Advanced operation schemes: two-color, split & delay

European XFEL

Production of two FEL pulses of different wavelengths with a controllable temporal delay

(and)

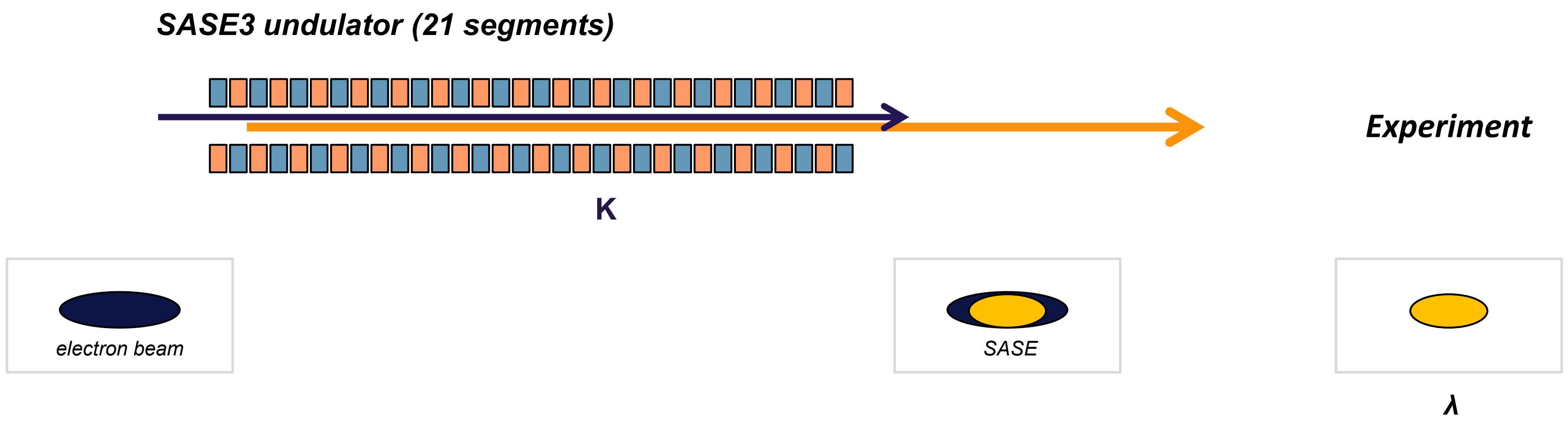
Splitting the FEL pulse into two sequential pulses

at SASE3

Outline

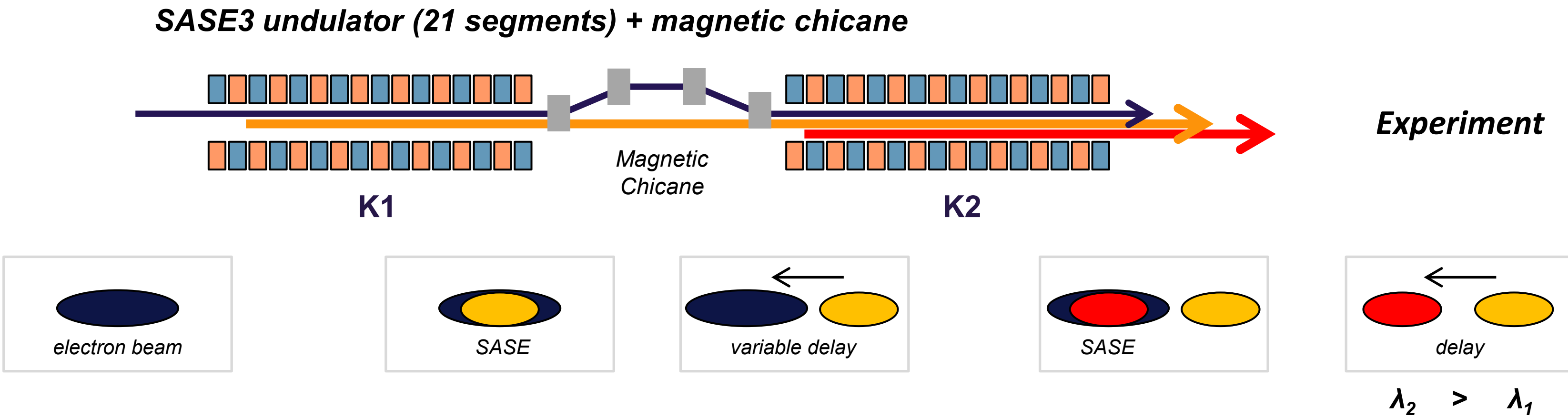
- ~~Why do we need two color pulses?~~
- How can we produce and deliver them
- X-ray split and delay device
- Combination of the both
- Other schemes under study

Baseline SASE3 operation



- SASE3 undulator tuned to radiate at wavelength λ
- Single SASE pulse is transported to the SQS/SCS instrument

Two-color SASE3 operation



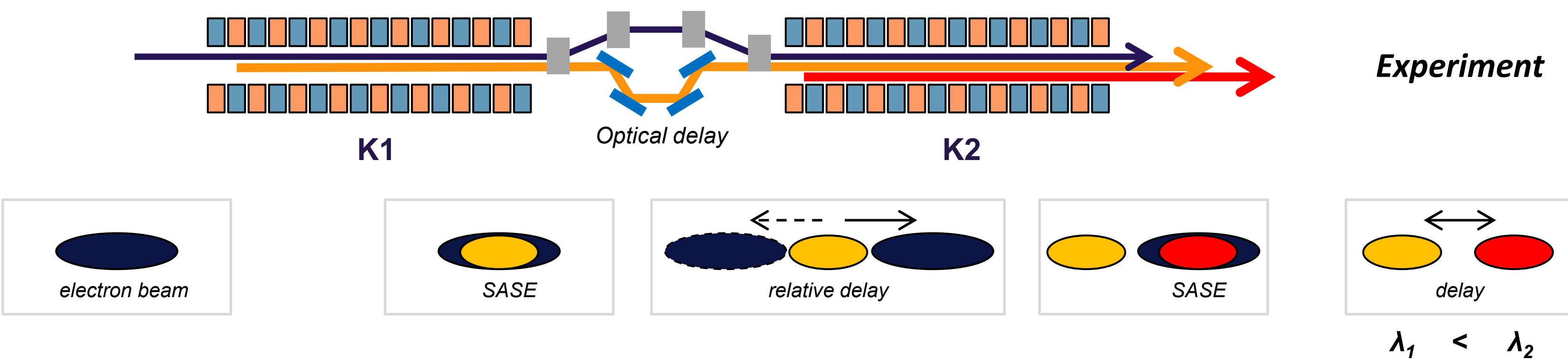
Magnetic chicane = electron beam delay

- Electron beam is delayed in the magnetic chicane
- Delay can be chosen by tuning the magnetic field (up to ***ps*** with sub-fs precision)
- U2 radiation comes always after (e-beam is delayed only)
- If wavelengths differ significantly, shorter wavelength goes first (preferably).

[1] G. Geloni, et al, “Scheme for femtosecond-resolution pump probe experiments at XFELs with two-color ten GW-level X-ray pulses”, arXiv:1001.3510
[2] T. Hara et al. “Two-colour hard X-ray free-electron laser with wide tunability”, doi:10.1038/ncomms3919.
[3] A. A. Lutman et al. “Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers”, doi:10.1103/PhysRevLett.110.134801.

Two-color SASE3 operation

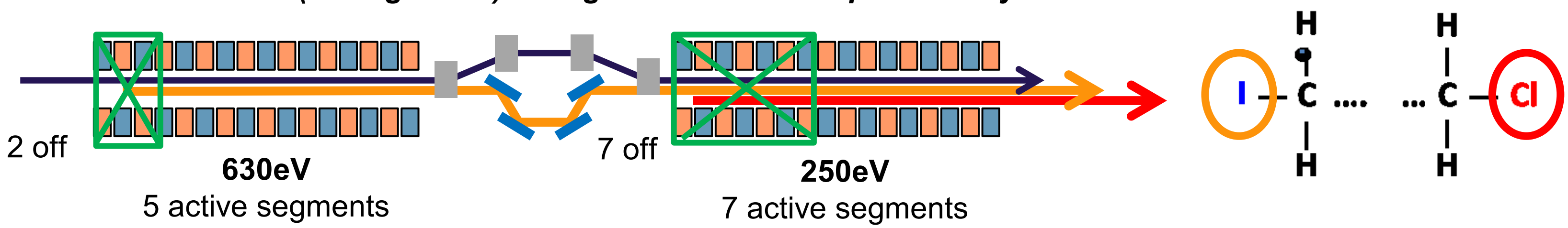
SASE3 undulator (21 segments) + magnetic chicane + optical delay



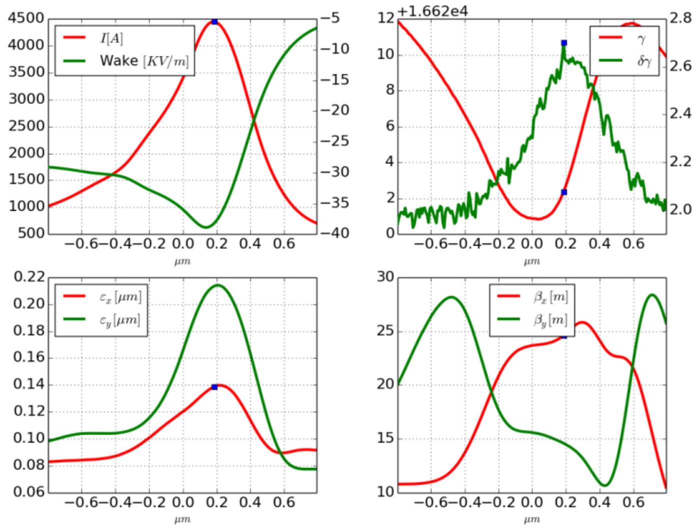
- Magnetic chicane + mirror chicane = arbitrary delay
  - Electron beam is delayed in the magnetic chicane
  - Photon beam gets delayed in the optical chicane
  - Keep the mirrors fixed, tune using the magnetic chicane

Case study for SQS at 630/250 eV

SASE3 undulator (21 segments) + magnetic chicane + optical delay

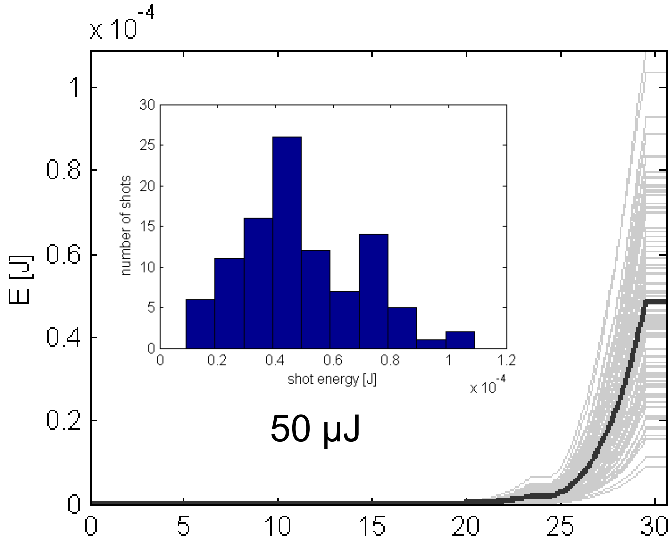


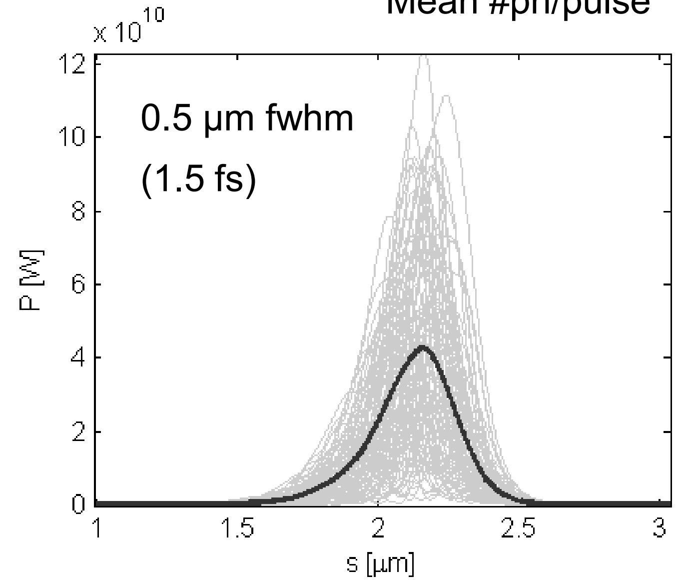
- Baseline 20pC e-beam after SASE1
- Here we optimized for short pulses

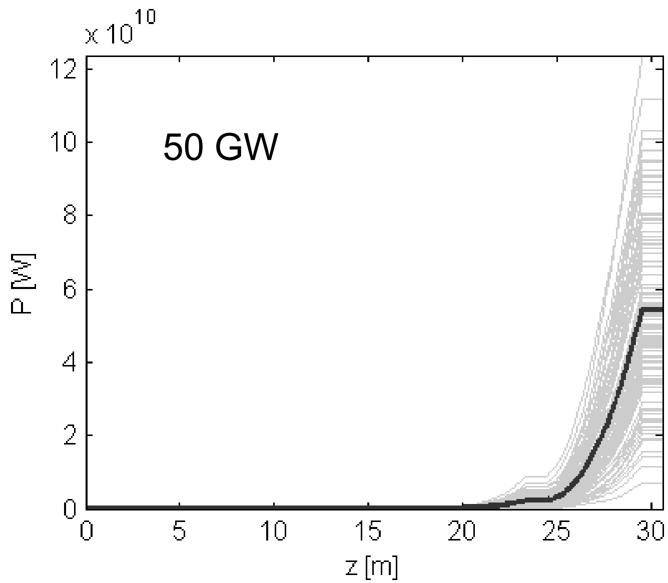


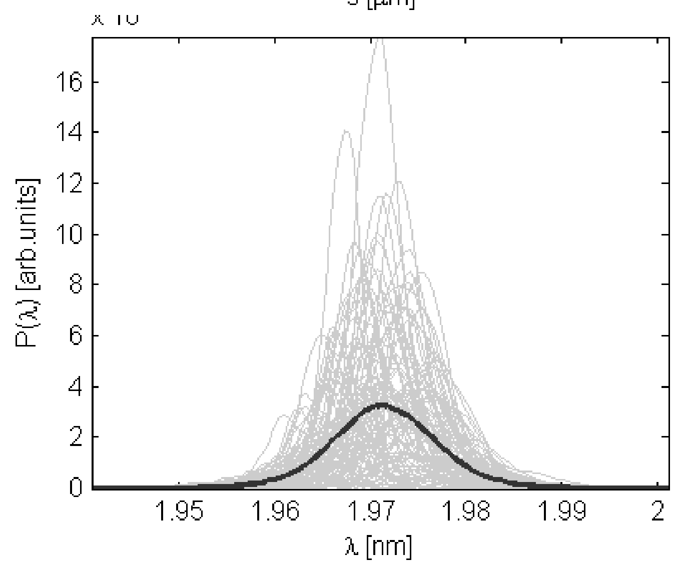
First undulator (second pulse) 630 eV

Mean Energy/pulse: 5e-5 J
Mean #ph/pulse : 5e11



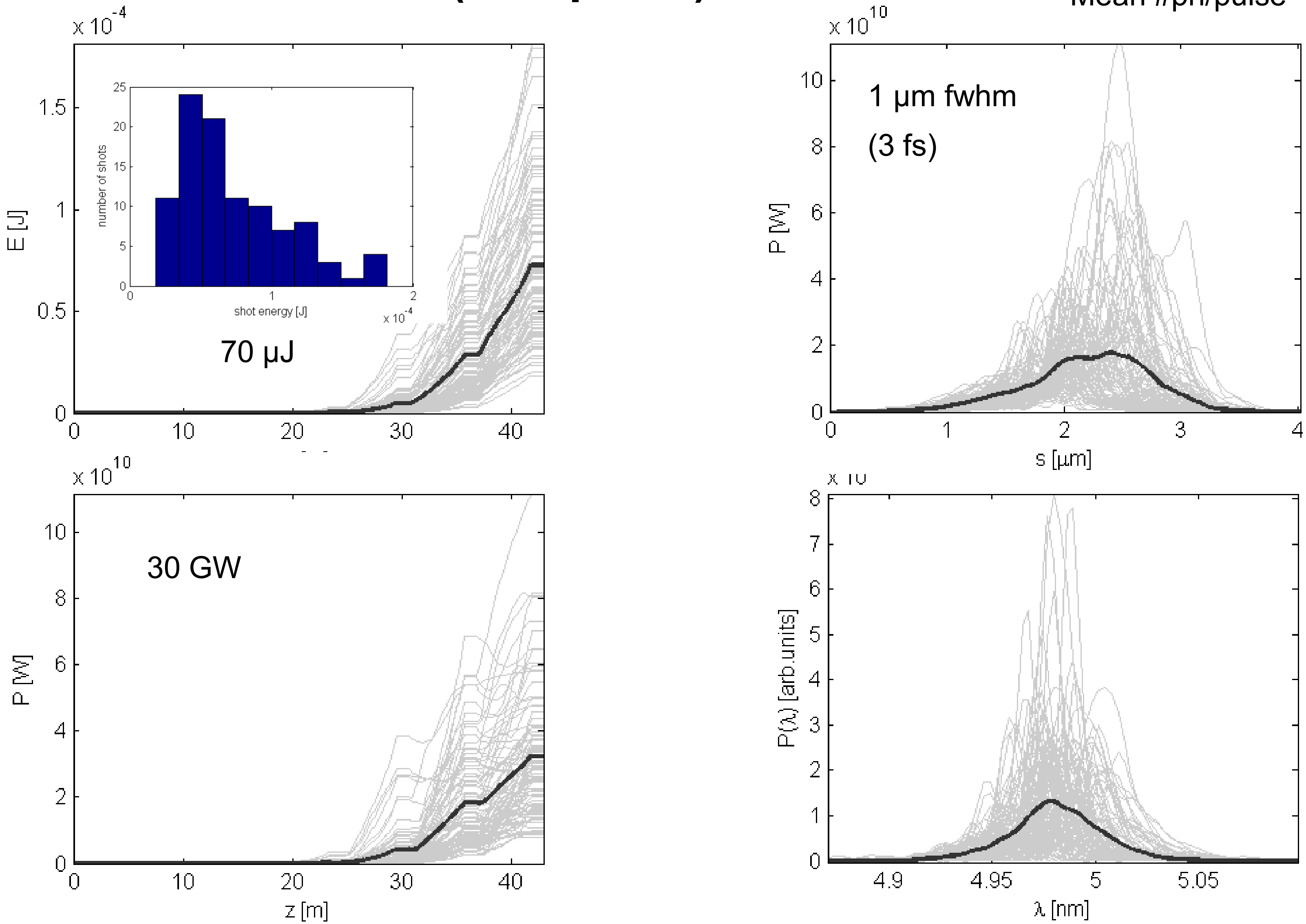






Second undulator (first pulse) 250 eV

Mean Energy/pulse: 7e-5 J
Mean #ph/pulse : 1.75e12

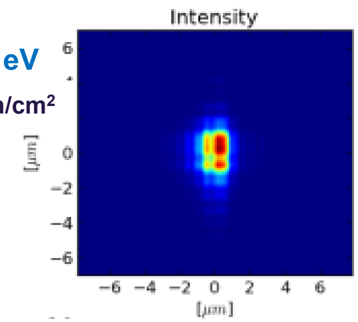


Two sources ~~problem~~

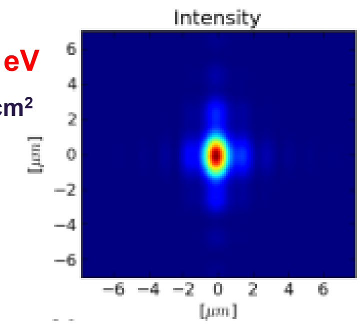
- Two sources and one focusing system -> two images
- Two mirrors -> only one image without aberrations

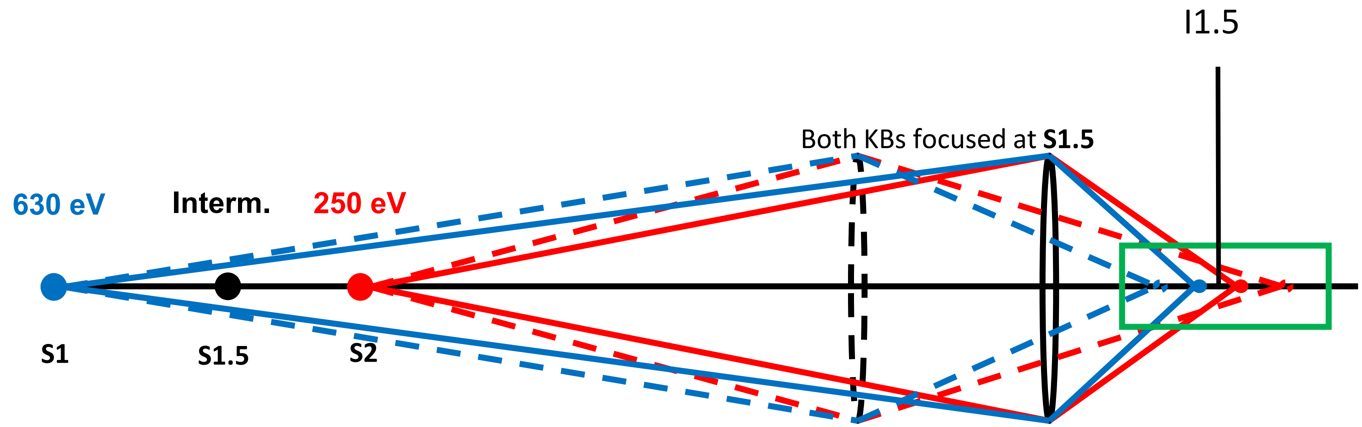
- We can tune both KB mirrors to image the intermediate spot in both planes

630 eV
1.8e18 ph/cm^2



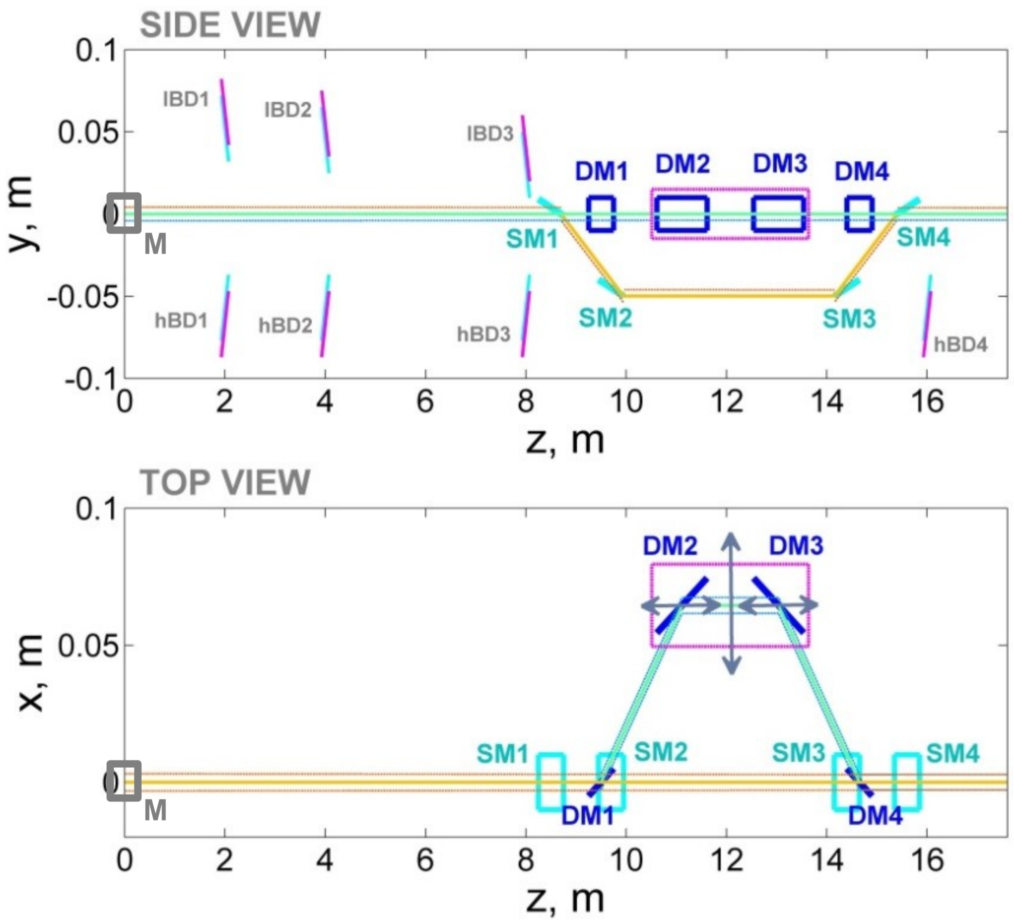
250 eV
4.5e18 ph/cm^2





Concept of optical X-ray split and delay device (XBSD) for SASE3

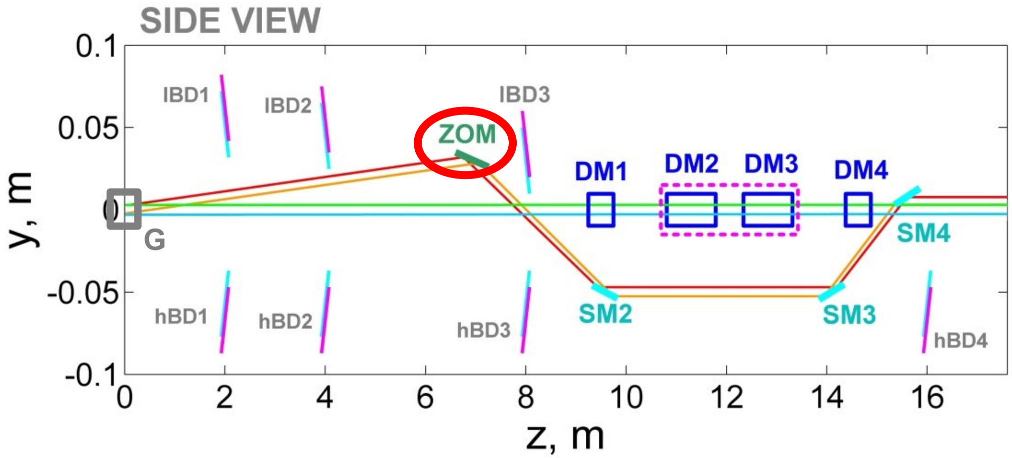
(by AlexanderYaroslavtsev)



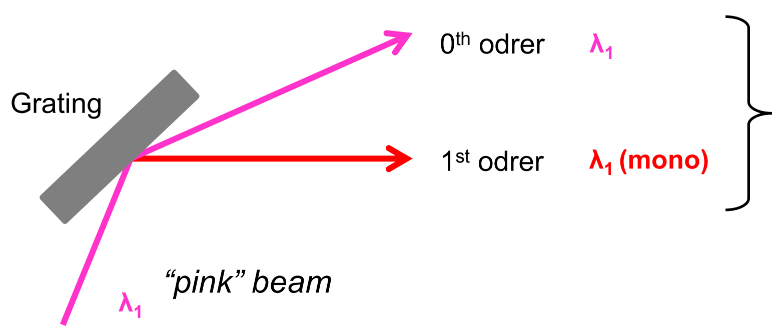
- Located upstream of both instruments
- Separated asymmetric paths
- Two mirror coatings:
  B4C (up to 1500 eV)
  Ni or Ru (up to 3000 eV)
- Plane mirrors -> does not affect focusing

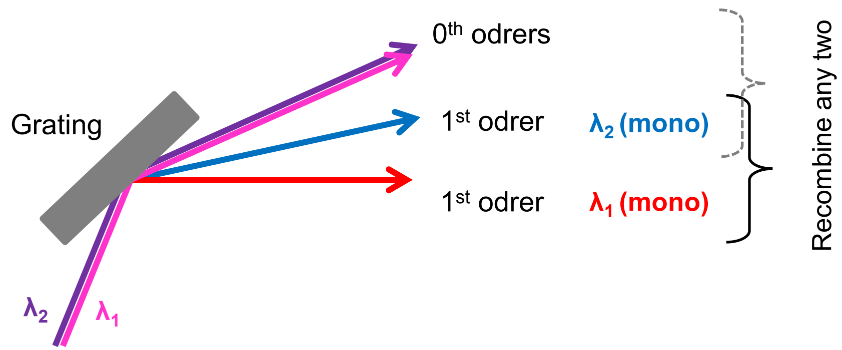
Concept of optical X-ray split and delay device (XBSD) for SASE3

(by AlexanderYaroslavtsev)



- Upgradeable with zero-order mirror (ZOM)
- Recombination of different grating reflection orders at optical axis possible



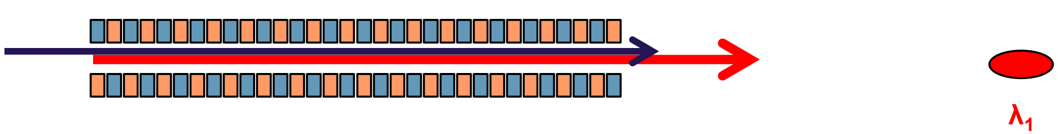


Two-color SASE + XBSD combination

(by AlexanderYaroslavtsev)

$\lambda_x == \lambda_x$ (sase)

Undulator mode	XBSD mode	Result	N. of pulses	N. of frequencies
(boring) λ_1	XFEL baseline			



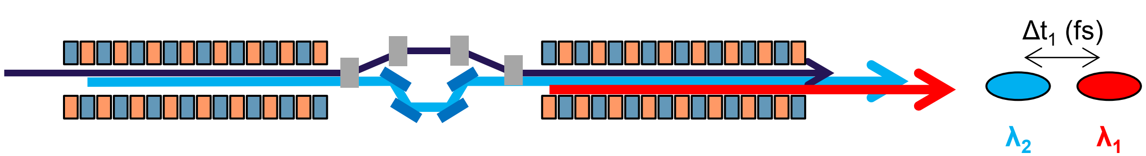
Two-color SASE + XBSD combination

(by AlexanderYaroslavtsev)

$\lambda_x == \lambda_x$ (sase)

Undulator mode	XBSD mode	Result	N. of pulses	N. of frequencies
λ_1				
λ_1 Δt_1 (fs) λ_1				
λ_1 Δt_1 (fs) λ_2				

Two-color scheme



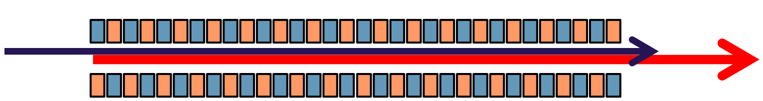
Two-color SASE + XBSD combination

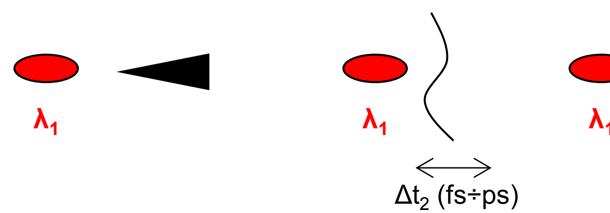
(by AlexanderYaroslavtsev)

λ_x== λ_x (sase)

Undulator mode	XBSD mode	Result	N. of pulses	N. of frequencies
λ_1	mono	λ_1 **(mono)** Δt (fs÷ps) λ_1 **(mono)**	**2**	1 mono
	mono + ZOM 0th	λ_1 Δt (fs÷ps) λ_1 **(mono)**	**2**	1 sase/mono
	pink	λ_1 Δt (fs÷ps) λ_1	**2**	2 sase
λ_1 Δt_1 (fs) λ_1				
λ_1 Δt_1 (fs) λ_2				

XBCD scheme





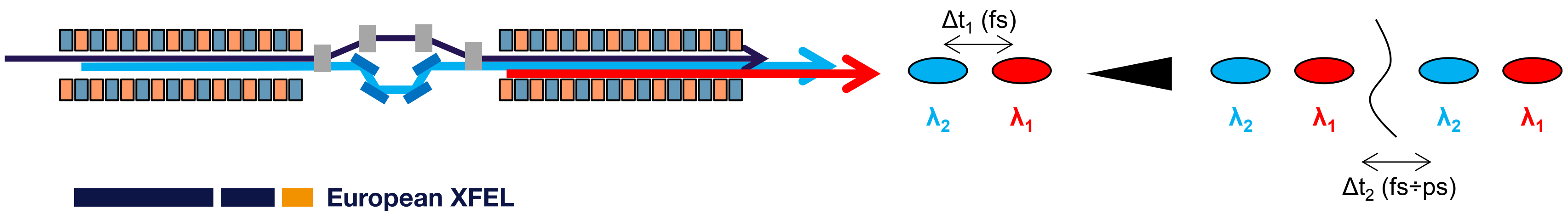
Two-color SASE + XBSD combination

(by AlexanderYaroslavtsev)

λ_x== λ_x (sase)

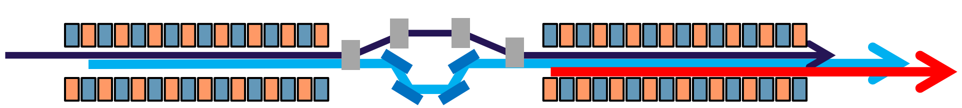
Undulator mode	XBSD mode	Result	N. of pulses	N. of frequencies
λ_1	mono	λ_1 (mono) Δt (fs÷ps) λ_1 (mono)	2	1 mono
	mono + ZOM 0th	λ_1 Δt (fs÷ps) λ_1 (mono)	2	1 sase/mono
	pink	λ_1 Δt (fs÷ps) λ_1		
λ_1 Δt_1 (fs) λ_1	mono	λ_1 (mono) Δt_1 (fs) λ_1 (mono) Δt_2 (fs÷ps) λ_1 (mono) Δt_1 (fs) λ_1 (mono)	4	1 mono
	mono + ZOM 0th	λ_1 Δt_1 (fs) λ_1 Δt_2 (fs÷ps) λ_1 (mono) Δt_1 (fs) λ_1 (mono)	4	1 sase/mono
	pink	λ_1 Δt_1 (fs) λ_1 Δt_2 (fs÷ps) λ_1 Δt_1 (fs) λ_1	4	1 sase
λ_1 Δt_1 (fs) λ_2	mono + ZOM 1st	λ_1 (mono) Δt_2 (fs÷ps) λ_2 (mono)	2	2 mono
	mono + ZOM 0th	λ_1 Δt_1 (fs) λ_2 Δt_2 (fs÷ps) λ_2 (mono)	3	2 sase/mono
	pink	λ_1 Δt_1 (fs) λ_2 Δt_2 (fs÷ps) λ_1 Δt_1 (fs) λ_2	4	2 sase

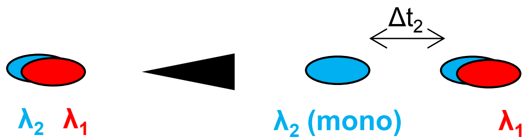
"Interference terms"



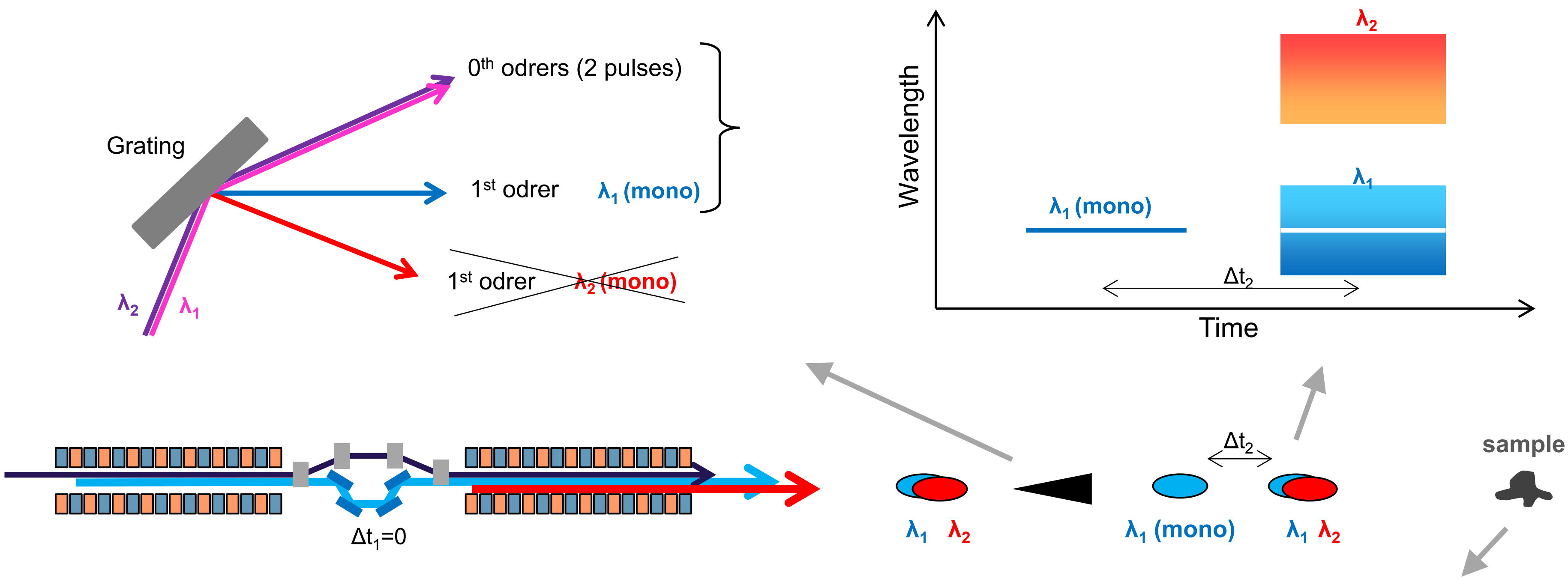
Coherent Anti-Stokes Raman Scattering (CARS) Correlation Spectroscopy

Undulator mode	XBSD mode	Result	N. of pulses	N. of frequencies
λ_1	mono	λ_1 **(mono)** Δt (fs÷ps) λ_1 **(mono)**	**2**	1 mono
	mono + ZOM 0th	λ_1 Δt (fs÷ps) λ_1 **(mono)**	**2**	1 sase/mono
	pink	λ_1 Δt (fs÷ps) λ_1	**2**	2 sase
λ_1 Δt_1 (fs) λ_1	mono	λ_1 **(mono)** Δt_1 (fs) λ_1 **(mono)** Δt_2 (fs÷ps) λ_1 **(mono)** Δt_1 (fs) λ_1 **(mono)**	**4**	1 mono
	mono + ZOM 0th	λ_1 Δt_1 (fs) λ_1 Δt_2 (fs÷ps) λ_1 **(mono)** Δt_1 (fs) λ_1 **(mono)**	**4**	1 sase/mono
	pink	λ_1 Δt_1 (fs) λ_1 Δt_2 (fs÷ps) λ_1 Δt_1 (fs) λ_1	**4**	1 sase
λ_1 Δt_1 (fs) λ_2	mono + ZOM 1st	λ_1 **(mono)** Δt_2 (fs÷ps) λ_2 **(mono)**	**2**	2 mono
	mono + ZOM 0th	λ_1 Δt_1 (fs) λ_2 Δt_2 (fs÷ps) λ_2 **(mono)**	**3**	2 sase/mono
	pink	λ_1 Δt_1 (fs) λ_2 Δt_2 (fs÷ps) λ_1 Δt_1 (fs) λ_2	**4**	2 sase

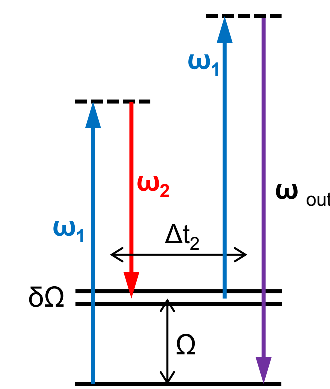




Coherent Anti-Stokes Raman Scattering (CARS) Correlation Spectroscopy

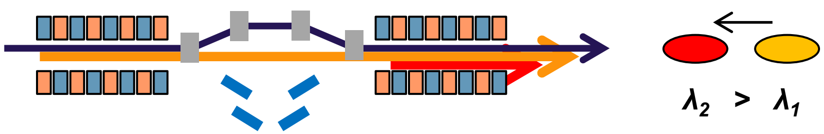


- Two pulses of different wavelengths are generated in the undulator
- Grating is tuned to monochromatize one of the pulses in 1st order reflection
- 0th order reflection carries both SASE pulses and is recombined with ZOM
- Monochromatic pulse is delayed in XBSD by Δt_2
- …
- Story continues in talk by Justine Schlappa later today



Comparison of delay ranges

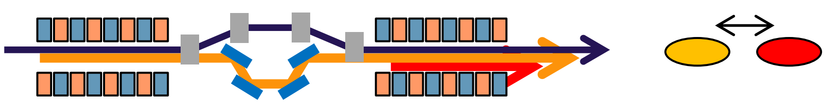
Two-color scheme:



optical delay out:

depends on electron beam energy

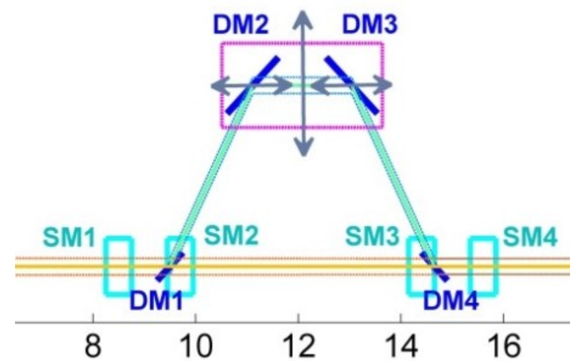
up to **(0÷1 ps)**



optical delay in:

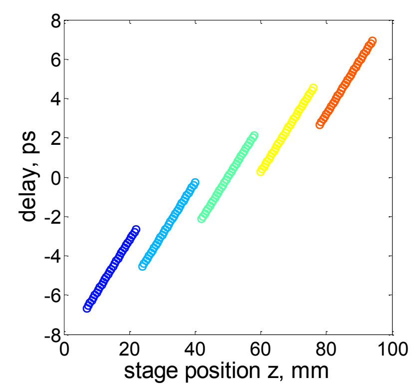
estimated **(-100÷100 fs)**

XBSD:



depends on photon energy, estimated **(-7÷7 ps)**

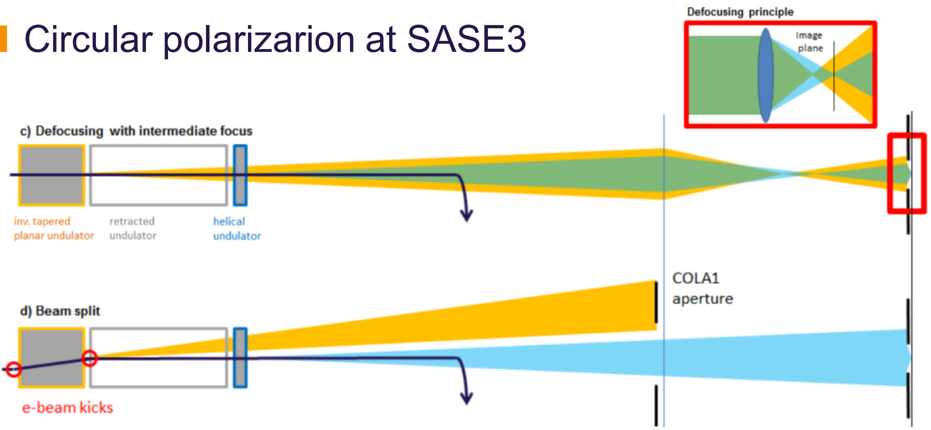
up to **4 ps per single scan**

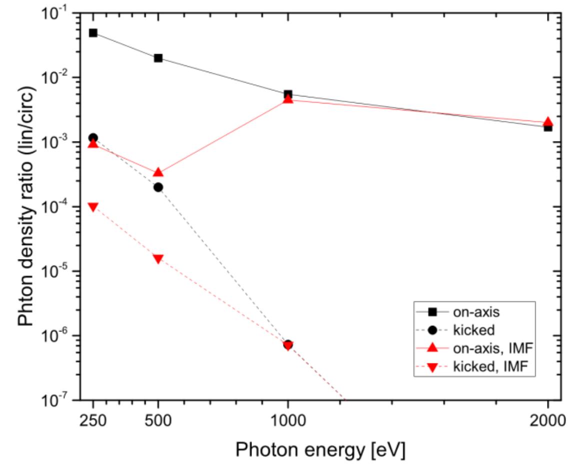


Example of the delay ranges 1000 eV, 5 fs pulse

Other schemes

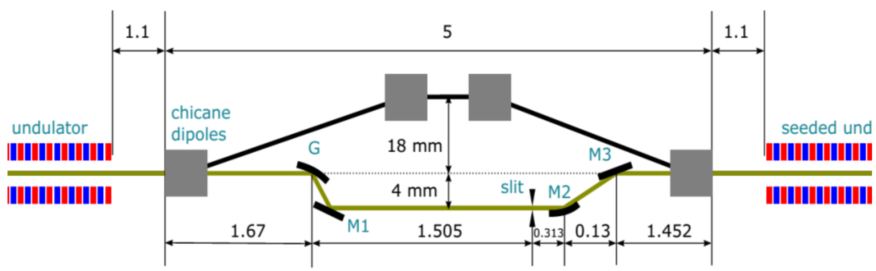
Circular polarizarion at SASE3

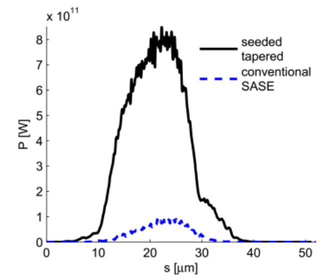


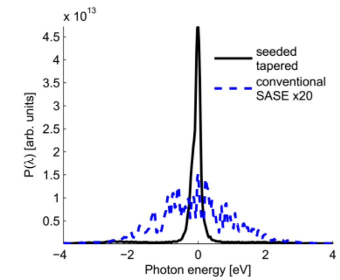


see S.Serkez, et al., "*Circular polarization opportunities at the SASE3 undulator line of the European XFEL*", arXiv:1608.08175

Self-seeding







see S.Serkez, "*Design and Optimization of the Grating Monochromator for Soft X-Ray Self-Seeding FELs*", doi:10.3204/DESY-THESIS-2015-043

Ongoing R&D on attosecond pulse generation

End words

- Two-color scheme:
  - robust, easy to set-up
  - same pulse duration
  - tunable delay, *scan possible*
  - large max. range, up to 2500 ÷ 250 eV, independent *scan possible* for both wavelengths
- XBSD:
  - introduces tunable delay, *scan possible*
  - does not affect baseline focusing
  - can create two <u>identical</u> pulses
  - allows delivery of SASE and monochromatic pulses with a given delay (with ZOM)
- Combination of the two:
  - gives large added values, see Table
- Other schemes are under active study
- If you are interested– **<u>please let us know</u>**

Thank you

WP72, SCS, SQS,

WP78, MPY(DESY)