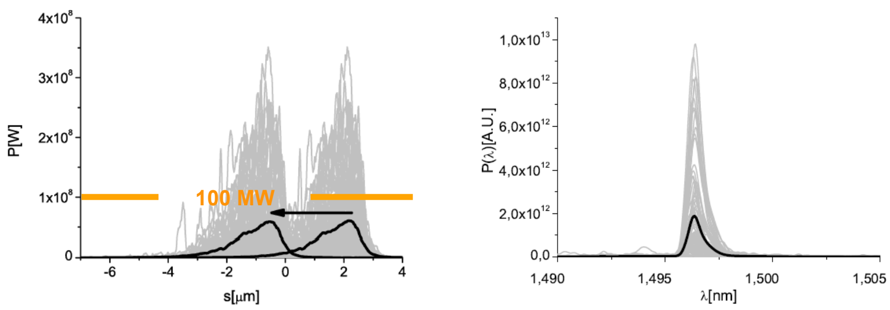




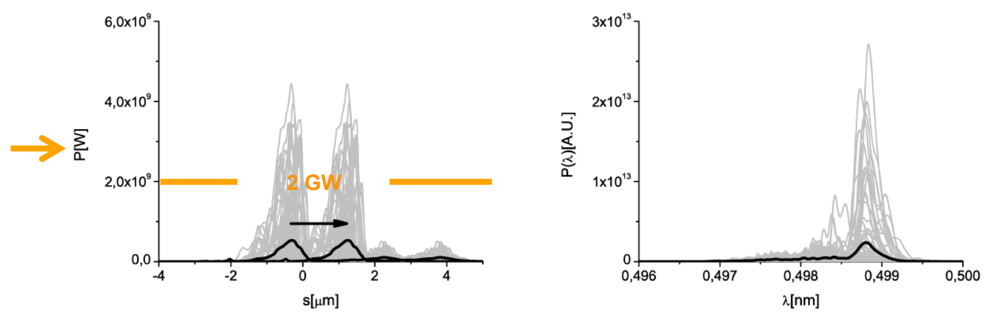
The second chicane now hosts a tunable X-ray mirror delay line

Operation around the Sulfur K-edge: 2 keV – 3 keV



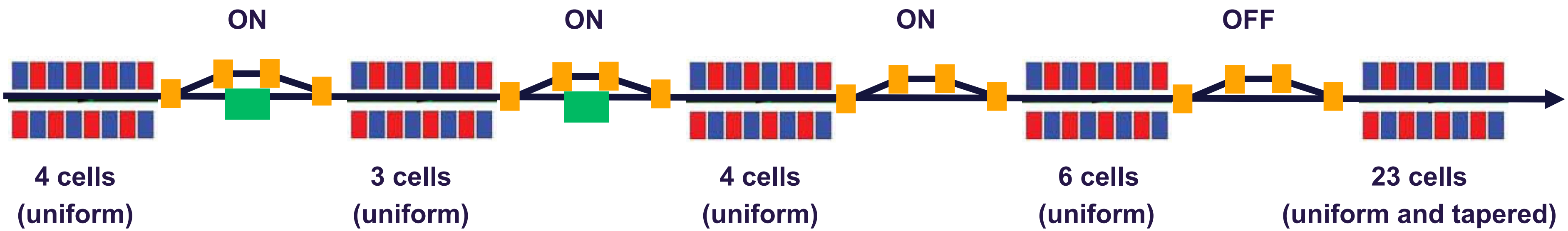


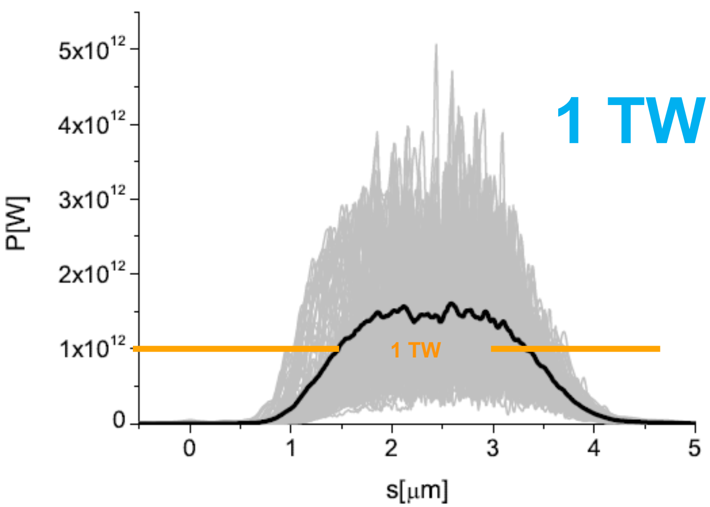
I harmonic after the second chicane

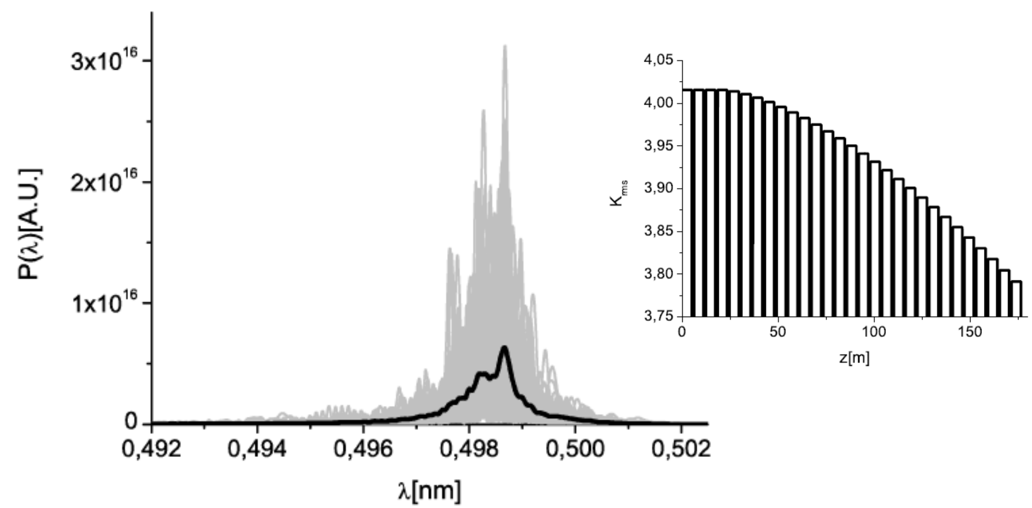


III harmonic after the third chicane

Operation around the Sulfur K-edge: 2 keV – 3 keV

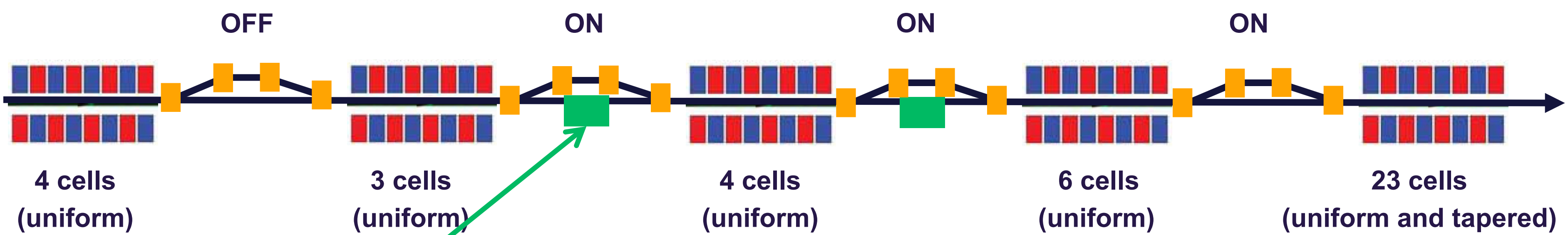


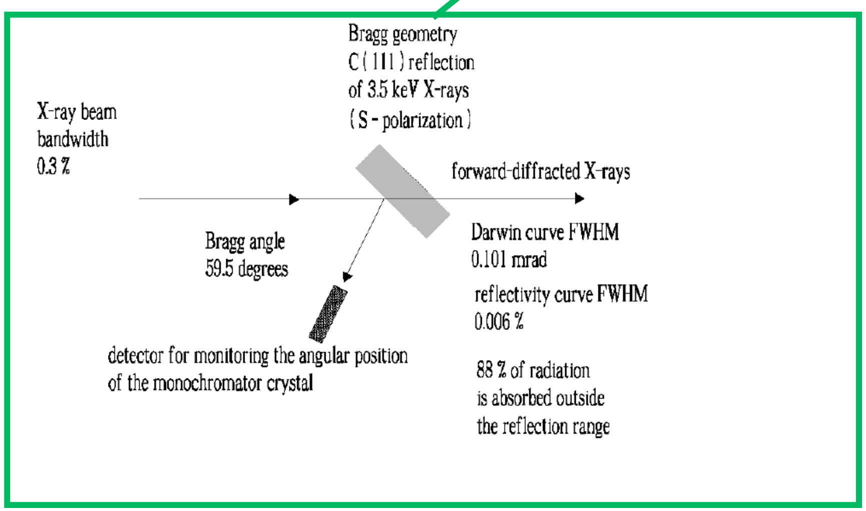


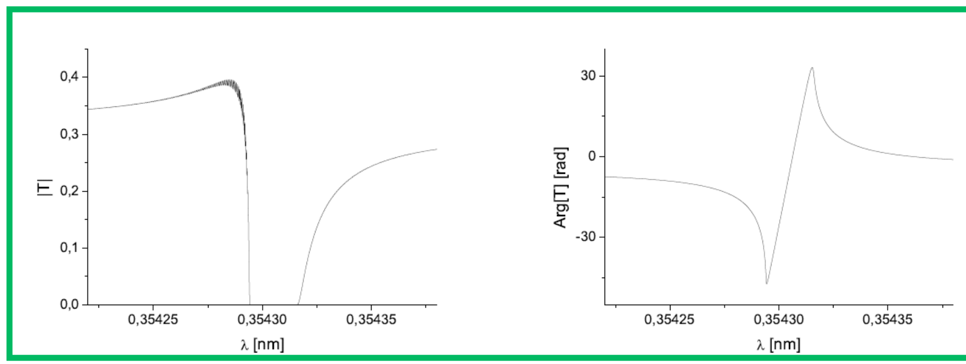


A recipe for a dedicated bio-imaging undulator system

Operation in the energy range: 3 keV – 5 keV



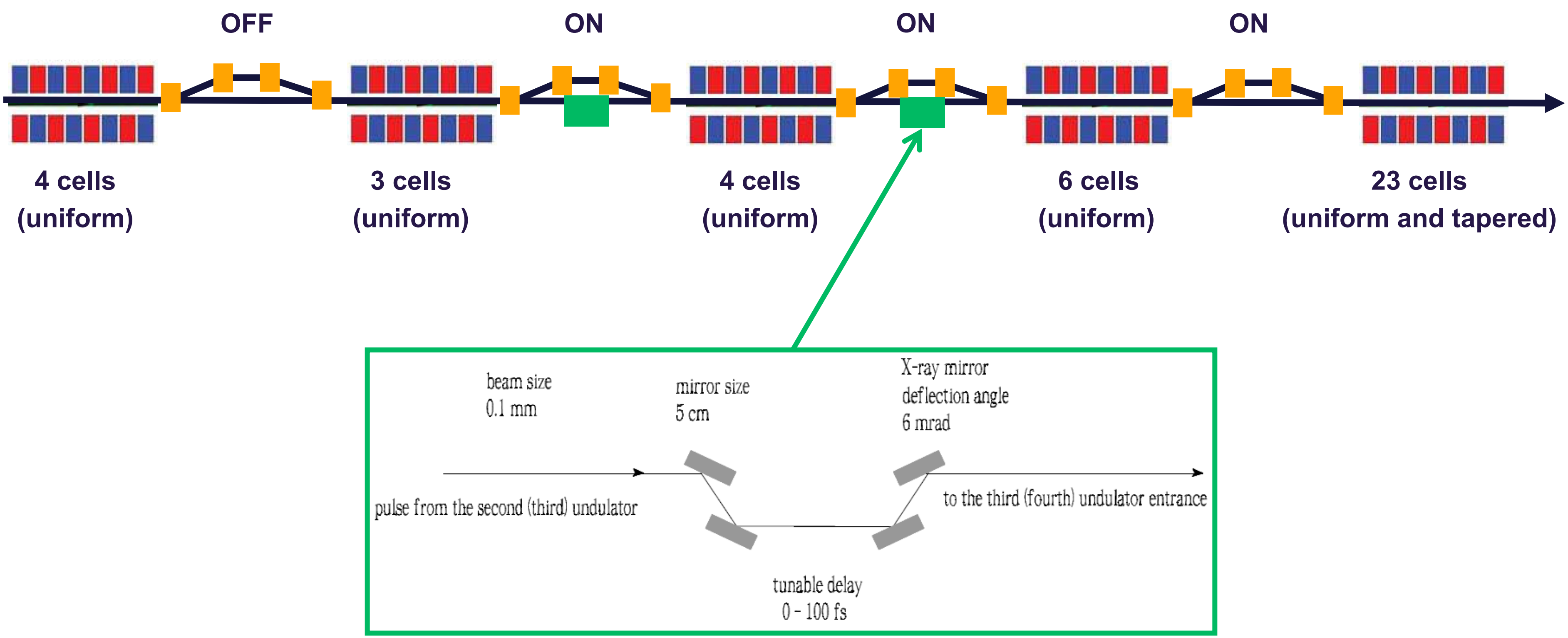




Hard X-ray self-seeding scheme with single-crystal monochromator can be used in the low energy range

A recipe for a dedicated bio-imaging undulator system

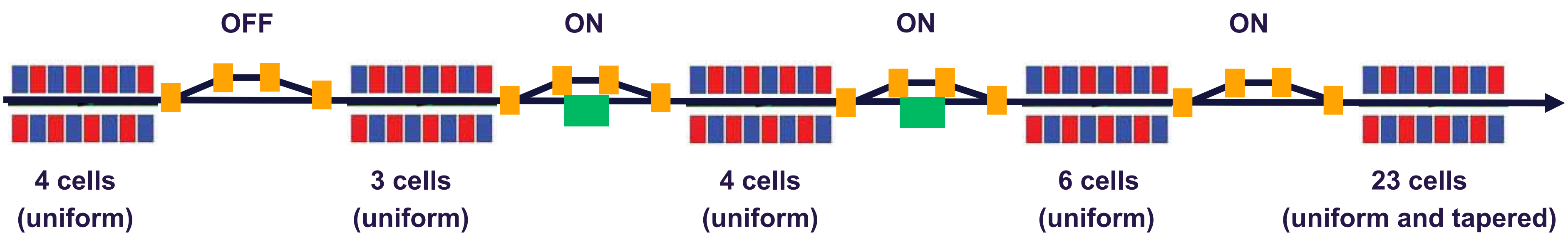
Operation in the energy range: 3 keV – 5 keV

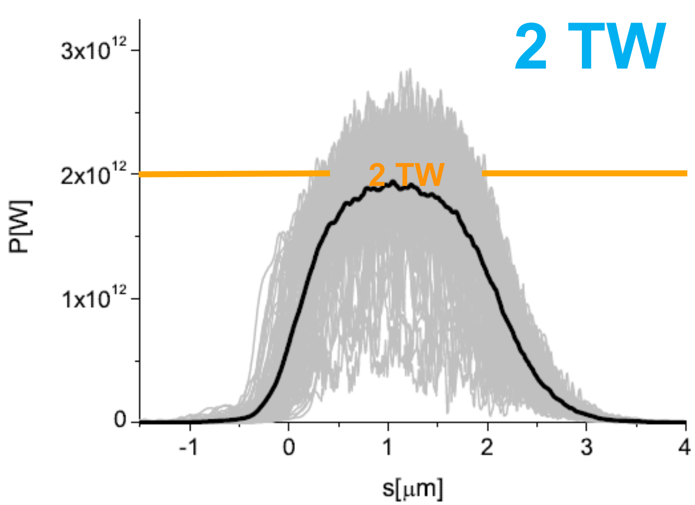


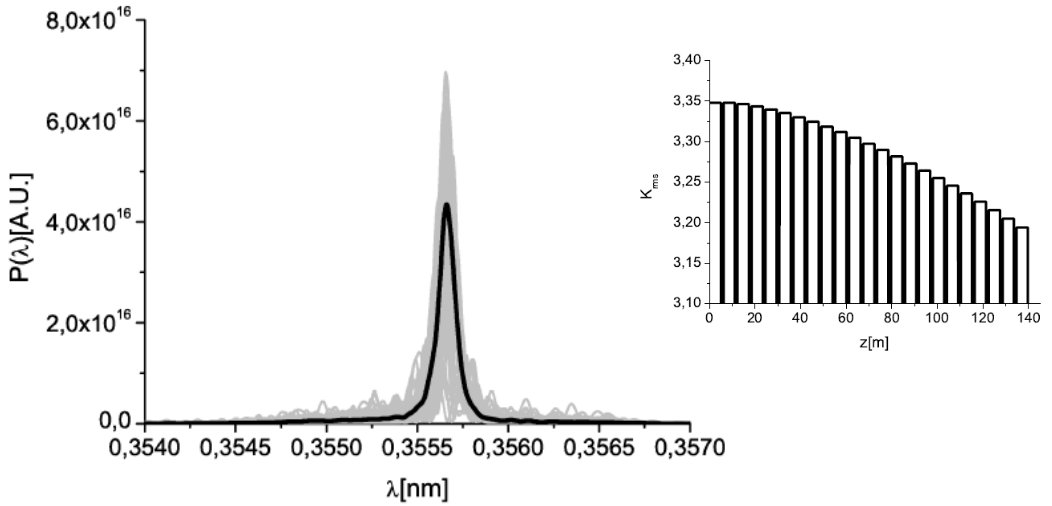
The third chicane now hosts a tunable X-ray mirror delay line

A recipe for a dedicated bio-imaging undulator system

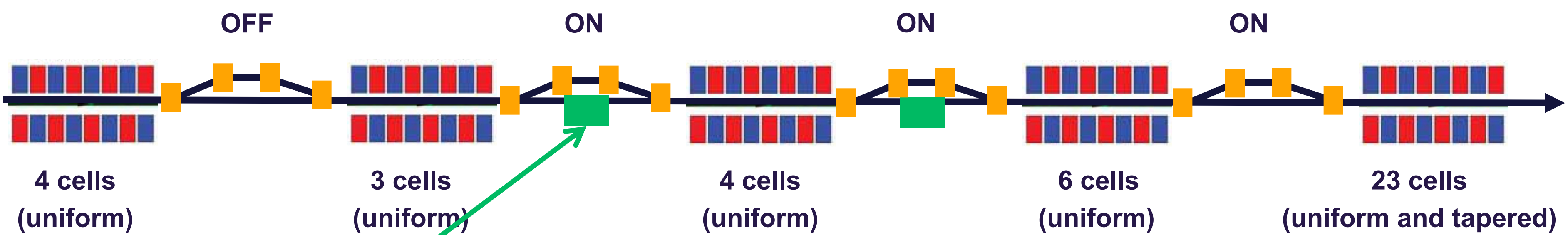
Operation in the energy range: 3 keV – 5 keV

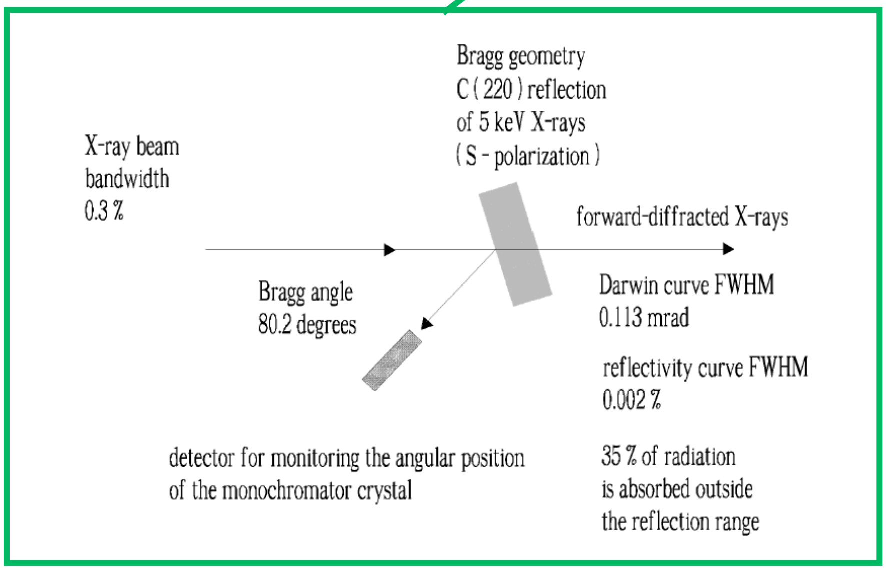


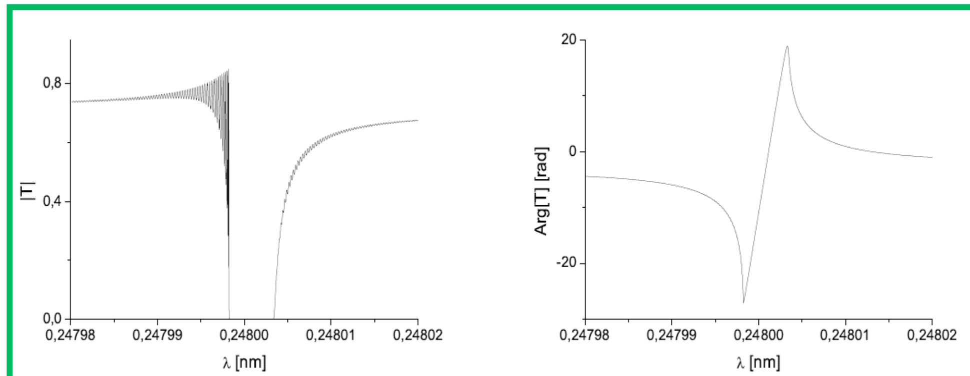




Operation in the energy range: 5 keV – 7 keV

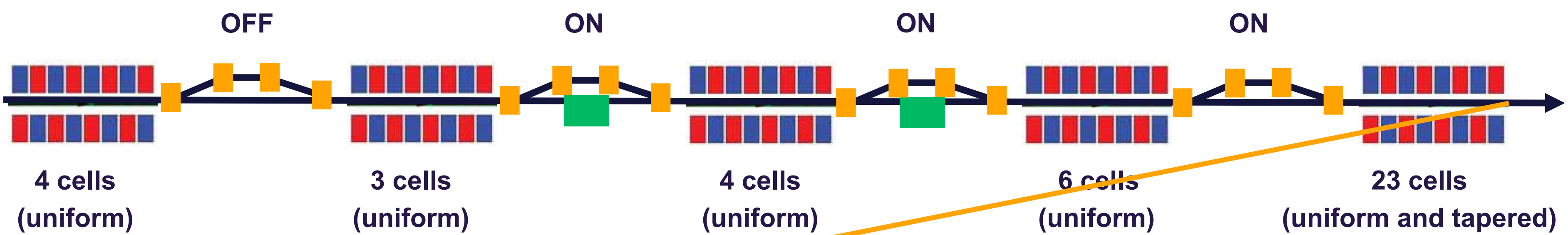


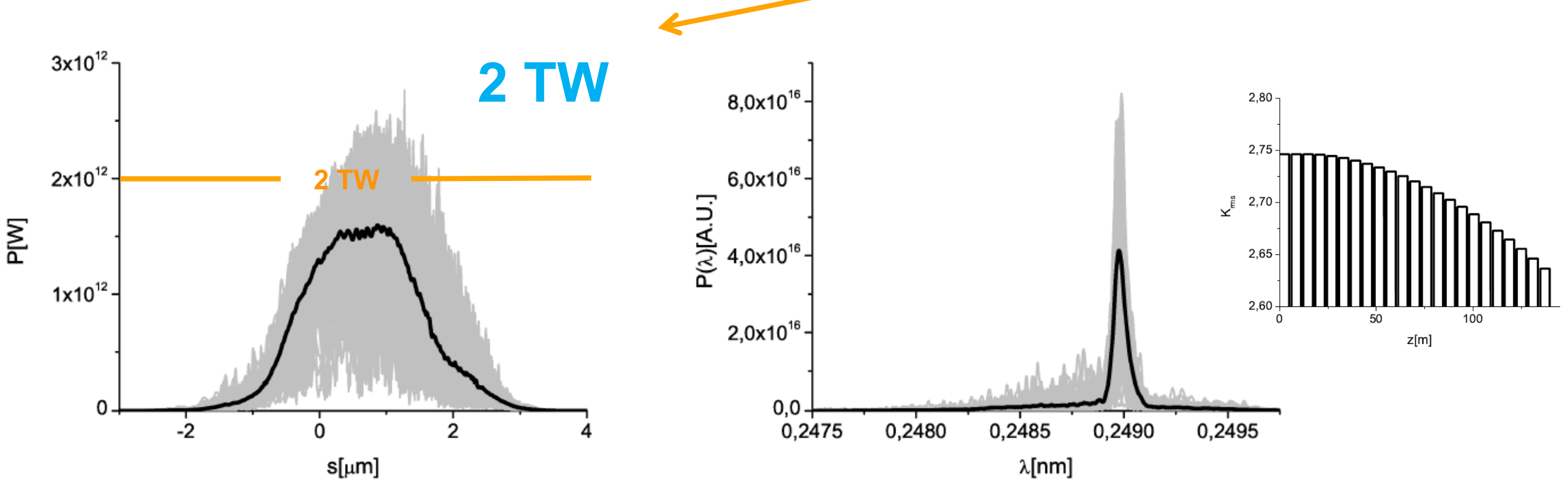




Hard X-ray self-seeding scheme with single-crystal monochromator can be used in the 5keV – 7keV energy range

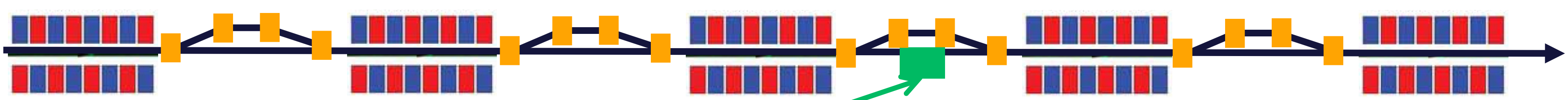
Operation in the energy range: 5 keV – 7 keV



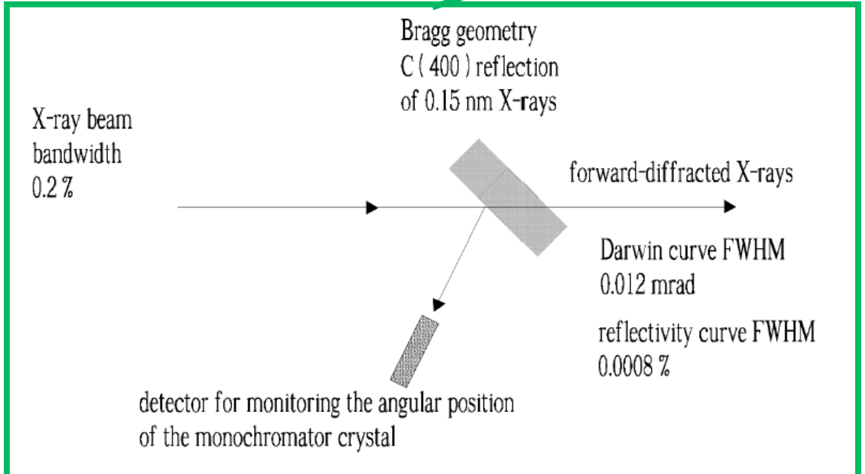


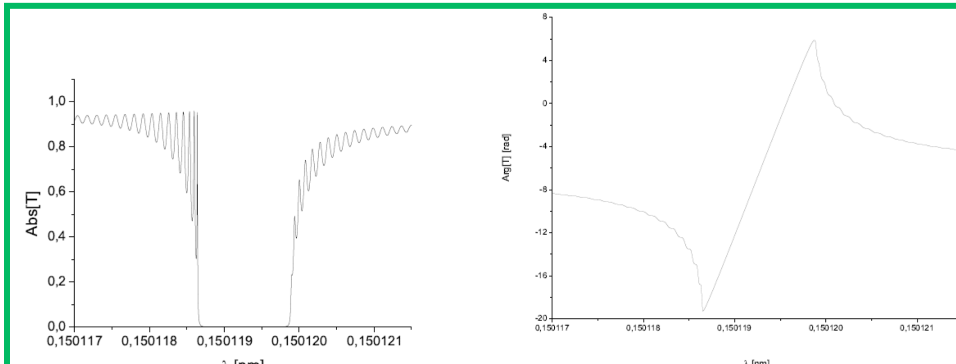
A recipe for a dedicated bio-imaging undulator system

Operation in the energy range: 7 keV – 9 keV



4 cells (uniform) | 3 cells (uniform) | 4 cells (uniform) | 6 cells (uniform) | 23 cells (uniform and tapered)

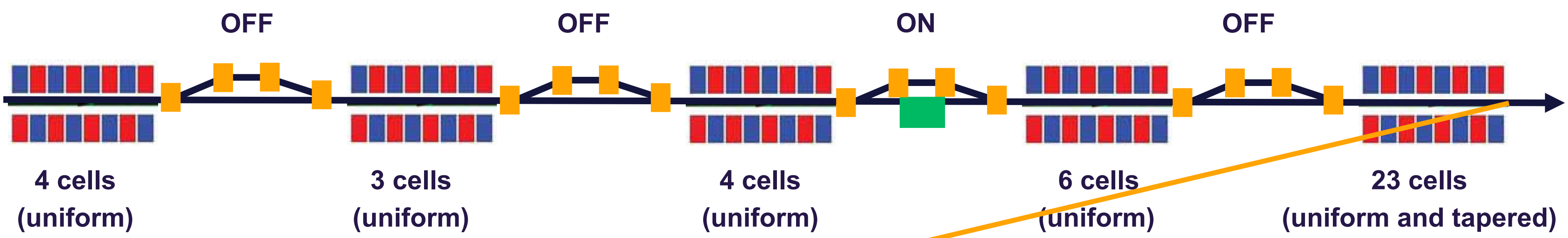


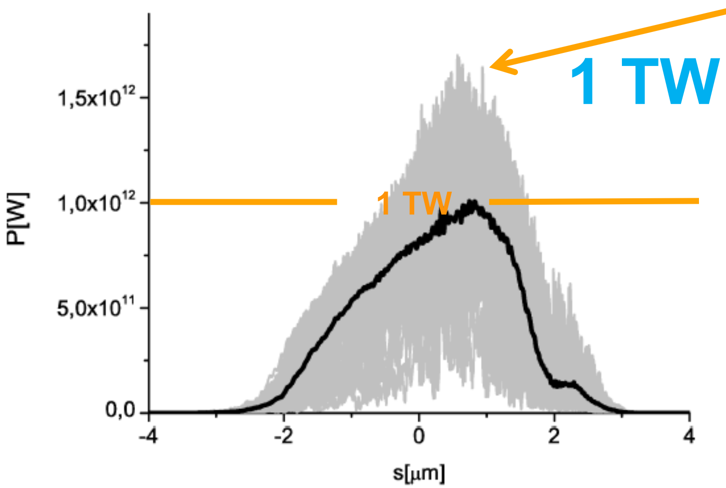


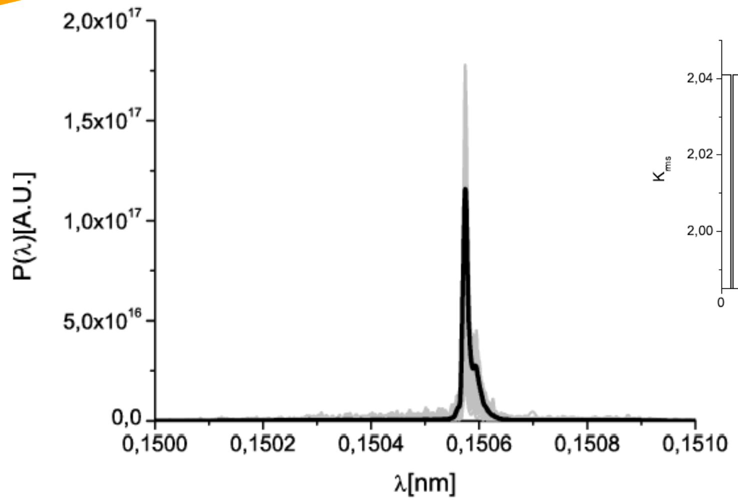
Hard X-ray self-seeding scheme with single-crystal monochromator can be used

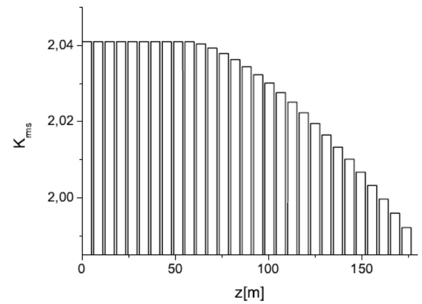
A recipe for a dedicated bio-imaging undulator system

Operation in the energy range: 7 keV – 9 keV



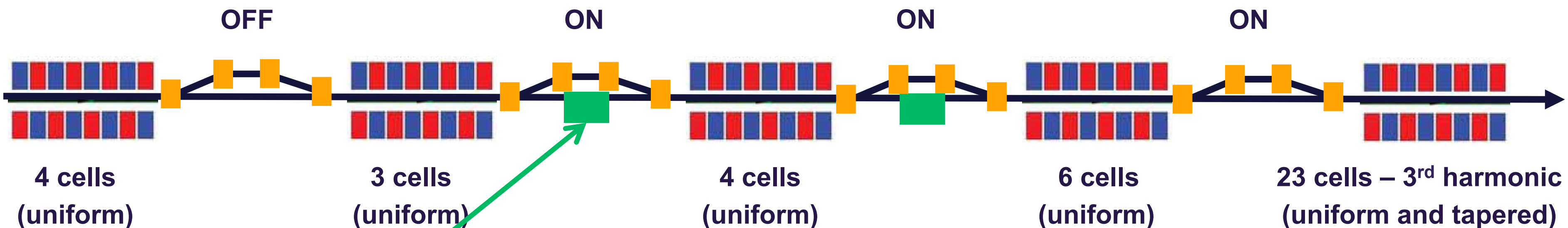


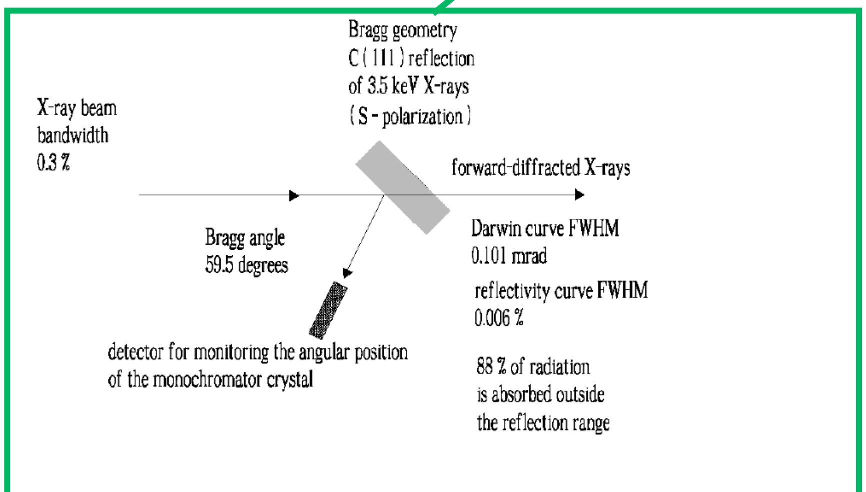


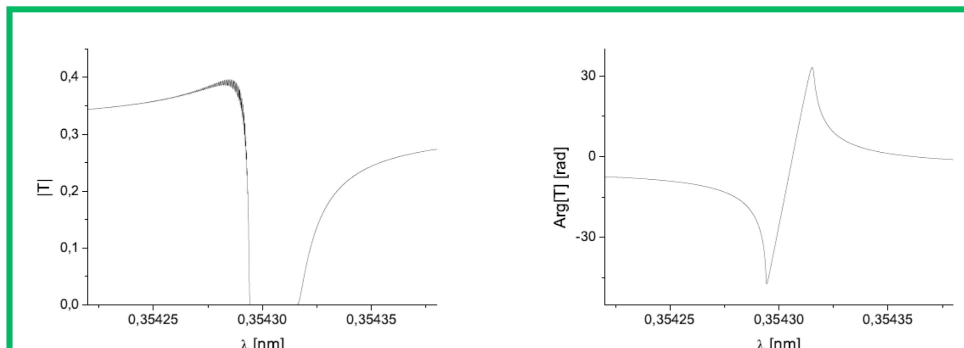


A recipe for a dedicated bio-imaging undulator system

Operation in the energy range: 9 keV – 13 keV

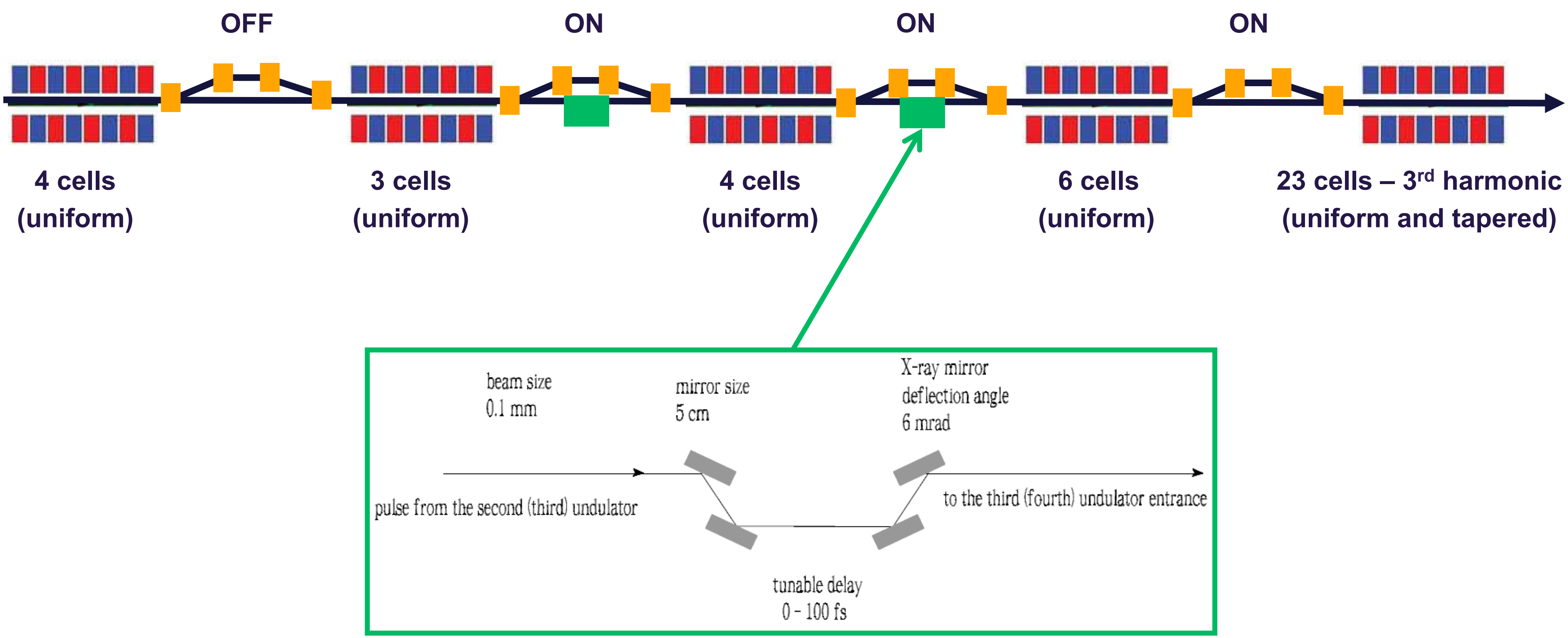






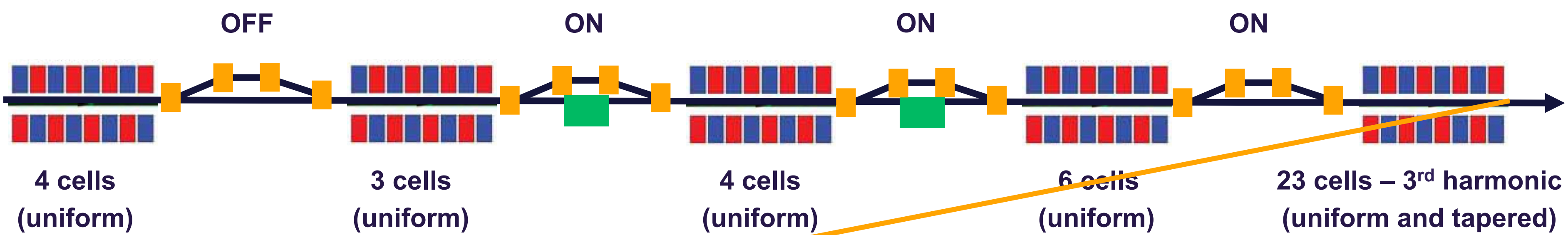
Hard X-ray self-seeding scheme with single-crystal monochromator can be used

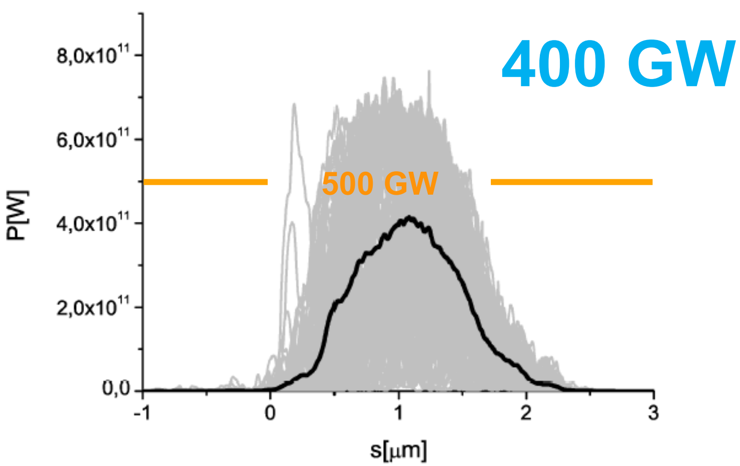
Operation in the energy range: 9 keV – 13 keV

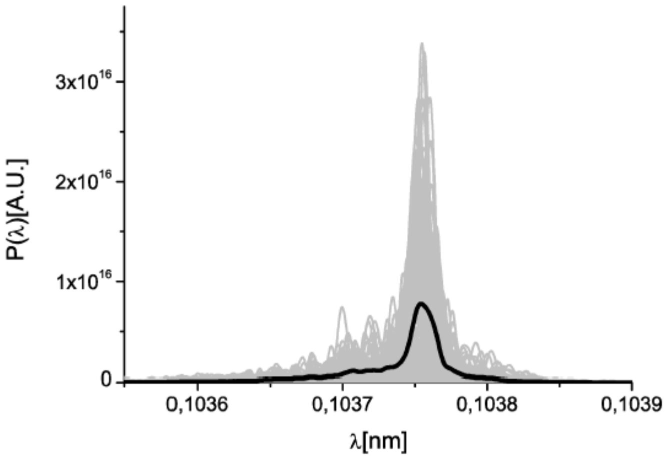


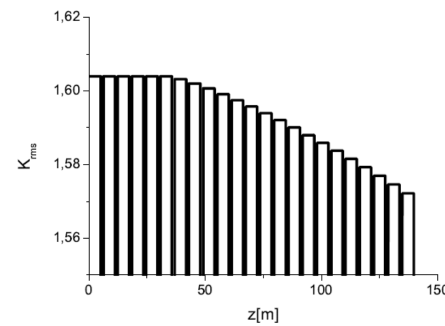
The third chicane now hosts a tunable X-ray mirror delay line

Operation in the energy range: 9 keV – 13 keV









Conclusions

-After experimental confirmation of HXRSS principle efforts are underway to enable HXRSS at the European XFEL

- *Two-chicane setup bears advantage in case of high rep-rate*
- *Different operation points are under study*
- *Implementation would yield ~ 1TW with the baseline setup*

-Ideas beyond the baseline are under discussion

- *Dreaming big: a recipe for a dedicated bio-imaging source at European XFEL*