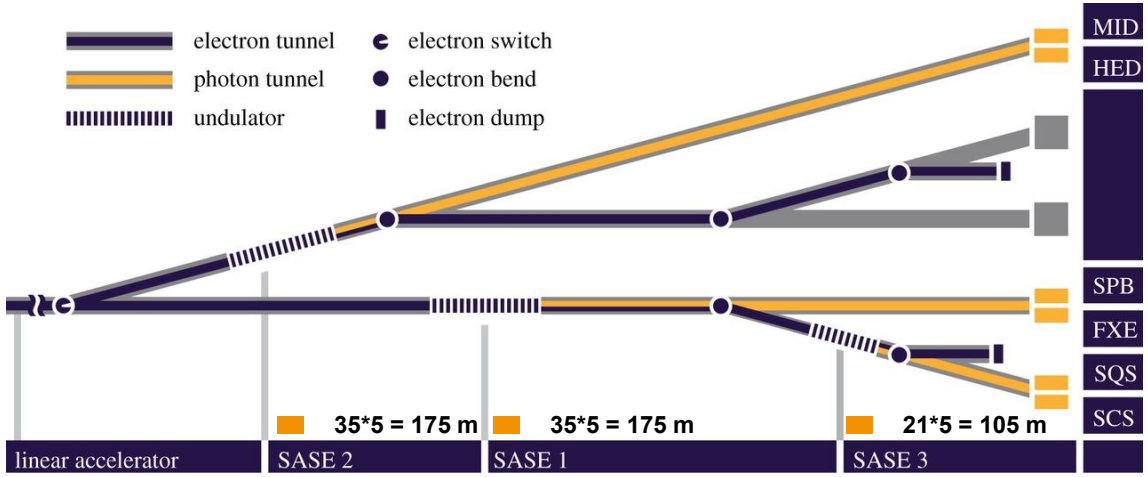
Approaches to obtain TW-class pulses at the European XFEL

Svitozar Serkez, Gianluca Geloni, Vitaly Kocharyan, Evgeny Saldin,
Igor Zagorodnov, Shan Liu, Sergey Tomin, Takanori Tanikawa

Underestimation Legacy



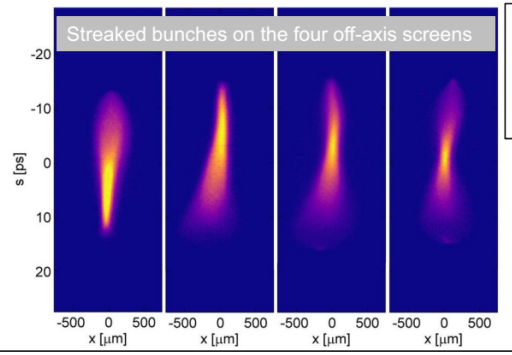
	Value	Unit
Electron energy	17.5	GeV
Bunch charge	1	nC
Peak current	5	kA
Bunch length (rms)	25	μm
Normalised emittance (rms)	1.4	mm mrad
Energy spread (rms)	1.5	MeV
Bunches per RF pulse	3000	
Repetition rate	10	Hz

Table 5.1.2 *Electron beam parameters used for the optimisation of the XFEL sources. The energy 17.5 GeV is already the result of an optimisation as is explained in Section 5.2.1 below.*

- M.Altarelli, et al. *The European X-ray Free-Electron Laser. Technical Design Report DESY2006-097* (2006).

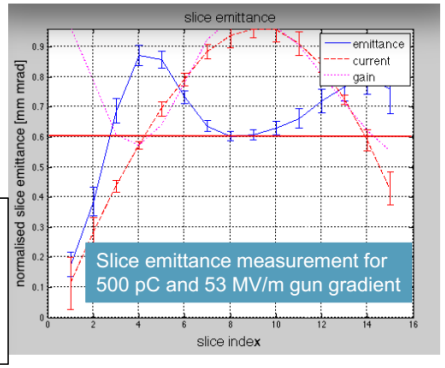
- Electron energy 8.5-17.5 GeV
- SASE1
  - 0.04m period, K_{max} = 3.9
- SASE3
  - 0.068m period, K_{max} = 9.05

Slice Emittance Measurements



We are able to match single slices of the bunch. One matching iteration takes about 2 minutes including the magnet cycling.

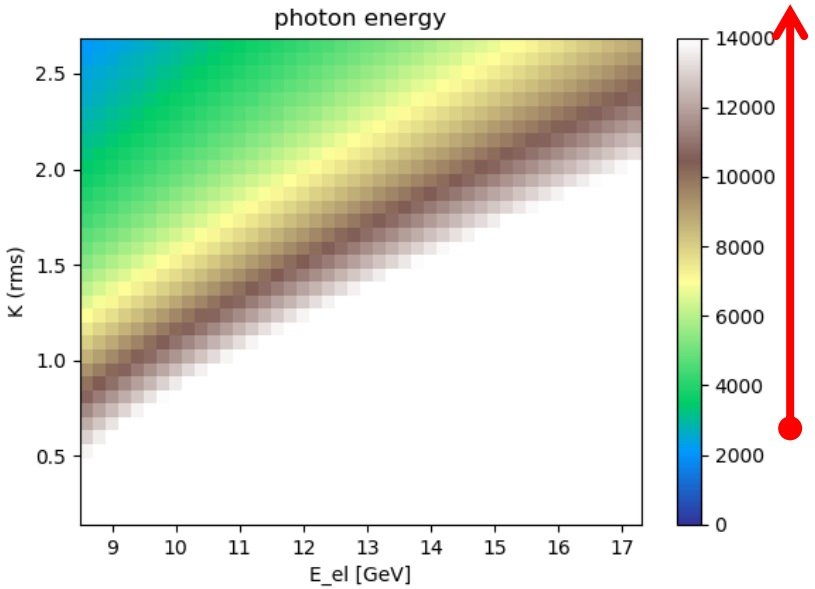
The smallest slice emittances achieved so far (four-screen method):
0.6 μm rad with 53 MV/m gun gradient (500 pC)
0.5 μm rad with 60 MV/m gun gradient (500 pC)
0.4 μm rad with 60 MV/m gun gradient (400 pC)



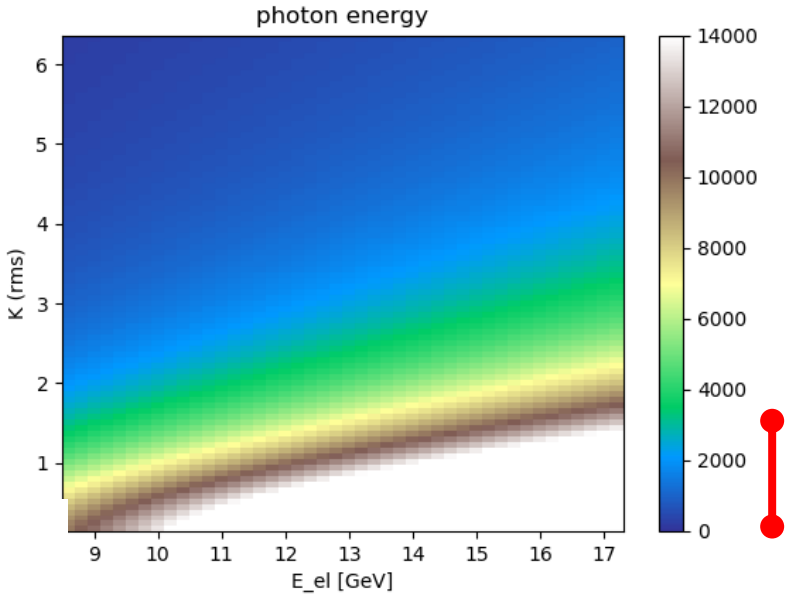
- B. Beutner *European XFEL Injector Commissioning Results,* talk at International FEL Conference, Santa Fe (2017), slide of M.Scholz

Expected efficiency

SASE 1/2

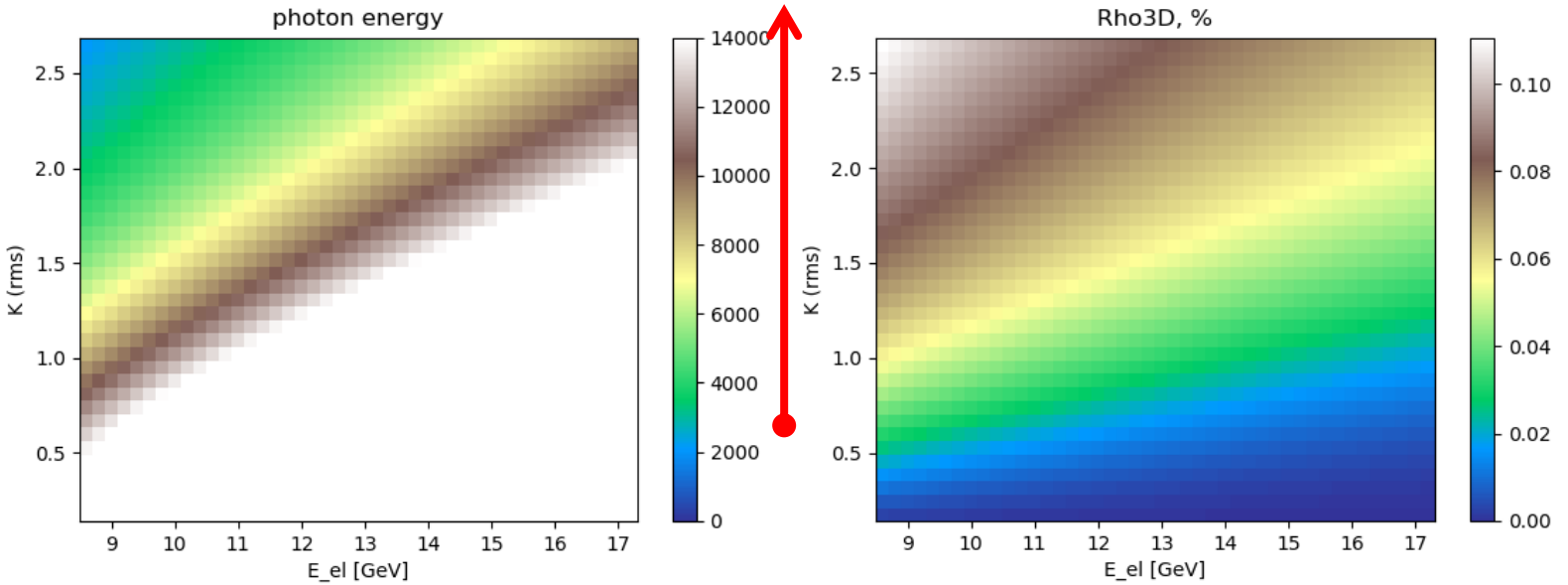


SASE 3

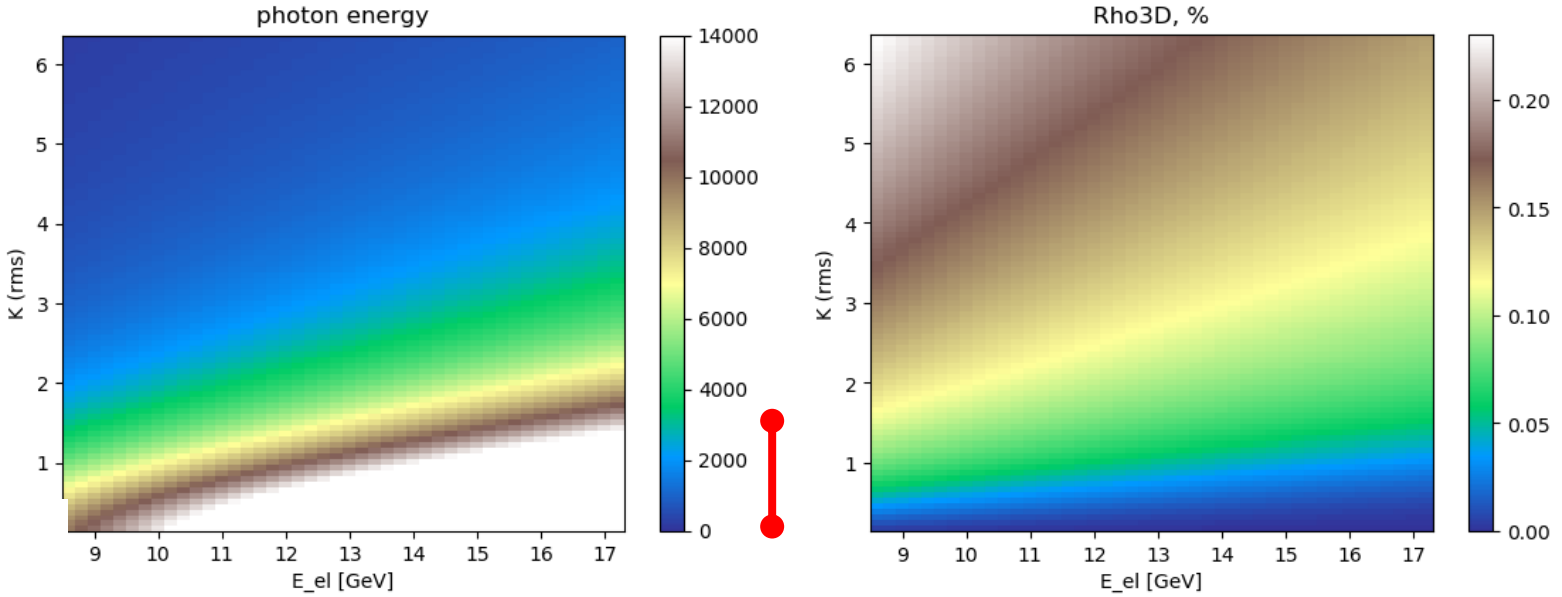


Expected efficiency

SASE 1/2



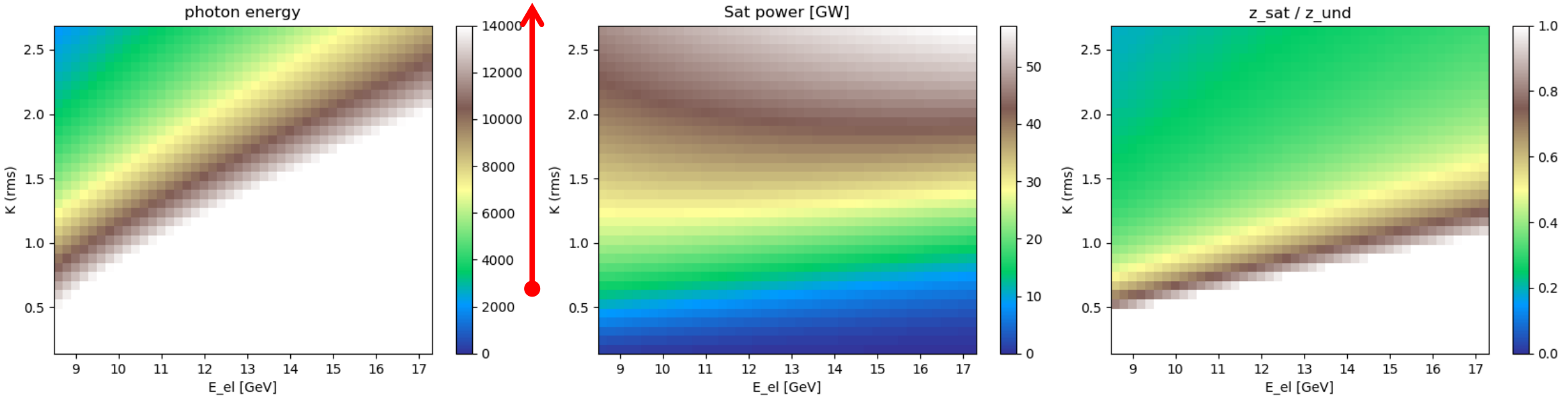
SASE 3



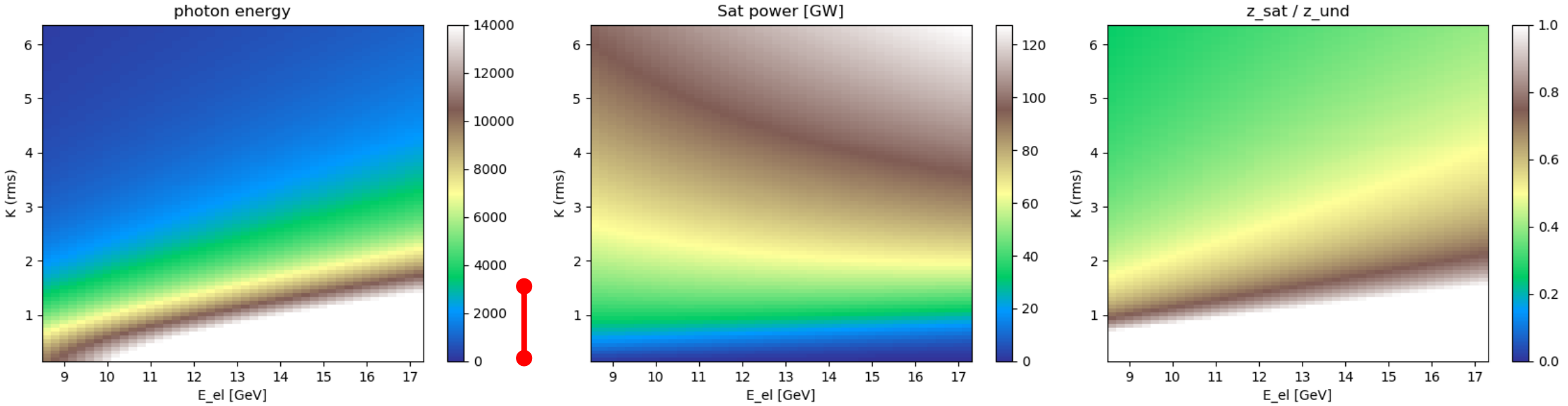
- 0.5urad emittance
- 5kA current
- 20m beta
- 10^{-4} energy spread

Expected efficiency

SASE 1/2

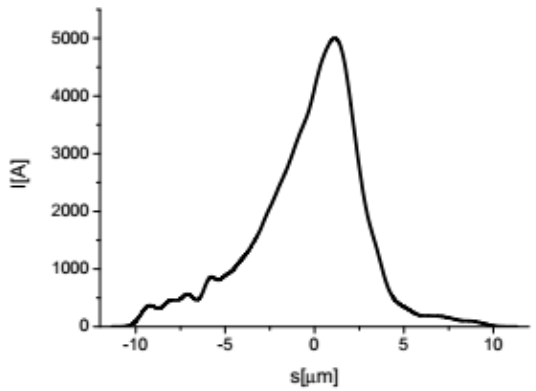


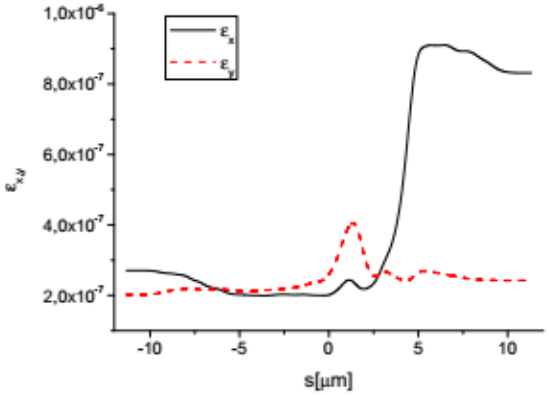
SASE 3

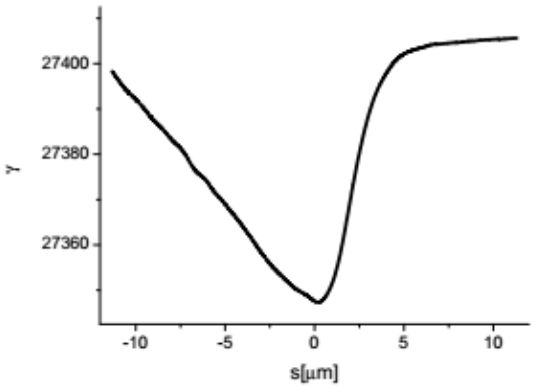


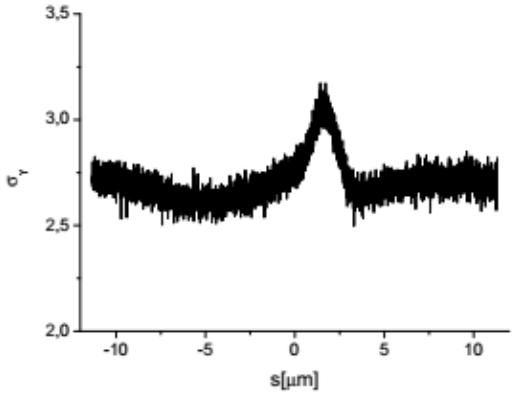
Tapering study at SASE3

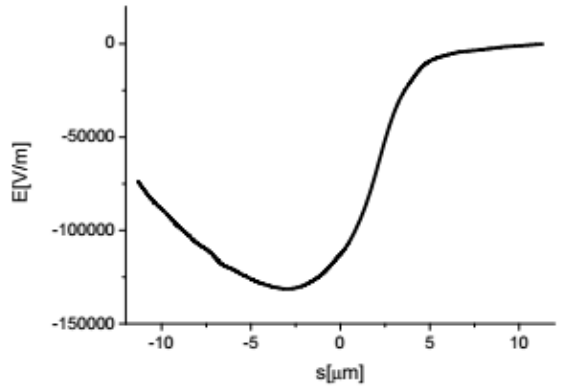
- 100 pC nominal beam
  - 5 kA peak current
  - 14 GeV beam energy
  - 0.35 urad emittance
  - 0.1% energy spread









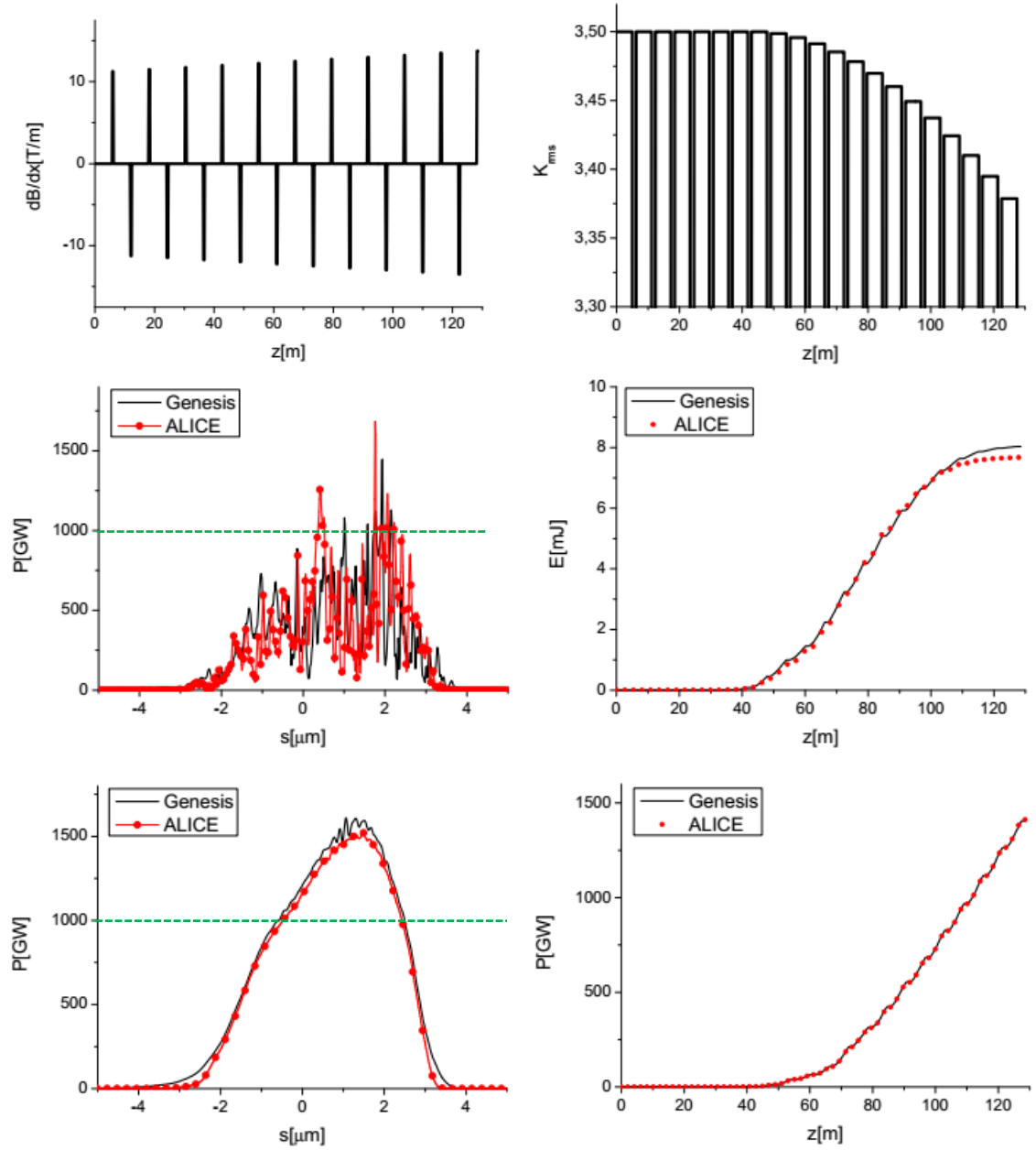


S. Serkez, V. Kocharyan, E. Saldin, I. Zagorodnov and G. Geloni *Nonlinear undulator tapering in conventional SASE regime at baseline electron beam parameters as a way to optimize the radiation characteristics of the European XFEL* (2013) http://arxiv.org/abs/1309.3149

Tapering study at SASE3

- SASE3 undulator
  - Period 68mm,
  - 73 periods per cell,
  - 21 cells (5m each),
  - 1.1m intersection,
  - 6.4 max K_{rms}
- 2keV ph.energy
- Tapering law:

$$K(z) = K(z_0)\,, \qquad \text{when } 0 < z < z_0\,,$$
$$K(z) = [K(z_0) + d] \cdot [1 - a(z - z_0)^b]\,, \text{when } z_0 < z < L_w\,,$$

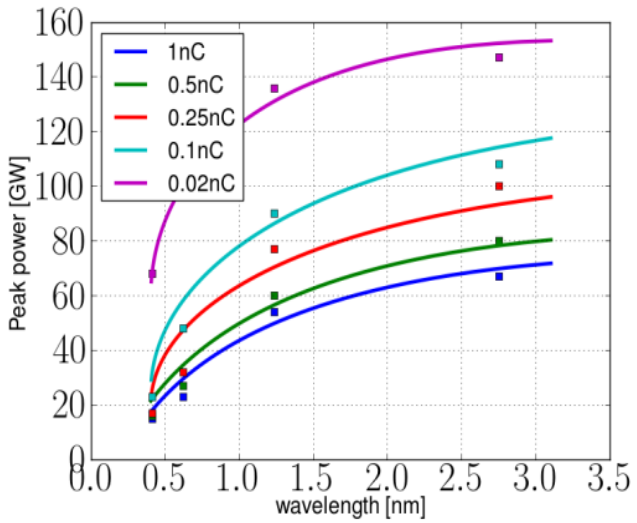


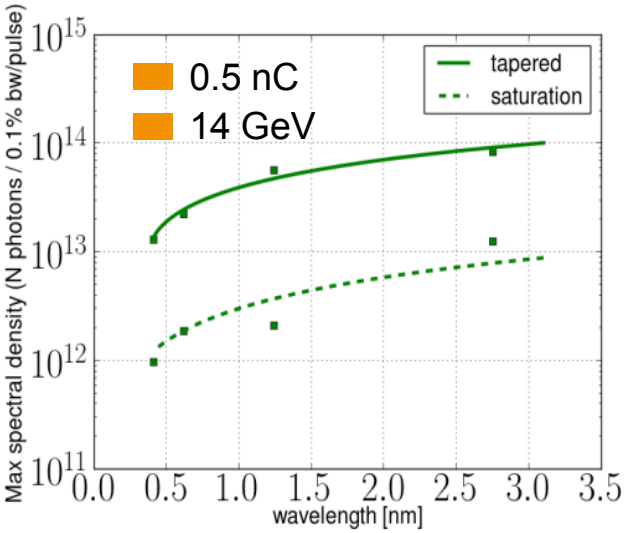
- S. Serkez, V. Kocharyan, E. Saldin, I. Zagorodnov and G. Geloni *Nonlinear undulator tapering in conventional SASE regime at baseline electron beam parameters as a way to optimize the radiation characteristics of the European XFEL* (2013) http://arxiv.org/abs/1309.3149
- Y. Jiao et al. Phys. Rev. ST Accel. Beams 15, 050704 (2012)

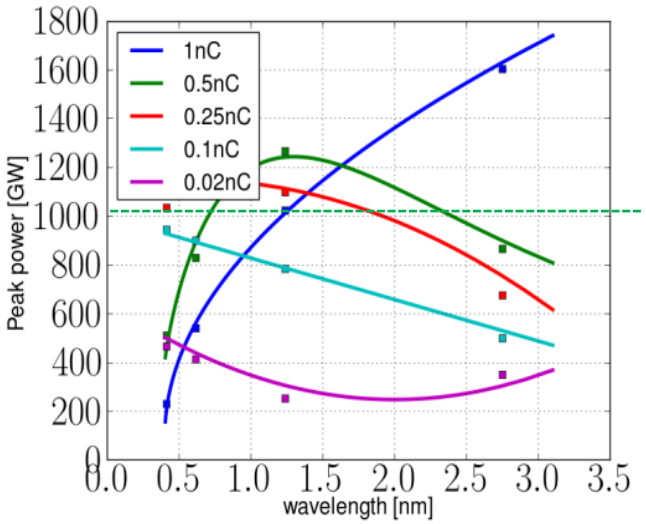
More tapering study at SASE3

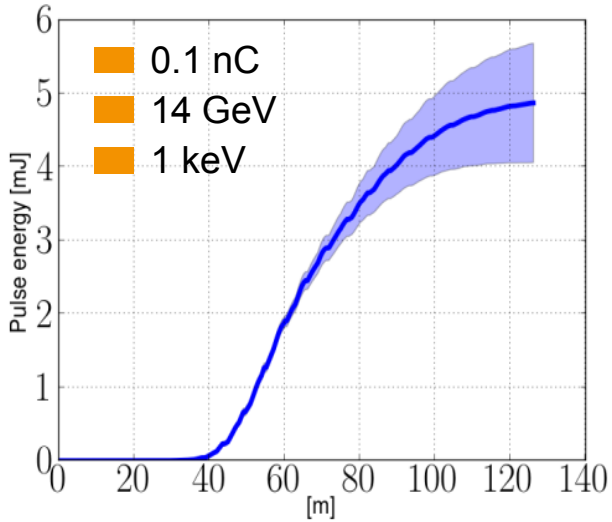
- For different
  - Bunch charges
  - Electron energies
  - Photon energies

- No seeding considered, only SASE





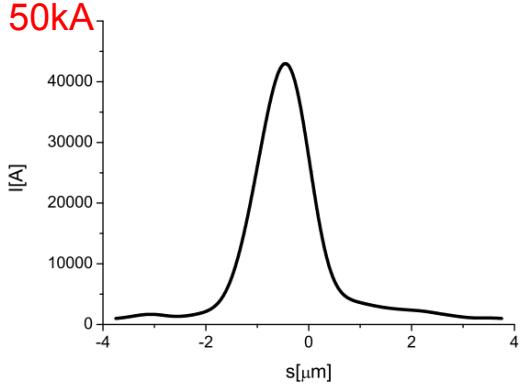


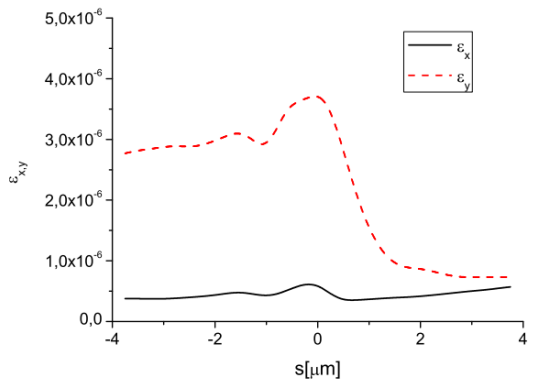


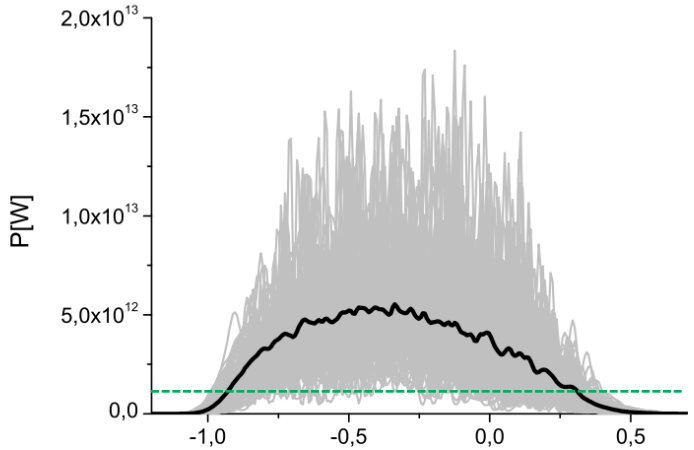
I.Agapov, G.Geloni, G.Feng, V.Kocharyan, E.Saldin, S.Serkez, I.Zagorodnov, *The Full Potential of the Baseline SASE Undulators of the European XFEL* (April 2014). http://arxiv.org/abs/1404.1177

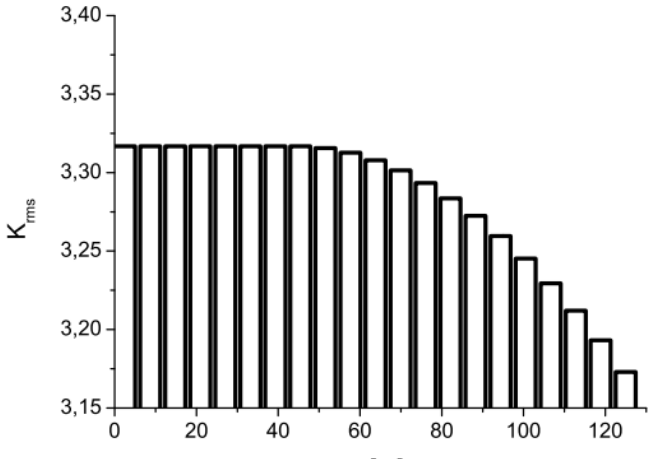
Extreme non-nominal compression at SASE3

50kA

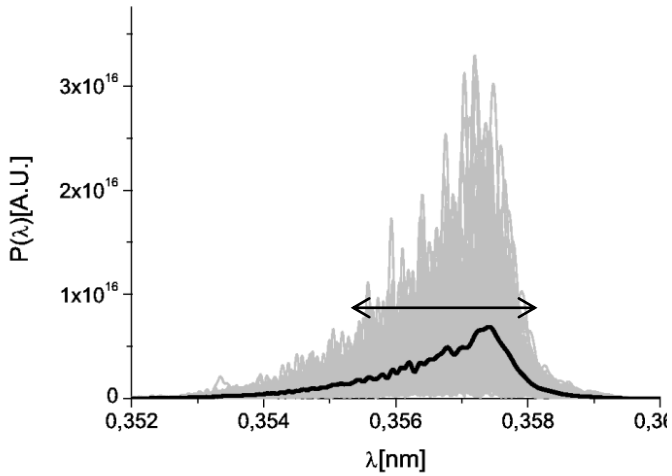


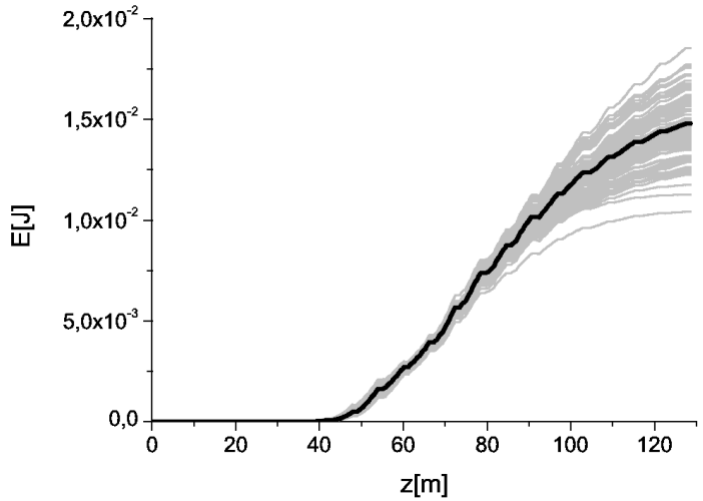






- 250 pC 17.5 GeV beam compressed up to 45 kA
- Poor emittance was compensated by large current
- 10TW at 3.5 keV
- 1% bandwidth

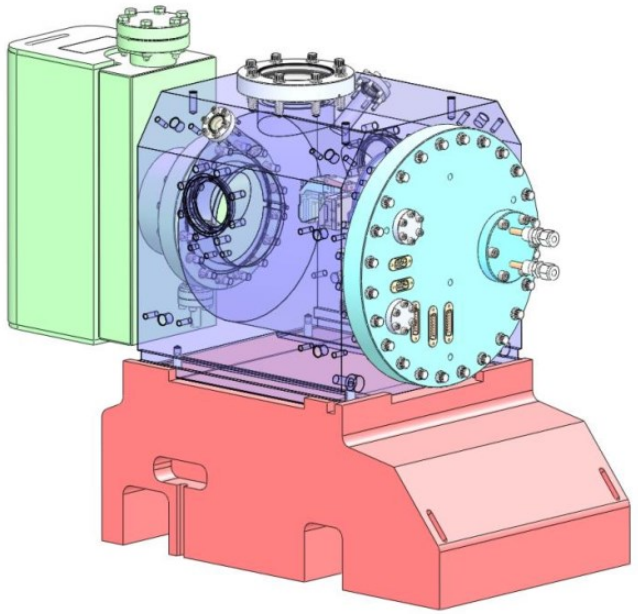




S. Serkez, V.Kocharyan, E.Saldin, I.Zagorodnov, G.Geloni, *Proposal to generate 10 TW level femtosecond x-ray pulses from a baseline undulator in conventional SASE regime at the European XFEL* (2013), http://arxiv.org/abs/1308.0448

Hard X-ray self-seeding

Slide from Shan Liu



Schedule for HXRSS implementation and commissioning

- Chamber design: *T. Wohlenberg (DESY)*
- Diamond and holder design:
  D. Shu (ANL), S. Terentiev (TISNUM)

- SASE2: first lasing in **May 2018**
- SASE2 chicanes, girders and monochromator chambers are assembled
- Monochromators will be ready by the end of 2018
- Self-seeding **chicane installation** in SASE2: **December 2018**
- Self-seeding chicane construction for **SASE1 (2018-2019)**

G.Geloni, V.Kocharyan, E.Saldin, *Cost-effective way to enhance the capabilities of the LCLS baseline* (2010) http://arxiv.org/abs/1008.3036

Self-seeded SASE2

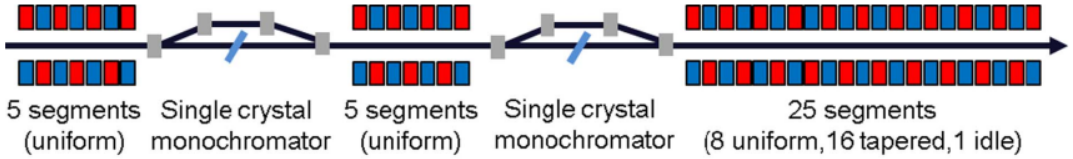


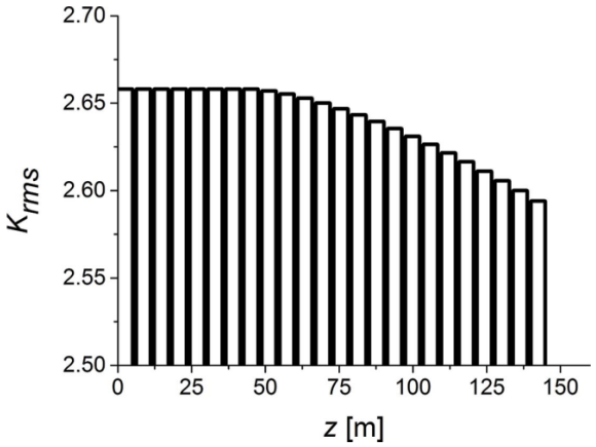
Figure 2
Layout of the SASE-2 undulator (35 segments) in the double-cascade self-seeding scheme for HXRSS. The monochromators are placed in the photon beam in between undulator segments where a magnetic chicane deviates the electrons.

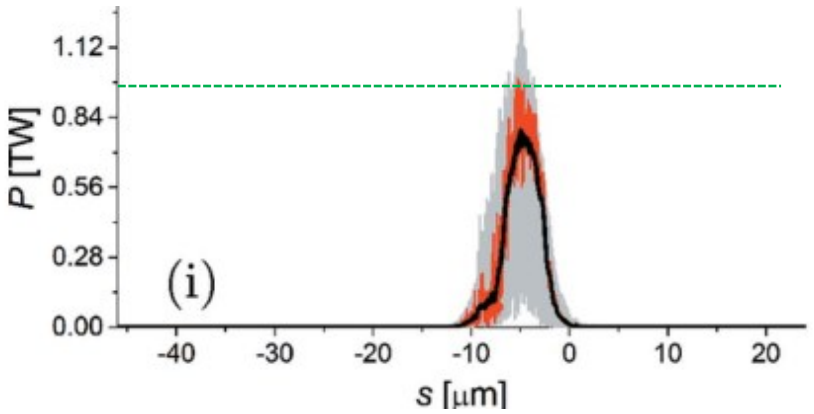
- High repetition rate
- Two-stage HXRSS at 9keV

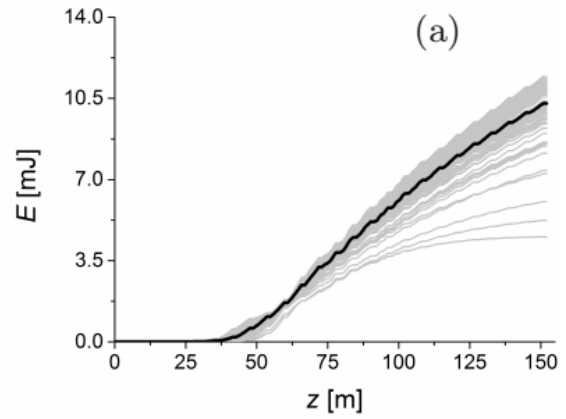
Operation parameters of the European XFEL used in this paper.

(*) refers to the position in the bunch with maximum peak current.

		Units
Undulator period	40	mm
Periods per segment	125	
Total number of segments	35	
K parameter (r.m.s.)	2.658	
Intersection length	1.1	m
Wavelength	0.1358	nm
Energy	17.5	GeV
Charge	250	pC
Horizontal normalized slice emittance (*)	4.0×10^{-7}	m rad
Vertical normalized slice emittance (*)	3.6×10^{-7}	m rad
Peak current	5.0	kA
Energy spread σ_γ (*)	0.96	

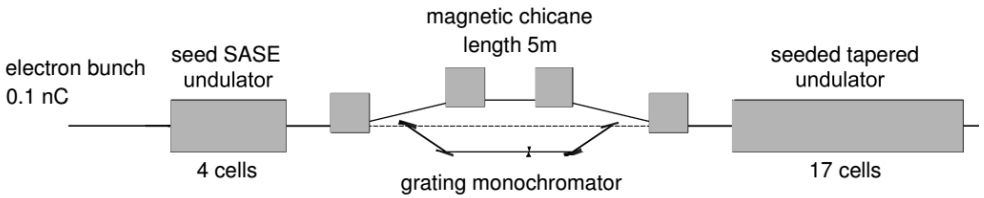




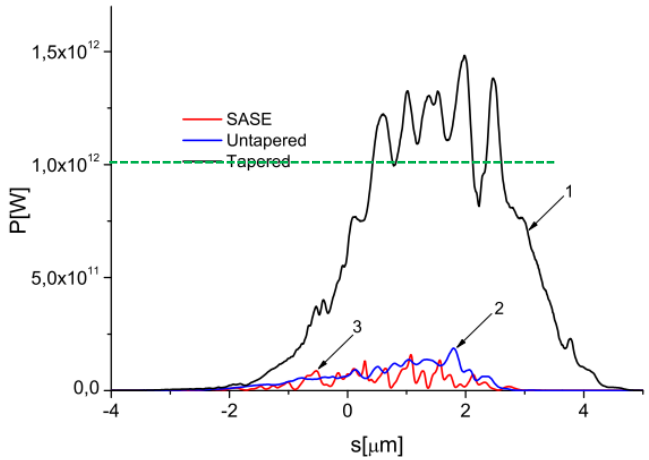


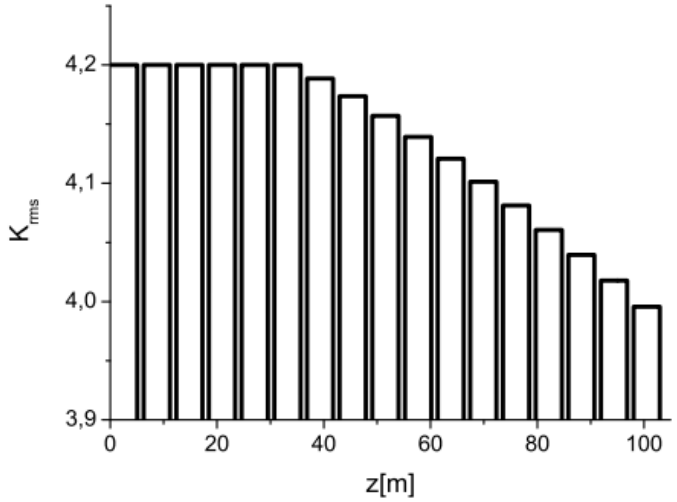
- O.Chubar et al., *Novel opportunities for sub-meV inelastic X-ray scattering at high-repetition rate self-seeded X-ray free-electron lasers* (2015). http://arxiv.org/abs/1508.02632
- O.Chubar et al., Ultra-high-resolution inelastic X-ray scattering at high-repetition-rate self-seeded X-ray free-electron lasers. *Journal of Synchrotron Radiation*, *23*(2), 410–424 (2016).

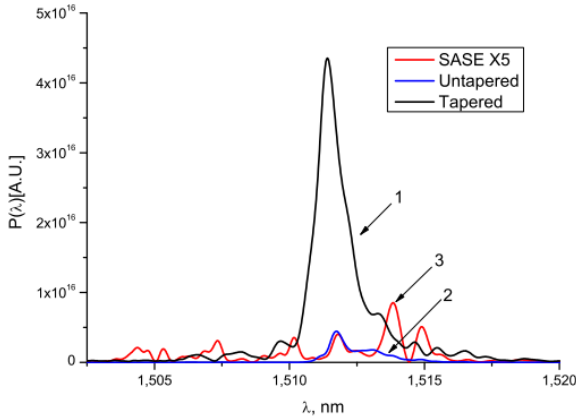
Self-seeded SASE3

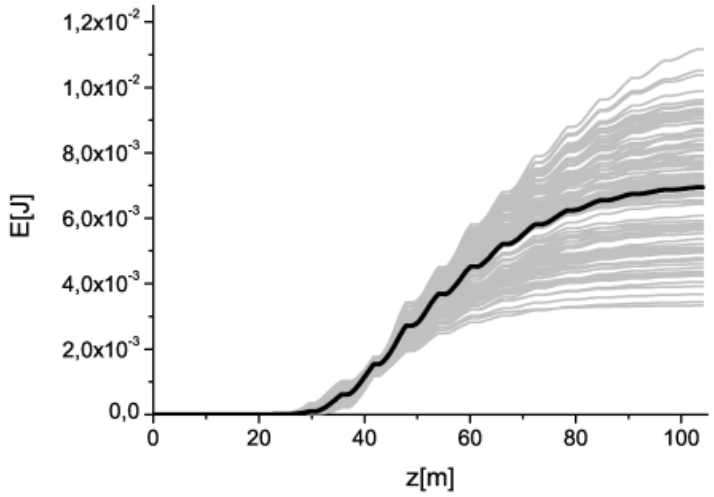


- SXRSS at 700 eV



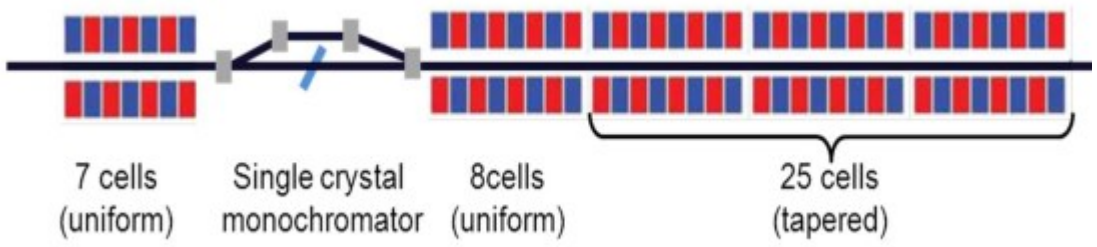


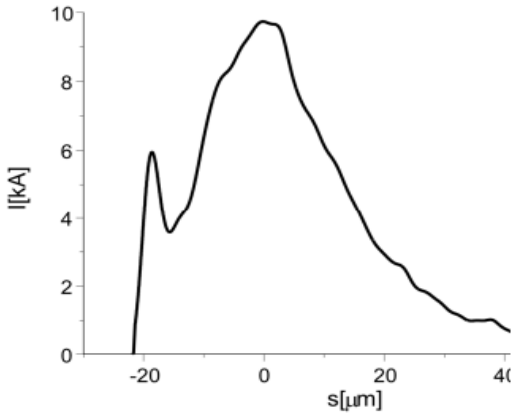


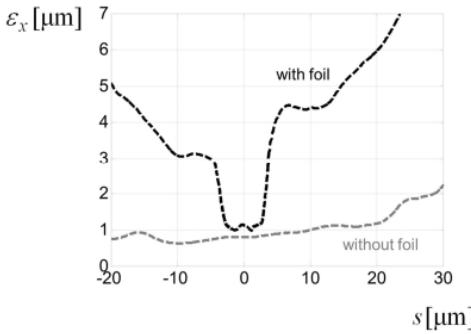


S. Serkez, G.Geloni, V.Kocharyan, E.Saldin, *Grating monochromator for soft X-ray self-seeding the European XFEL* (2013). http://arxiv.org/abs/1303.1392

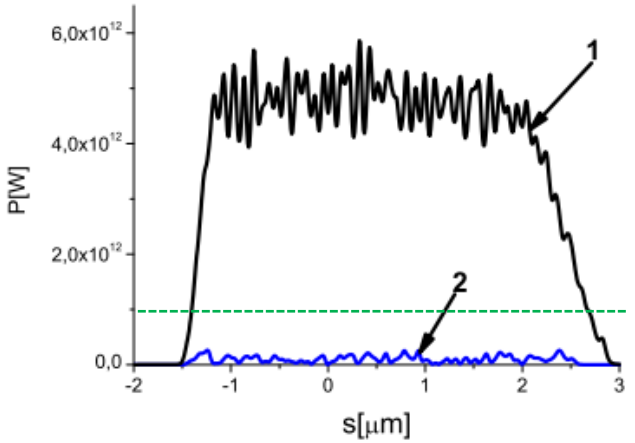
Idea of bioimaging beamline at SASE3

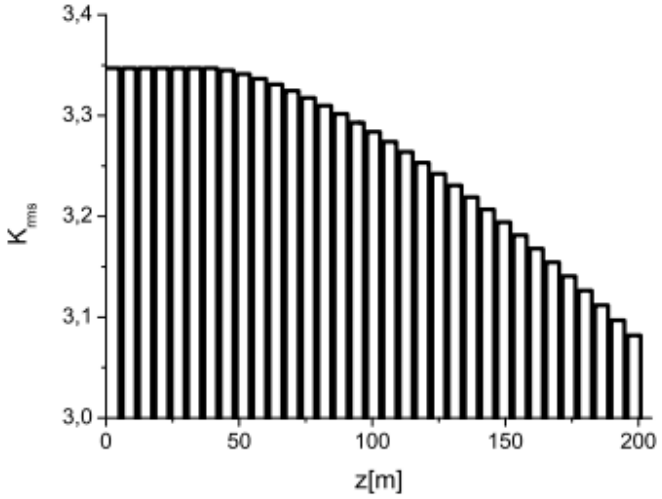


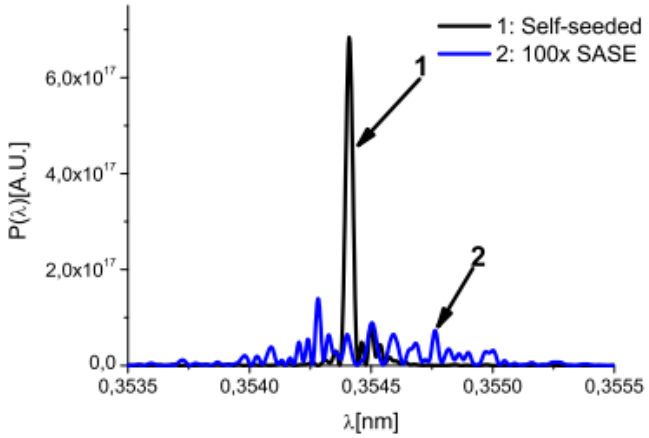


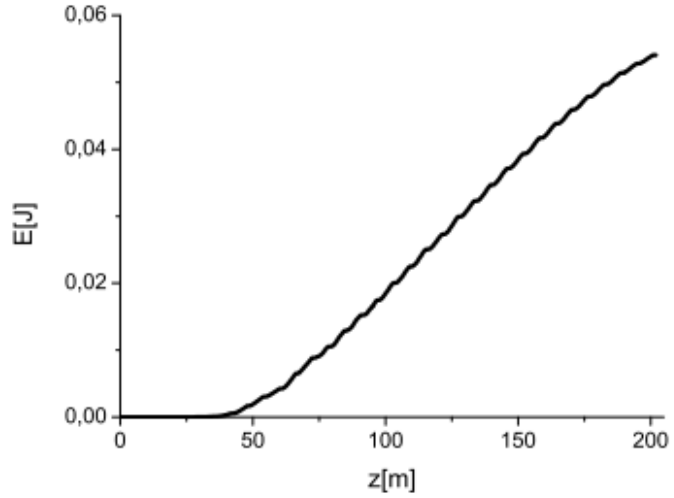


- 17.5 GeV beam
  - compressed to 10 kA
  - 12 fs lasing window
- **40 undulator cells**
- 3.5 keV



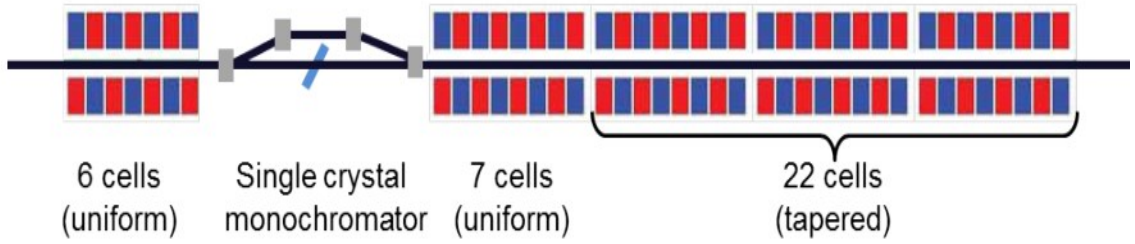


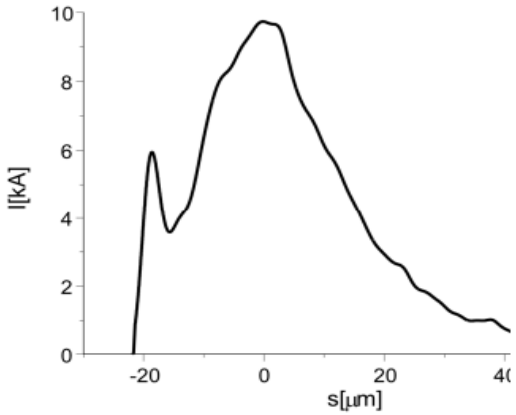


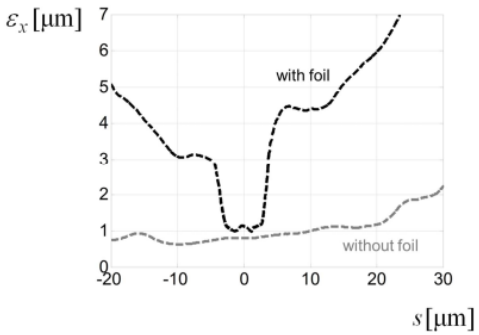


S.Serkez, V.Kocharyan, E.Saldin, I.Zagorodnov, G.Geloni, O.Yefanov, Proposal for a scheme to generate 10 TW-level femtosecond x-ray pulses for imaging single protein molecules at the European XFEL (2013). http://arxiv.org/abs/1306.0804

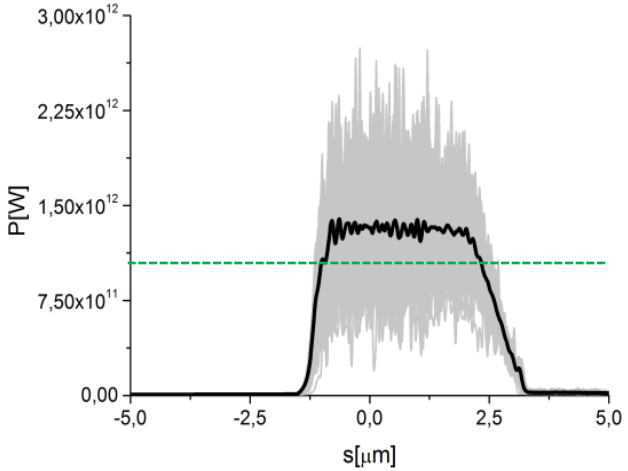
Study of SPB beamline at SASE1

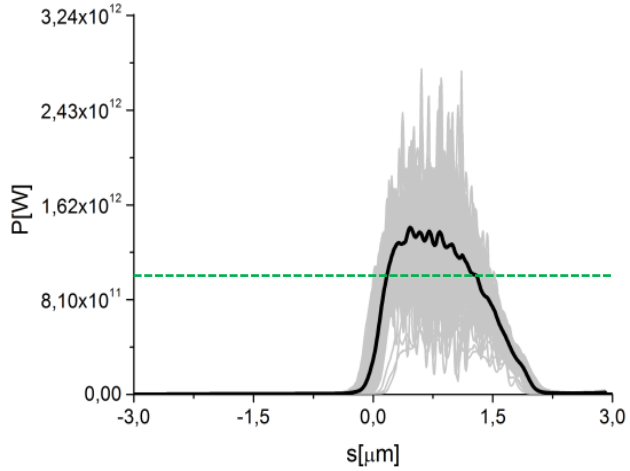


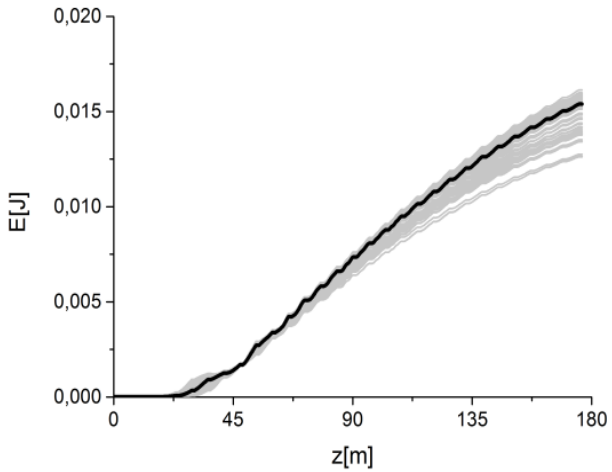


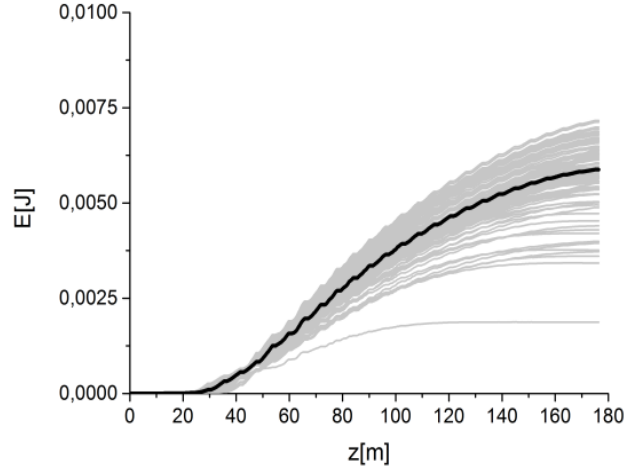


- HXRSS assumed
- Same electron beam
  - Two different lasing windows
- 4.1 keV









12 fs 4 fs

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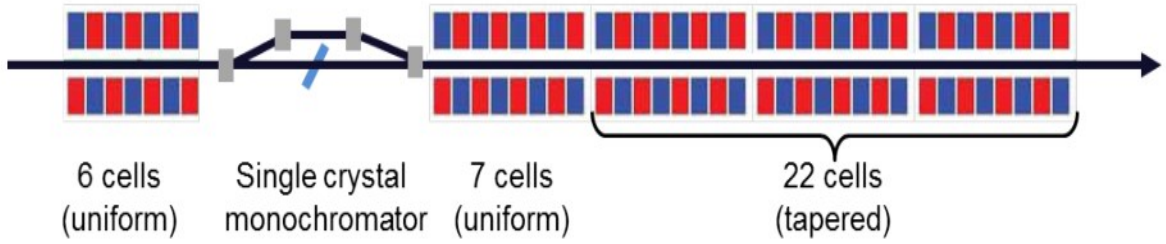
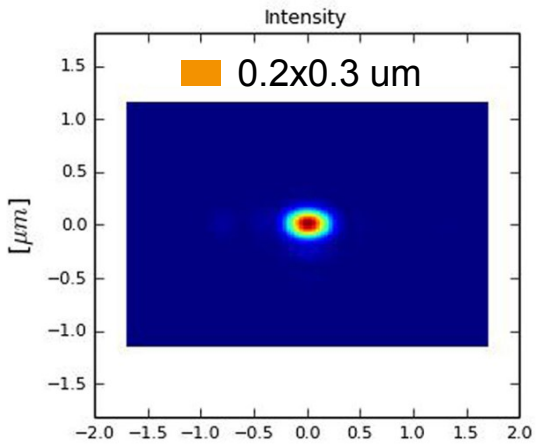
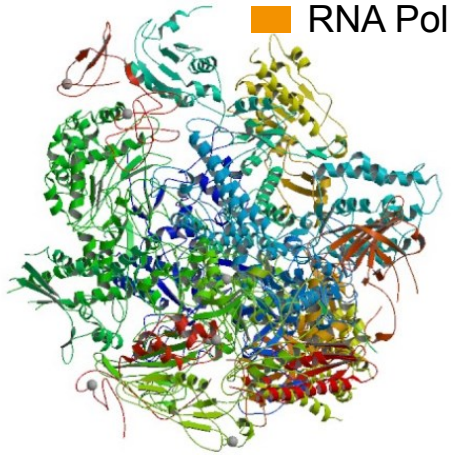
- K. Ayyer, G.Geloni, V.Kocharyan, E.Saldin, S.Serkez, O.Yefanov, I.Zagorodnov, I. Perspectives for imaging single protein molecules with the present design of the European XFEL. *Structural Dynamics*, *2*(4), 41702 (2015) http://doi.org/10.1063/1.4919301

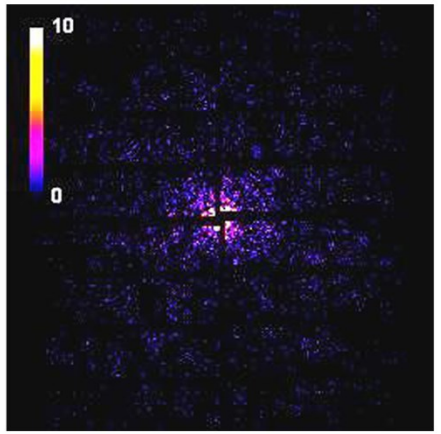
Study of SPB beamline at SASE1

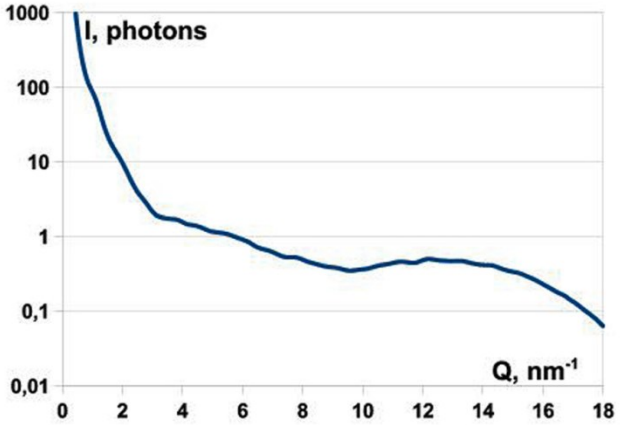


0.1 photons per Shannon pixel per shot at 4A resolution with 10^{13} photons in a 4fs pulse at 4keV photon energy and in a 0.3um focus, corresponding to a fluence of 10^{14} photons/um^2









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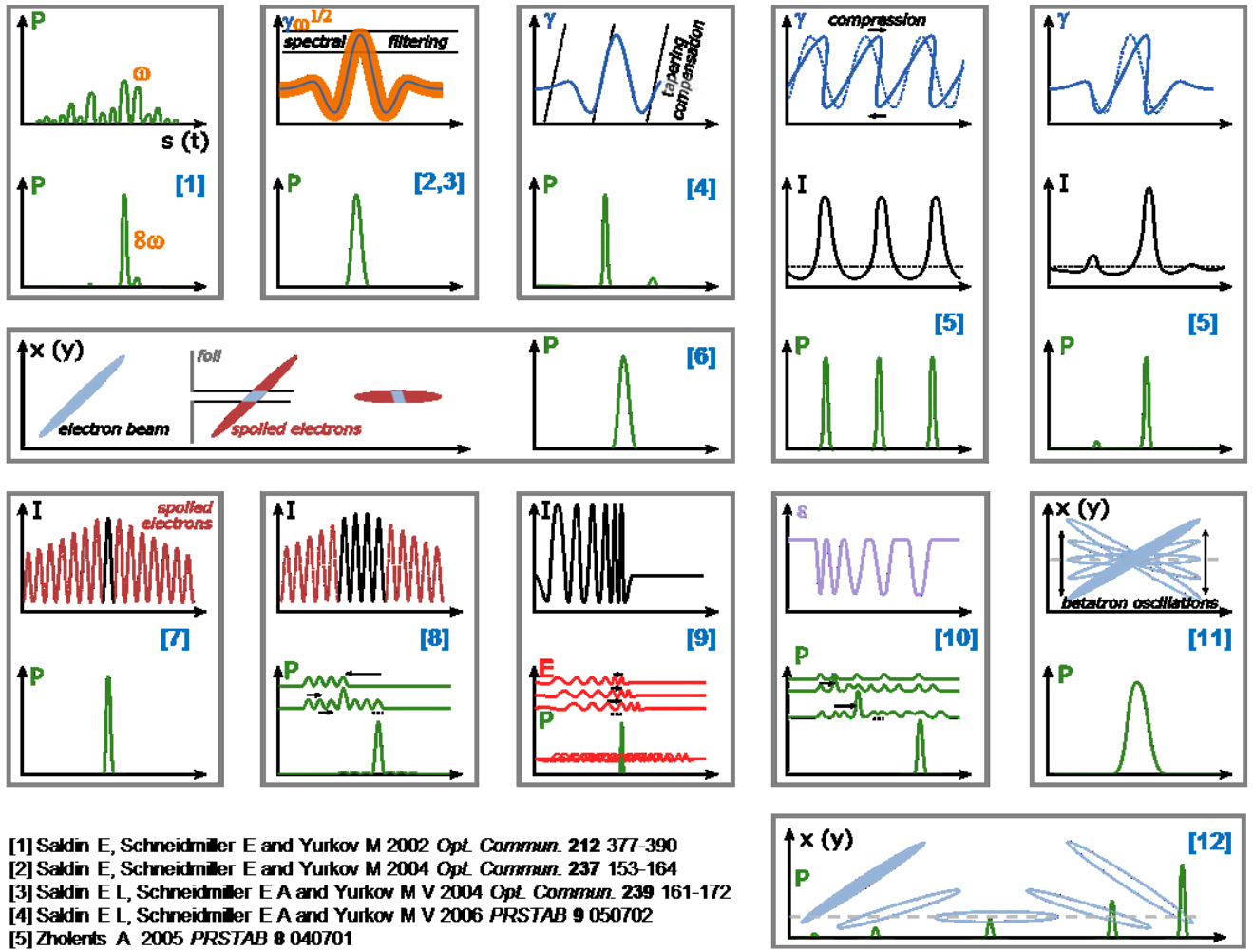
Sub – femtosecond?

- Plenty of schemes already developed



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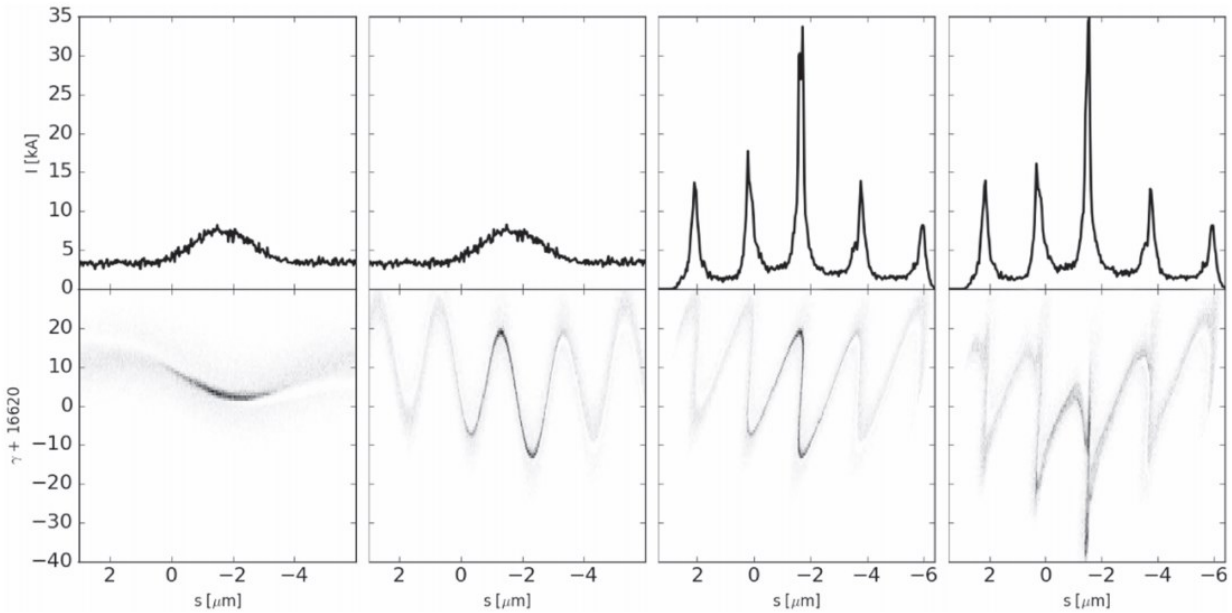
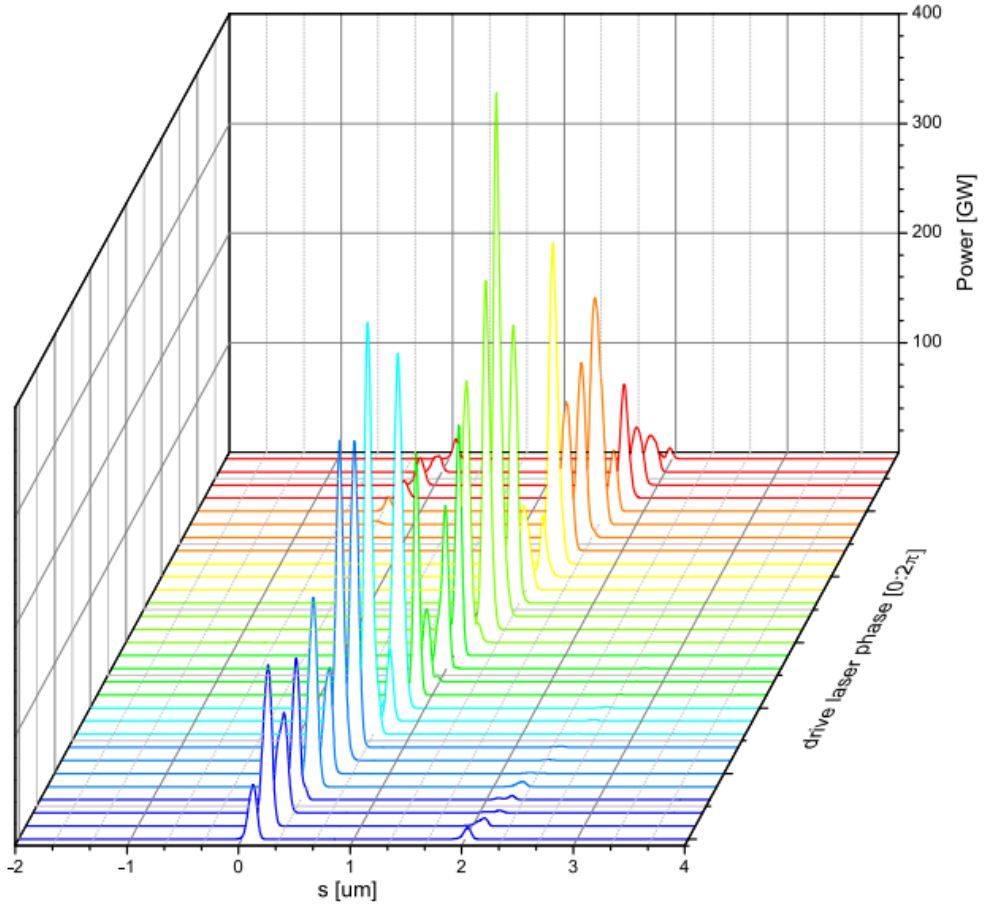
Sub – femtosecond?

- Estimated XLEAP efficiency at SASE3 beamline
  - 8.5 GeV beam with emittance spoiler
  - Around 0.5 TW at saturation within 0.4 fs fwhm
  - No tapering applied



(a) before modulator (b) after modulator (c) after chicane (d) CSR&SC included



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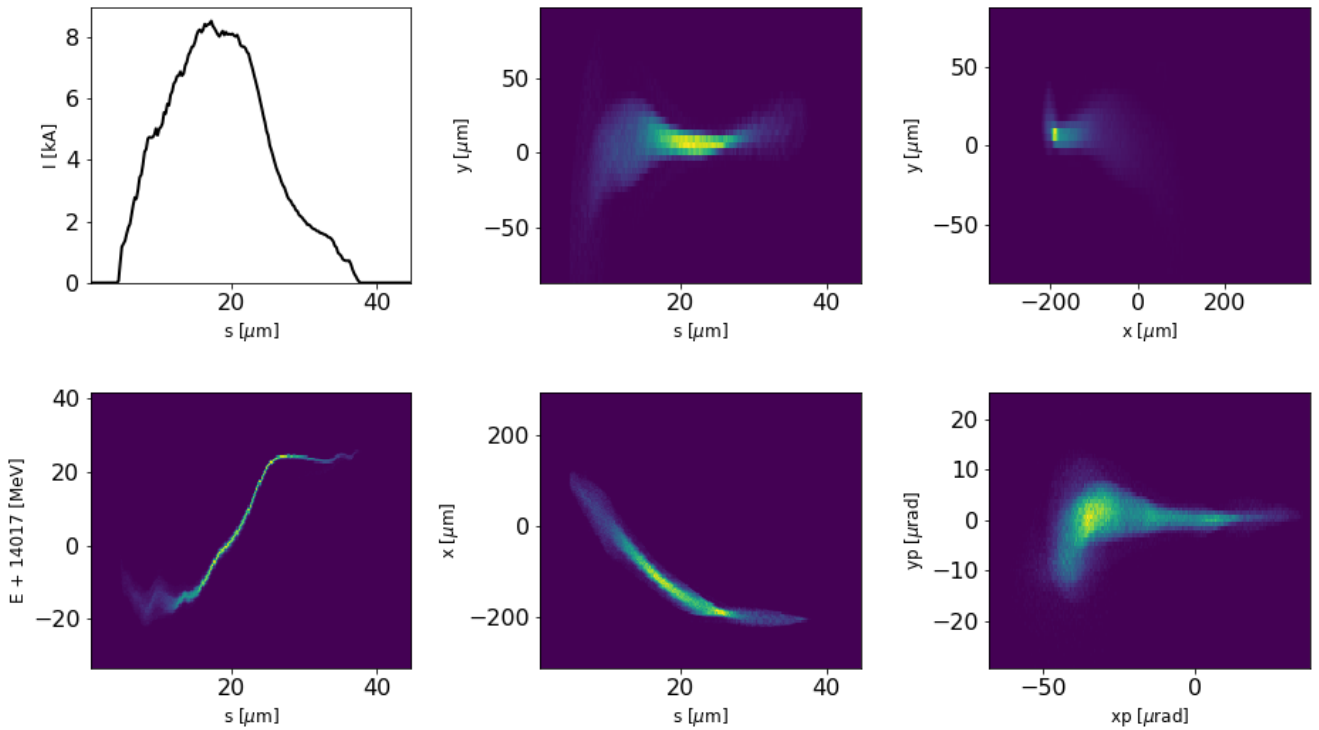
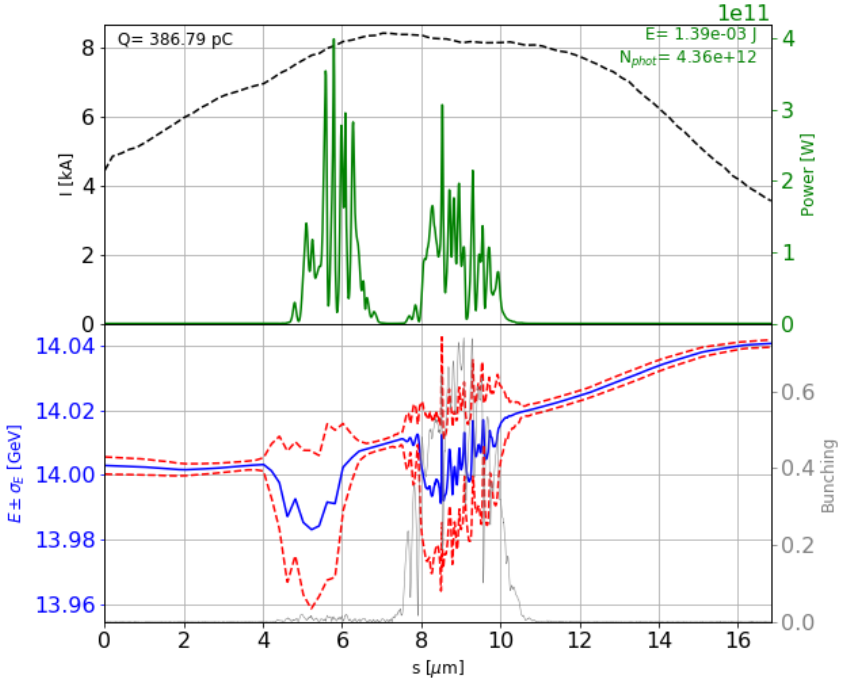
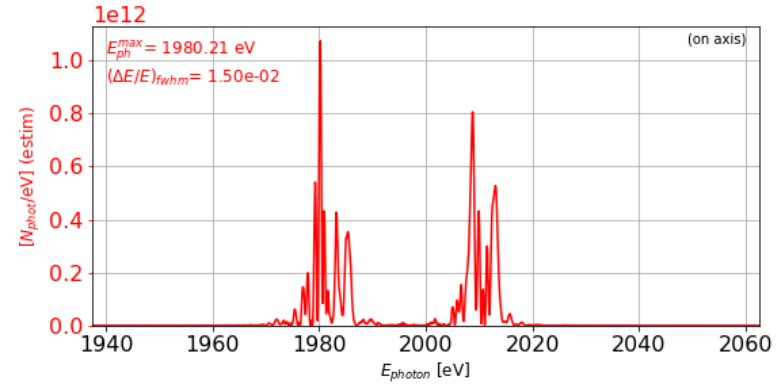
Double saturation at SASE3

- Corrugated structure considered upstream SASE3
  - With fresh bunch we can saturate twice at 2keV
  - Two pulses 100 GW each







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