Self-Seeding:
energy limits and possibilities

Gianluca Geloni, Shan Liu, Svitozar Serkez

European XFEL and DESY

X. Dong, S. Karabekyan, L. Samoylova, H. Sinn –
European XFEL, Hamburg
W. Decking, C. Engling, N. Golubeva, B. Krause, E. Negodin, A. Petrov, T. Wohlenberg - **DESY, Hamburg**
D. Shu - **ANL, Argonne, Illinois**
V. Blank, S. Terentiev - **TISNCM, Troitsk**

European XFEL:

- Sergey Tomin
- Takanori Tanikawa

DESY:

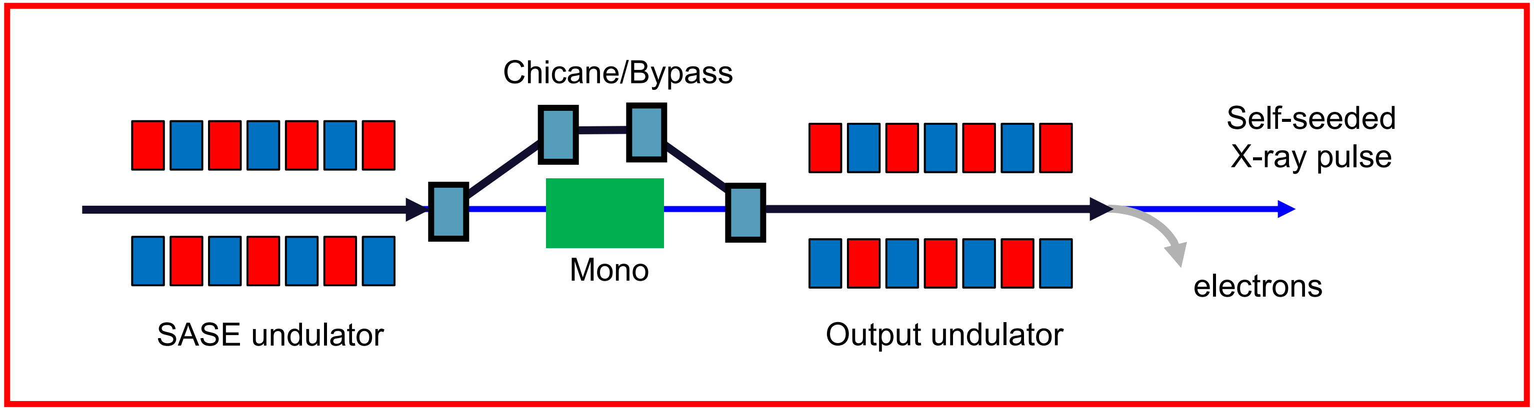
- Vitali Kocharyan
- Evgeni Saldin

Shaping the future of the European XFEL: options for the SASE4/5 tunnels
European XFEL, Schenefeld, December 7th, 2018

Contents

A short introduction to self-seeding

Method first introduced for soft x-rays [J. Feldhaus et al., Optics Comm. 140, 341 (1997)]: basically an active filter in frequency



- First part: usual SASE pulse in the linear regime
- Chicane needed for:
  - Creating an offset 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

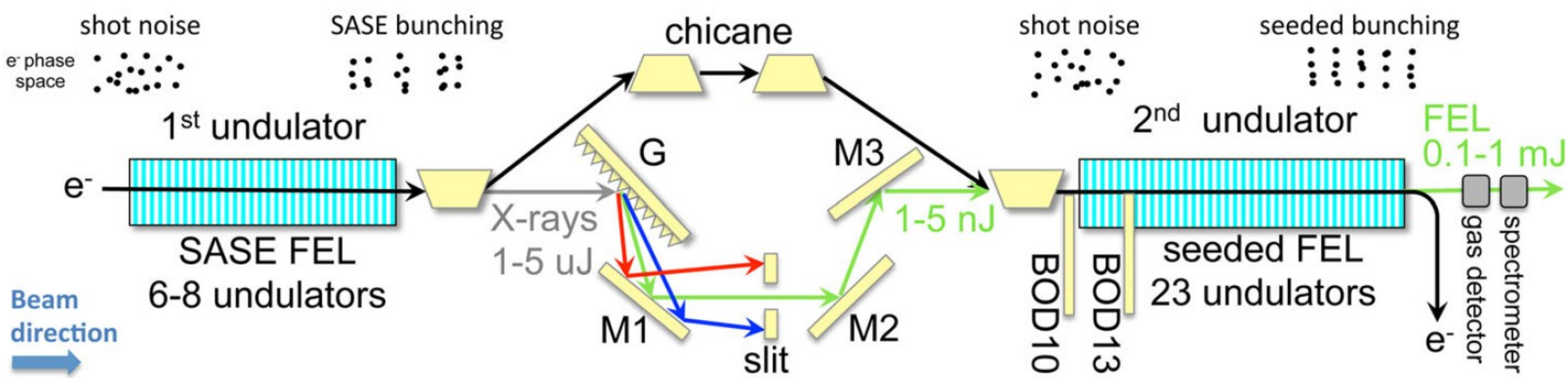
- Independently of Self-Seeding:
  - Chicane for 2 colors
  - Chicane for autocorrelation
  - Sinergy with corr. structure

Challenging: compensating the optical delay from the mono within a compact setup

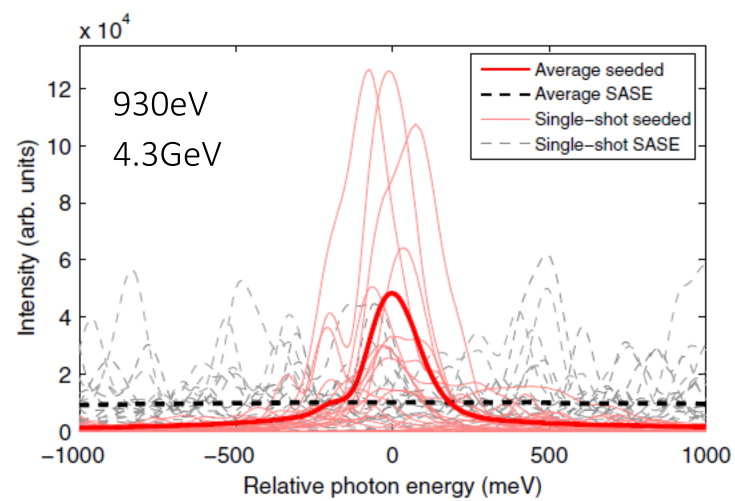
A short introduction to self-seeding

PRL **114,** 054801 (2015) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2015

Experimental Demonstration of a Soft X-Ray Self-Seeded Free-Electron Laser

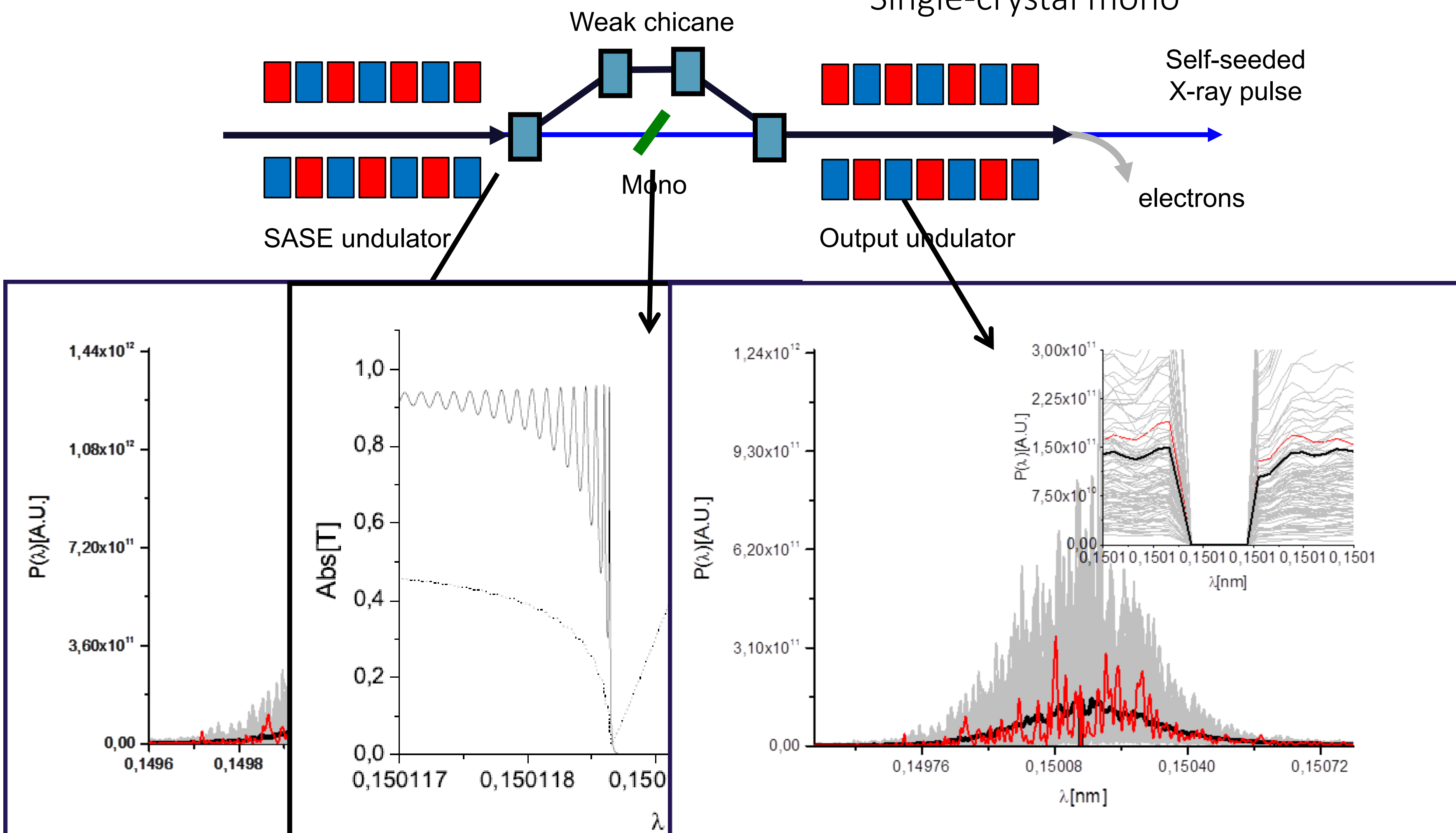


Nominal energy range: 500 eV -1000 eV



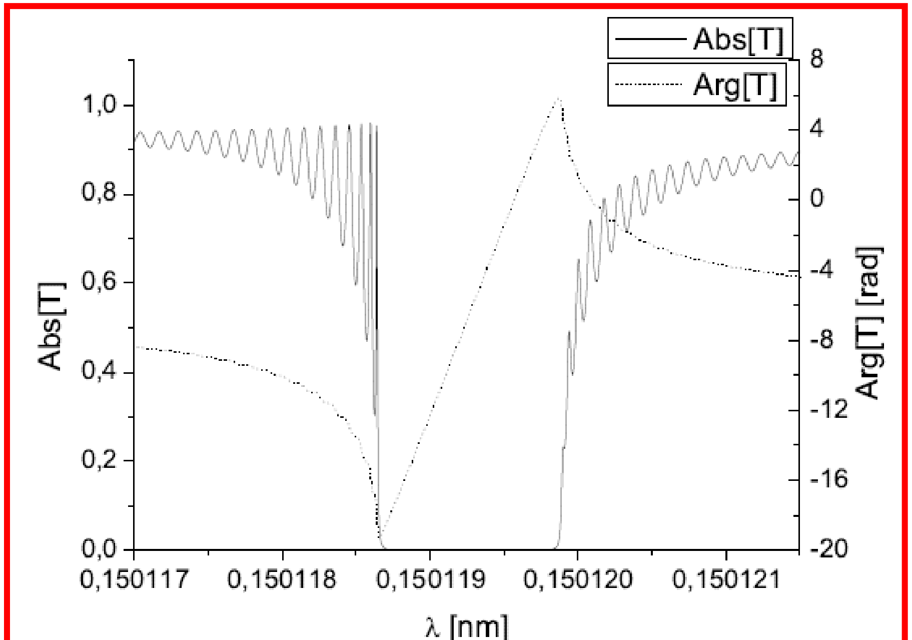
A short introduction to self-seeding

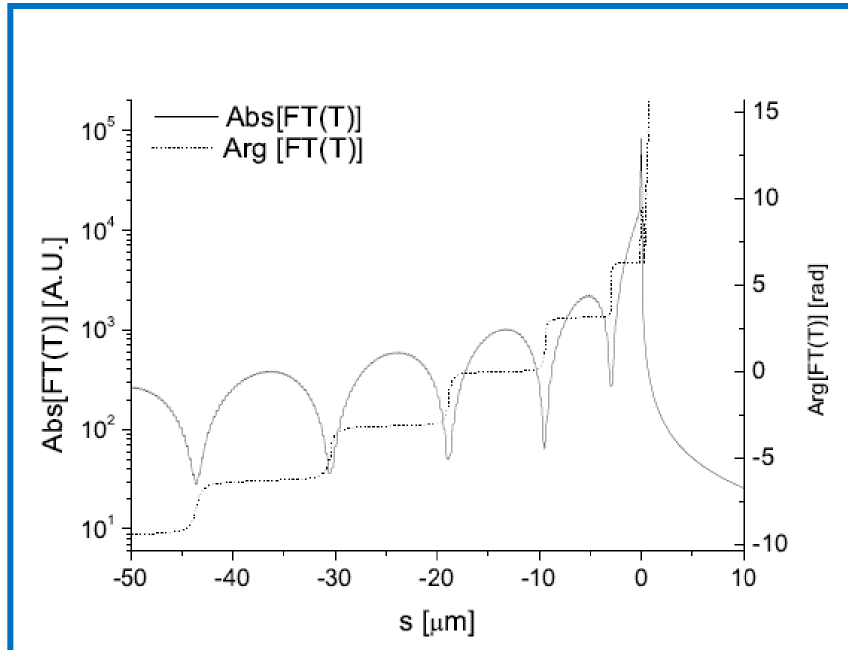
Method made “easy” for HXR
Single-crystal mono



G. Geloni, V. Kocharyan, E. Saldin ‘A novel self-seeding scheme for hard X-ray FELs’ Journal of Modern Optics 58, 16 1391 (2011)

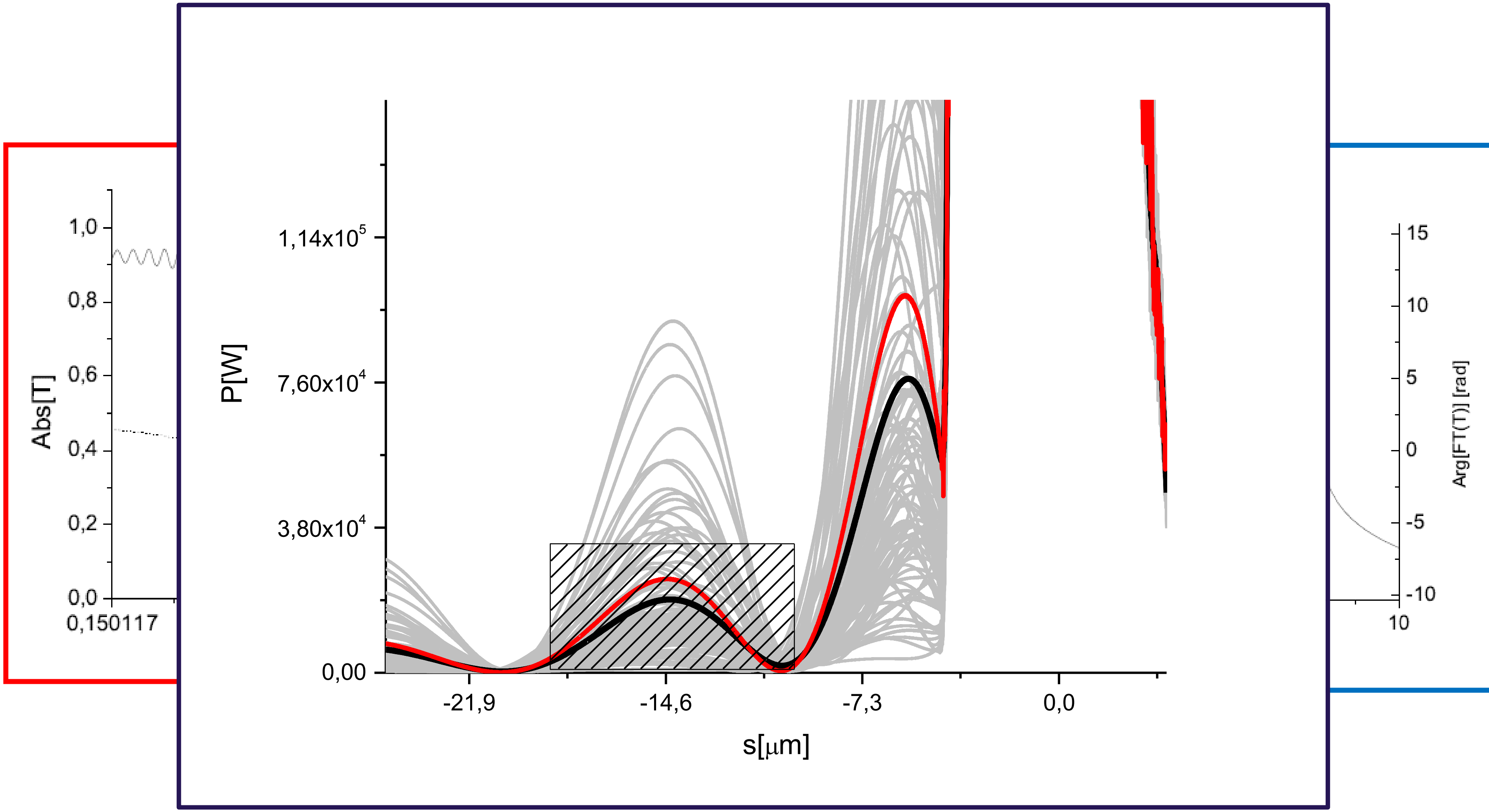
A short introduction to self-seeding





G. Geloni, V. Kocharyan, E. Saldin 'A novel self-seeding scheme for hard X-ray FELs' Journal of Modern Optics 58, 16 1391 (2011)

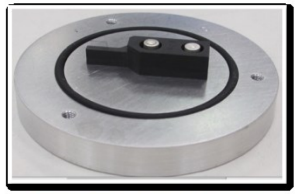
A short introduction to self-seeding

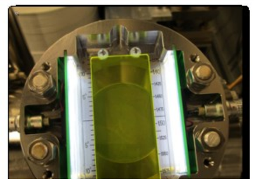


G. Geloni, V. Kocharyan, E. Saldin 'A novel self-seeding scheme for hard X-ray FELs' Journal of Modern Optics 58, 16 1391 (2011)

A short introduction to self-seeding

Courtesy of Paul Emma

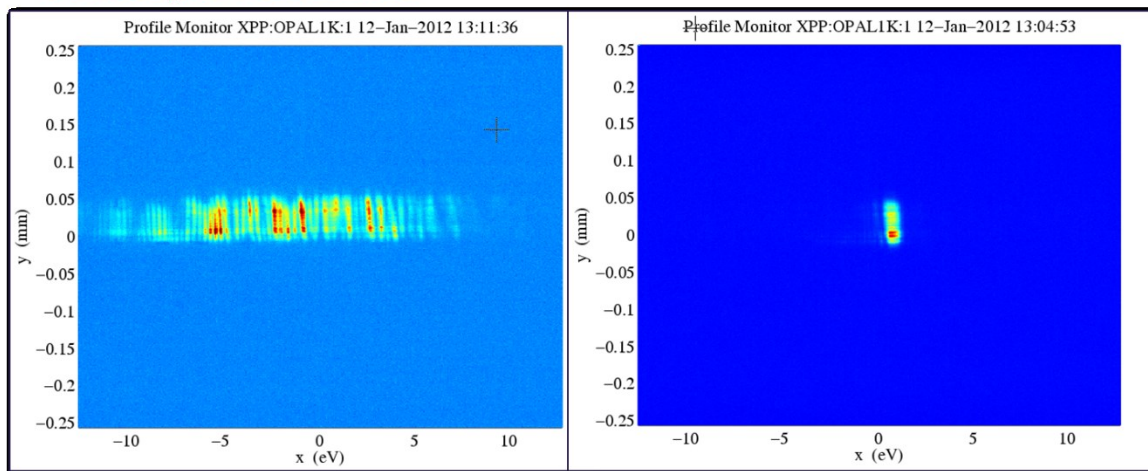




First experimental verification at the LCLS (Jan 2012)

- A number of different C* reflections used

Courtesy of Paul Emma



150 pC, 3 kA, diamond OUT

150 pC, 3 kA, diamond IN

See also: 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)

A few recent developments

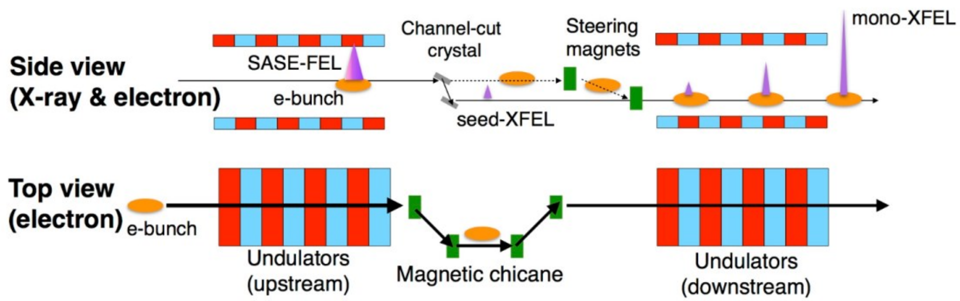
Reflection self-seeding at SACLA

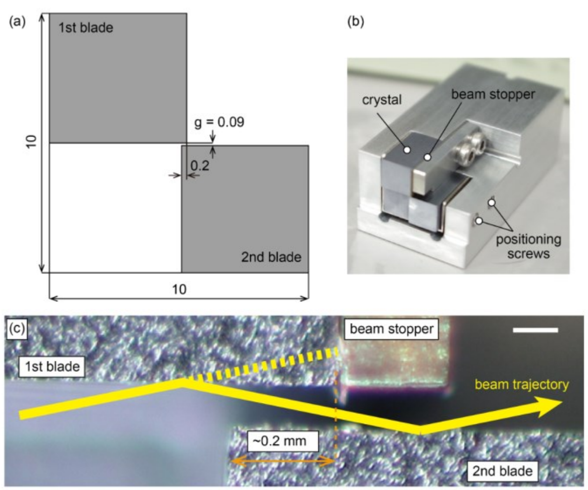
Ichiro Inoue*[1], Taito Osaka[1], Takahiro Inagaki[1], Shunji Goto[1,2], Toru Hara[1], Yuichi Inubushi[1,2], Ryota Kinjo[1], Haruhiko Ohashi[1,2], Takashi Tanaka[1], Kazuaki Togawa[1], Kensuke Tono[1,2], Hitoshi Tanaka[1], and Makina Yabashi[1,2]

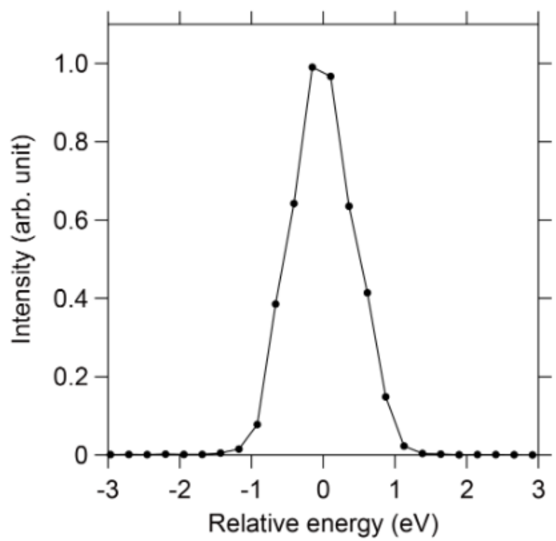
A micro channel-cut crystal X-ray monochromator for a self-seeded hard X-ray free-electron laser

Taito Osaka,[a,*] Ichiro Inoue,[a] Ryota Kinjo,[a] Takashi Hirano,[b] Yuki Morioka,[b] Yasuhisa Sano,[b] Kazuto Yamauchi[b] and Makina Yabashi[a,c]

→ A recent reflection-based mono at SACLA



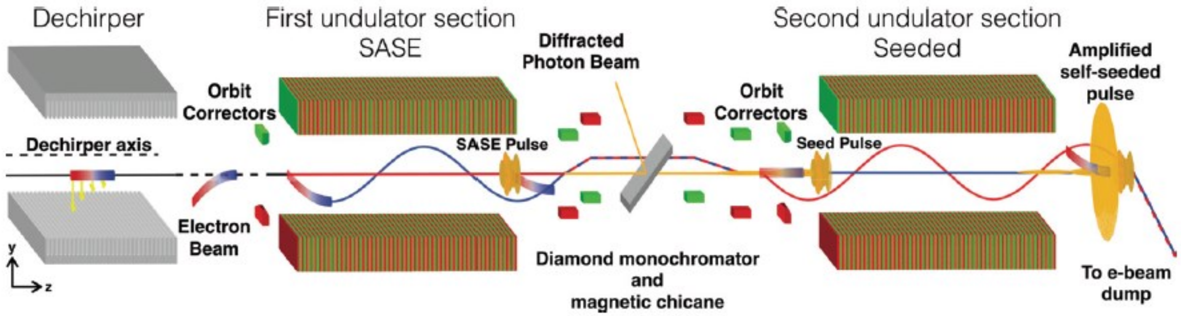




Averaged spectrum of the seed measured with a Si(220) channel-cut crystal. The number of accumulation at each point is 100 shots. The central photon energy is 10 keV

A few recent developments

Combination with fresh bunch



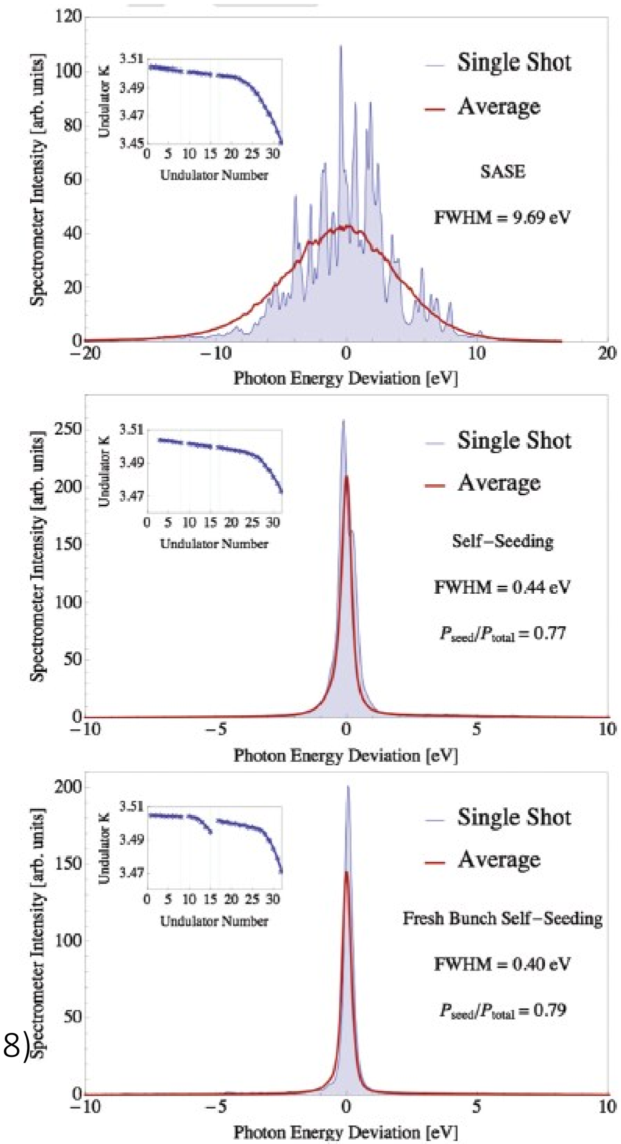
Claudio Emma et al, APL, 2017

E_{ph}=5.5keV, Q=250pC

$$B_{FBSS}/B_{SASE} = 12.5$$

$$B_{FBSS}/B_{self\text{-}seeding} = 2.4$$

Comment:
could be problematic at high rep-rate
(crystal heat-load)

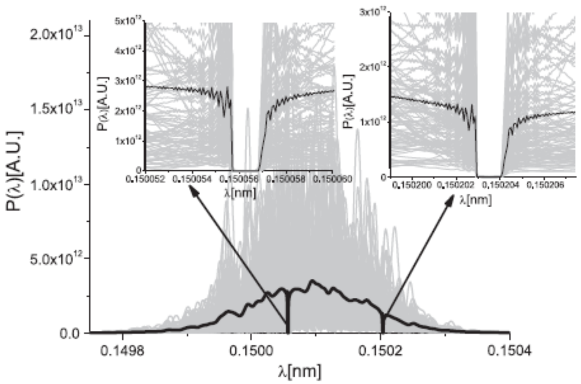


- Still B increase for usual self-seeding is 12.5/2.4 = 5.2
- And FBSS can be used at low rep-rate
- Dechirper can have a number of other uses too
  - → 2 colors fresh slice
  - → Diagnostics tool
  - → Sinergy with SDL line (W. Lu et al, Rev. Sci Instruments 89, 063121, 2018)
  - → Larger BW than usual SASE
  - → Possibly seeding simultaneously at two different colors > SASE BW

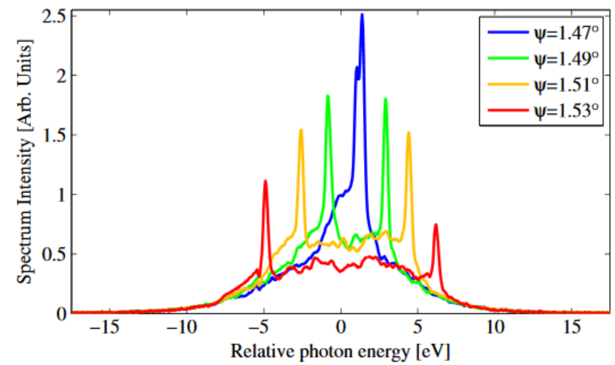
A few recent developments

Within the (relatively narrow) SASE BW, HXRSS can be used to seed simultaneously

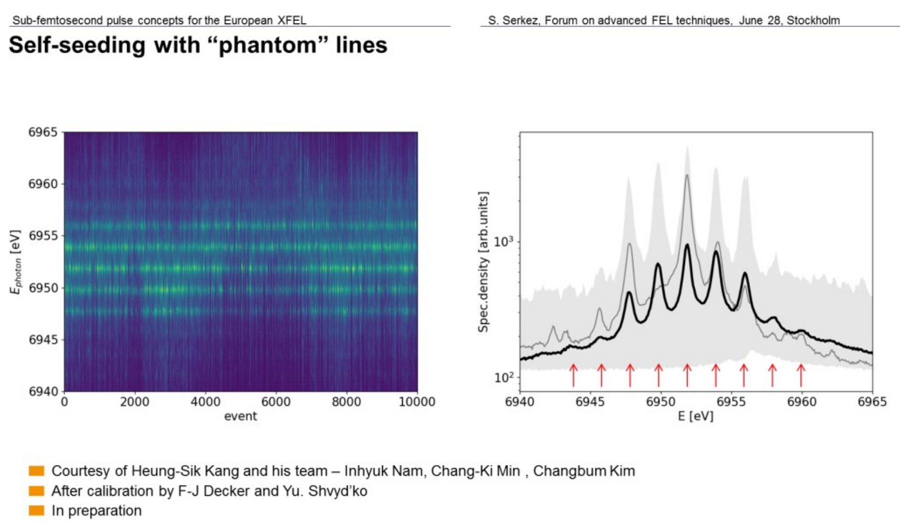
→ Either use "crossing" reflections or play with Yaw/Roll of the crystal



G. Geloni, V. Kocharyan, E. Saldin,Opt. Comm. 284 (2011) 3348–3356 (original suggestion: using two crystals)



A.A. Lutman et al., PRL 113, 254801 (2014)



S. Serkez, Forum on advanced FEL techniques, Stockholm 2018 (courtesy of Heung-Sik Kang)

European XFEL-specific facts

High repetition-rate. Overall, more pulses but:

Larger heat-load. For example HXRSS:

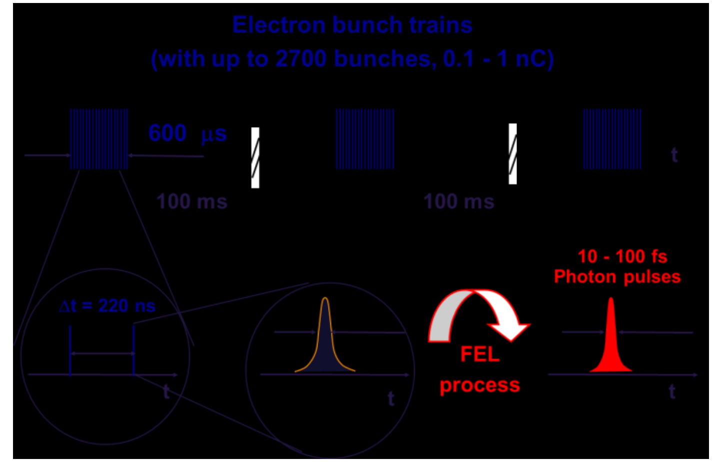
→ ω-shift beyond Darwin width (conservative)

→ Spectrum broadening

Two sources:

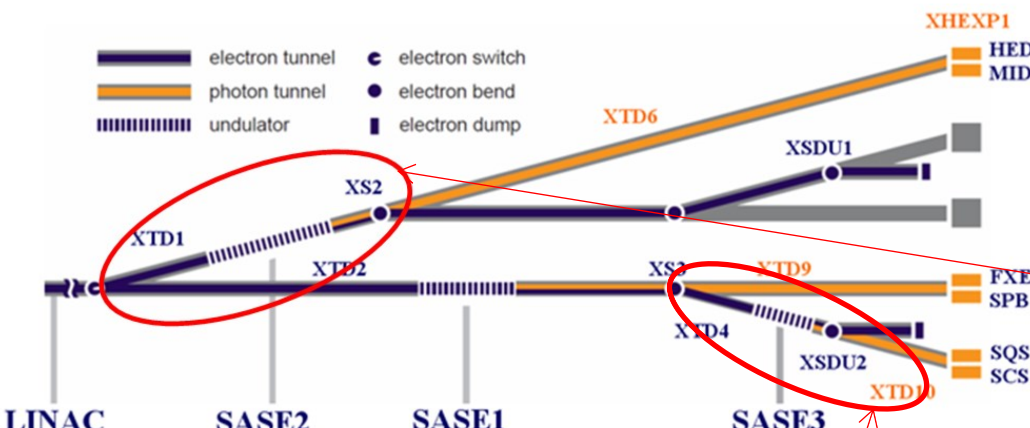
→ SR: for 100 pC, 17.5 GeV, 8keV fundamental,100 μm thick diamond, 8 segments → 6μJ/pulse deposited energy

→ FEL-based : depends heavily on photon energy



Long undulators (175m magnetic length at SASE2)

→ Tapering



HXRSS at SASE2 (2019)
(3 keV -25 keV)

→ to be first equipped with HXRSS

SXRSS natural at SASE3
(250 eV - 3 keV)

SXRSS

Svitozar Serkez' Ph.D. Thesis

Energy range: 300eV – 1200eV

Complementary to external seeding

Heat-loading issues at high rep-rate

Follows LCLS design with modifications

Design and optimization of the Grating Monochromator for Soft X-Ray Self-Seeding FELs

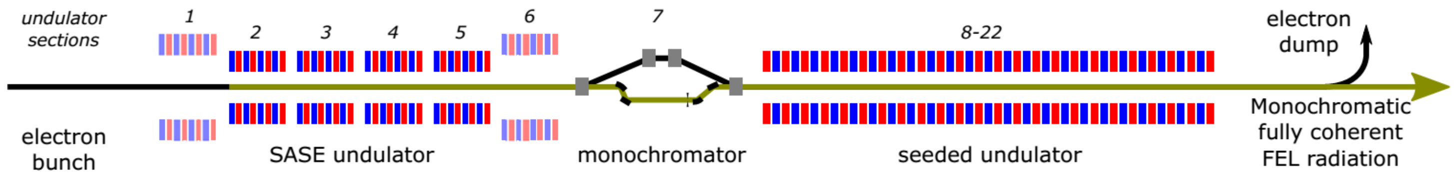
Dissertation

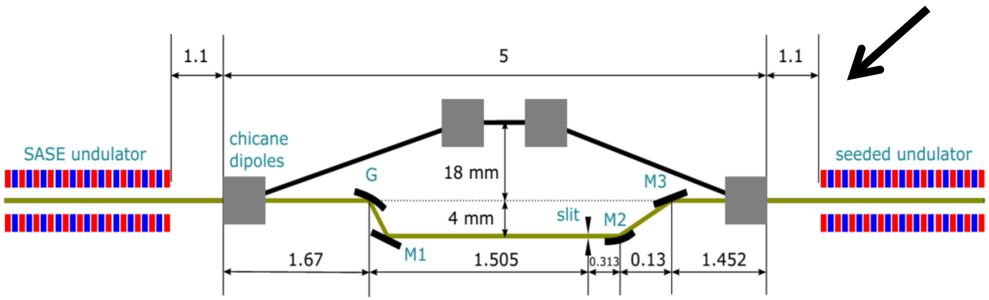
zur Erlangung des Doktorgrades an der Fakultät
für Mathematik, Informatik und Naturwissenschaften
Fachbereich Physik
der Universität Hamburg

vorgelegt von
Svitozar Serkez

Hamburg
2015

European XFEL self-seeding setup design





Main differences from the LCLS design:

Nominal operation with the upstream undulator retracted (optical design initially optimized)

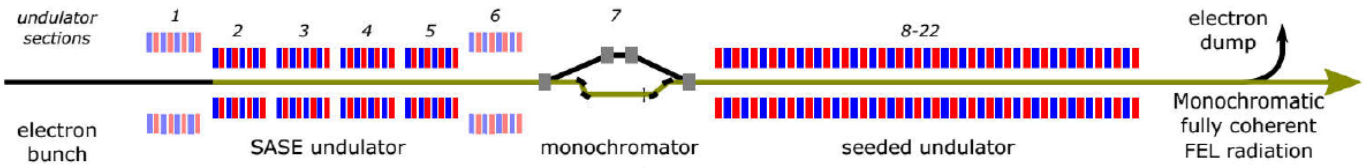
Reduction of the grating line density allowed to improve the grating efficiency by a factor of 1.5-2

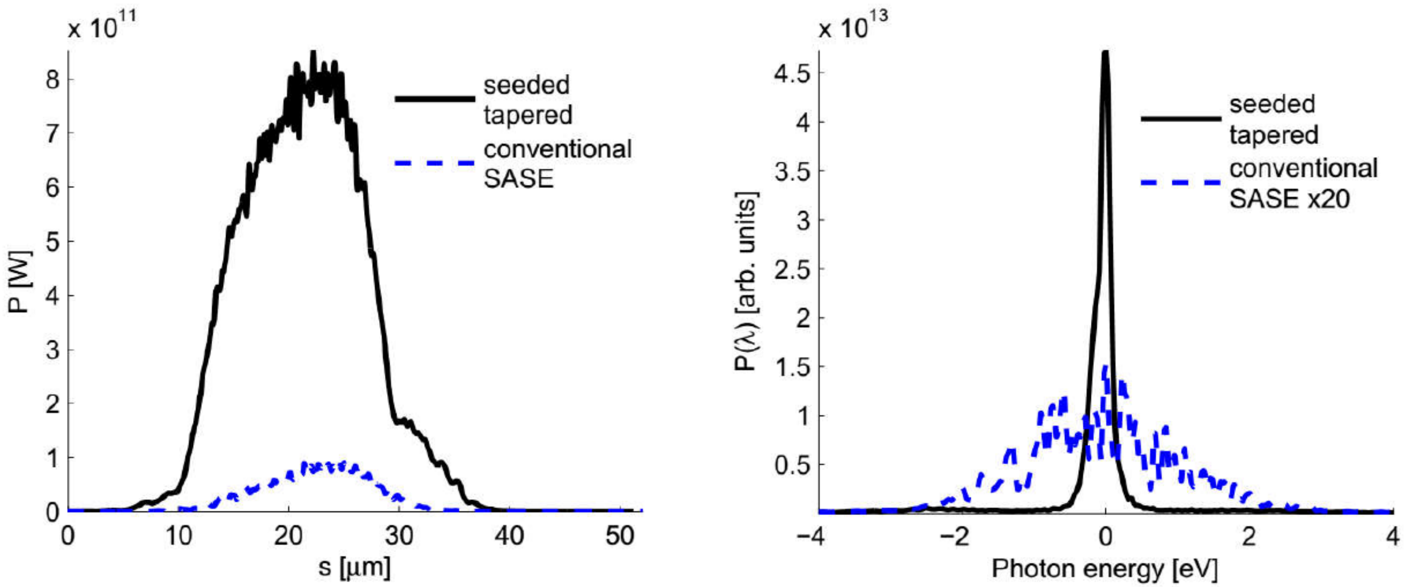
Optical delay was minimized in order to transport the 8.5 and12GeV electron beams through the chicane.

Element	Parameter	Value at photon energy			Required precision	Unit
		300 eV	700 eV	1200 eV		
G	Line density (n)	500			0.2%	l/mm
G	Linear coeff (n_1)	0.615			0.5%	l/mm^2
G	Quad coeff (n_2)	0.001			50%	l/mm^3
G	Groove profile	Blazed 0.8°			-	-
G,M1	Roughness (RMS)	-			1	nm
G	Tangential radius	195			1%	m
G	Sagittal radius	0.32			10%	m
G	Diffraction order	+1				-
G	Incident angle	1			-	deg
G	Exit angle	3.82	2.61	2.09	-	deg
	SASE undulator distance[1]	8870			-	mm
	Source distance[1]	9640	9810	11500	-	mm
	Source size ($\sigma_{intensity}$)	20.0	16.3	14.8	-	μm
	Image distance[1]	1507	1501	1513	-	mm
	Image size ($\sigma_{intensity}$)	0.83	0.87	0.93	-	μm
	Seeded undulator distance[1]	4430			-	mm
M1	Location[1,2]	47.4	63.4	73.9	-	mm
M1	Incident angle	2.41	1.80	1.55	-	deg
S	Slit location[1]	1505			1	mm
S	Slit width	variable			-	-
M2	Location[1]	1818			1	mm
M2	Incident angle	0.859			-	deg
M2	Tangential radius	39.4			1%	m
M3	Location[1]	1948			-	mm
M3	Incident angle	0.859			-	deg
	Optical delay	740	605	547	-	fs

Table 4.2: Parameters for the SXRSS monochromator x-ray optical elements
[1]Distance to the grating.
[2] Principal ray hit point.

New XFEL SXR monochromator design





@700eV

~**TW** pulses

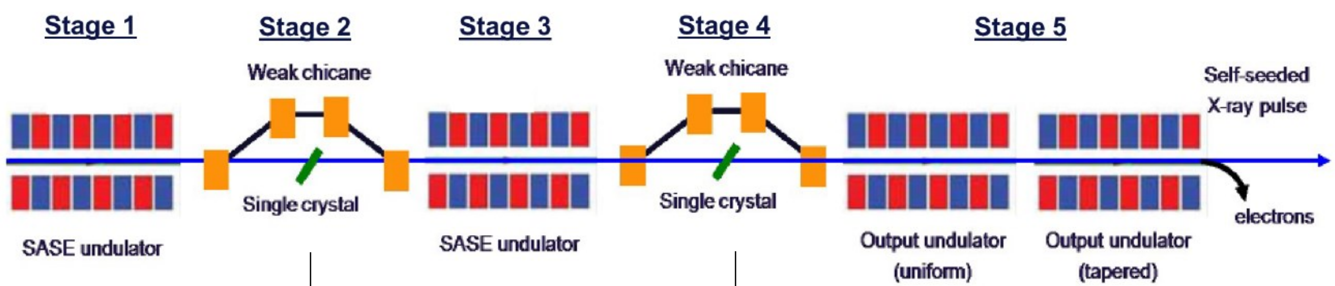
Within 0.16eV bandwidth (**4400** resolving power)

40mJ average pulse energy

Carrying **$1.8 \cdot 10^{14}$** photons/<u>0.02% b/w</u> per pulse

HXRSS

2-chicane HXRSS for improving SNR ratio : chicane position? Energy limits?



SASE

-"large" BW σ_{SASE}

- Power P

Seeded

-"narrow" BW σ_{seed}

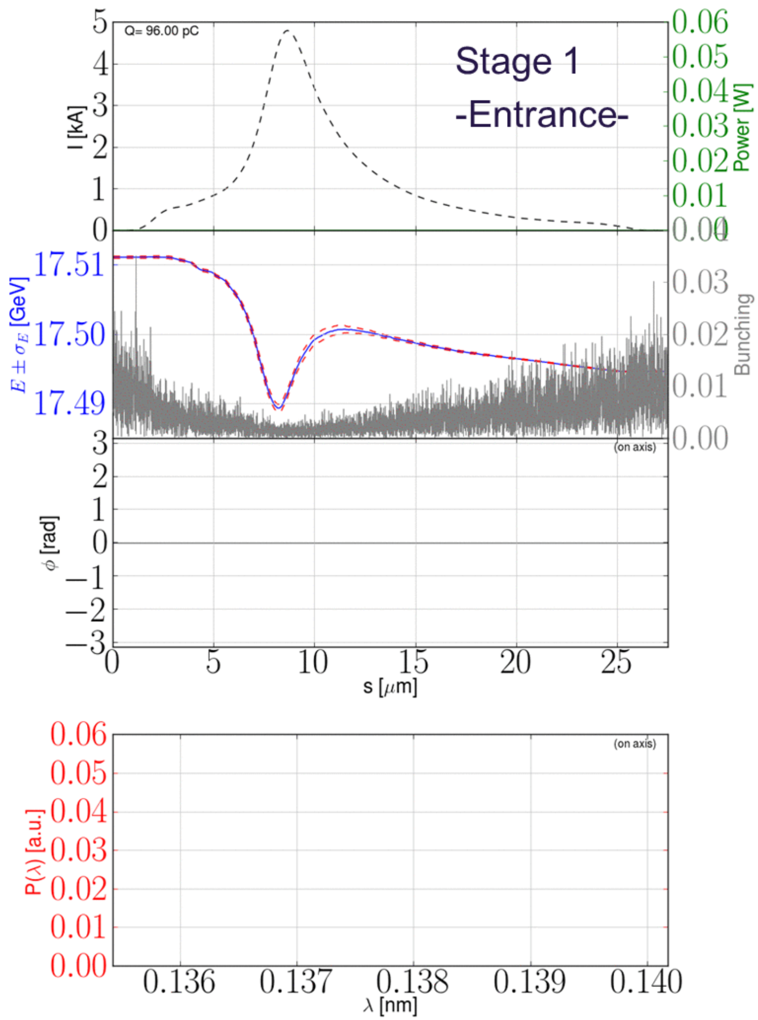
- Power P

Larger spectral density
(seeded signal)
Compared to one-chicane

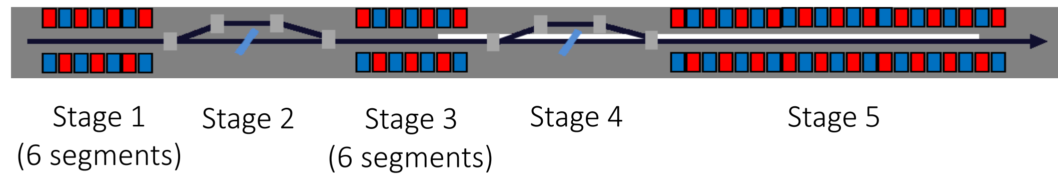
$$\boxed{\frac{S_2}{N_2} \simeq \frac{S_1}{N_1}\frac{\sigma_{\mathrm{SASE}}}{\sigma_{\mathrm{seed}}}}$$

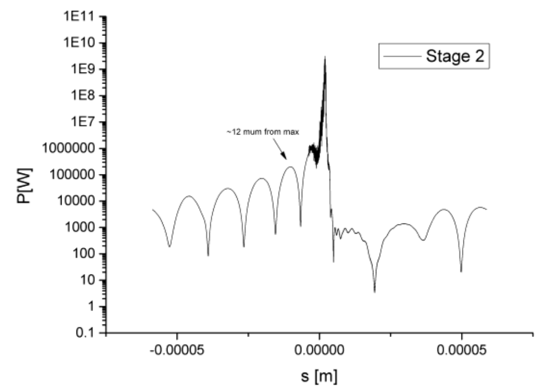
HXRSS

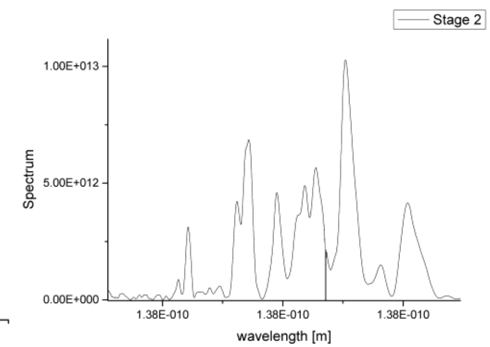
One example for 17.5GeV 100pC electron beam

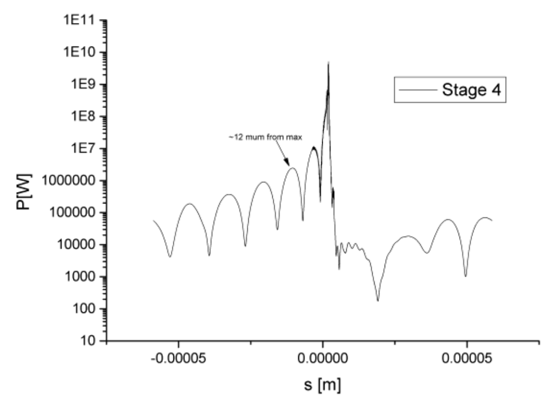


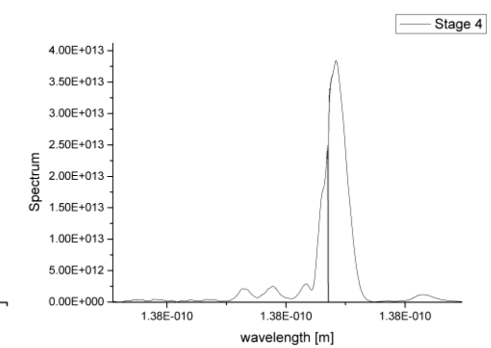
C004 symmetric, 100mum







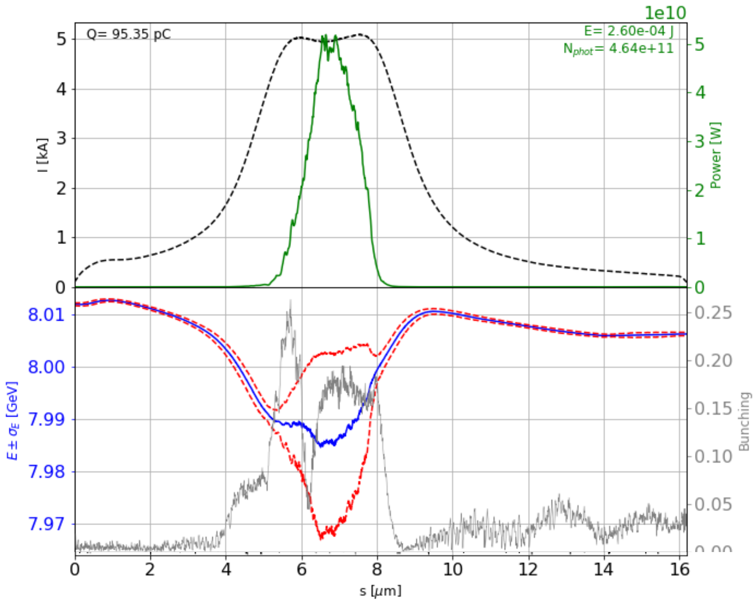


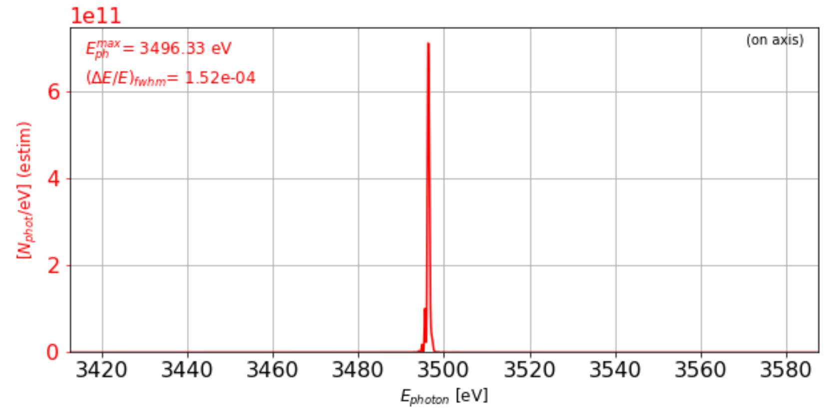


HXRSS – low energy

S. Liu, S. Serkez, G. Geloni et al., In preparation

Lower limit around 3 keV. We took 3.5 keV as a case study - C111 symm. 50μm thick, 8GeV, 100pC





Simulations **up to 6 segments, with reduced K**

Heat load:

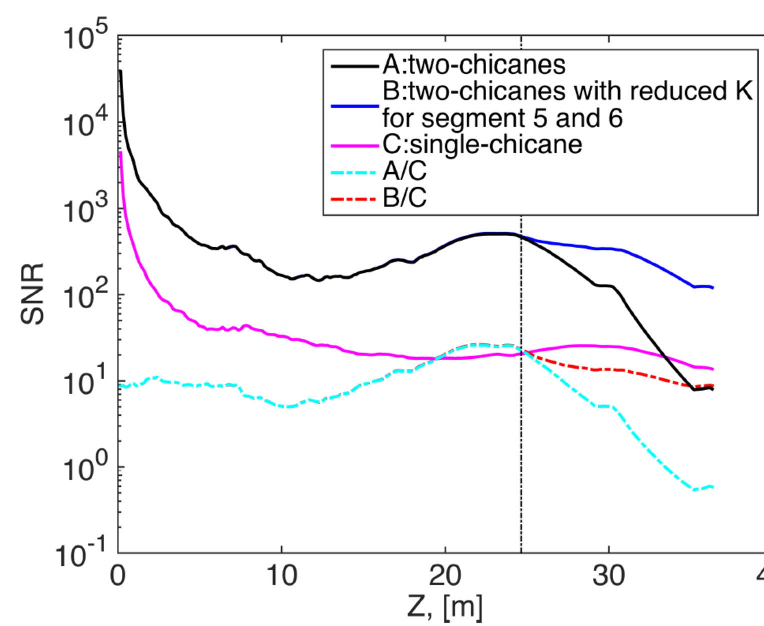
4+4: FEL energy deposited on 2nd crystal: 2 μJ/pulse

→Comparable with SR deposited heat

→SNR increase for 2-chicanes

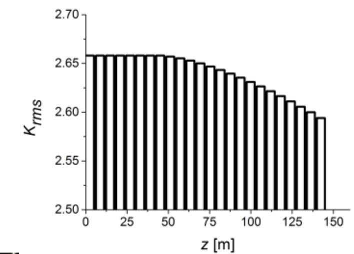
→After saturation SNR drops for 2 chicanes

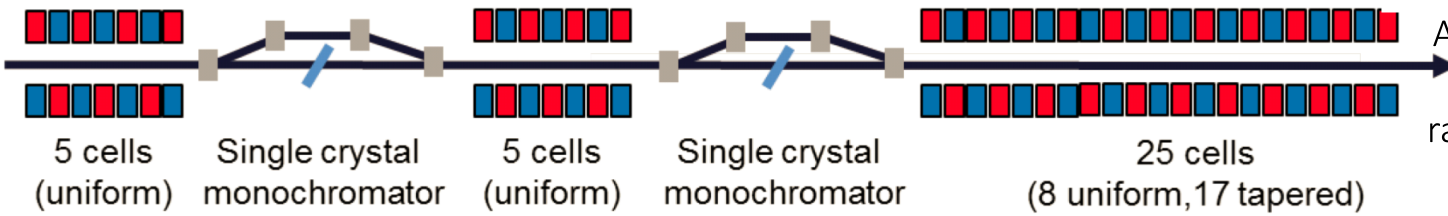
(1 chicane saturates further downstream)



HXRSS – mid energy

Baseline SASE2 undulator (35 cells)



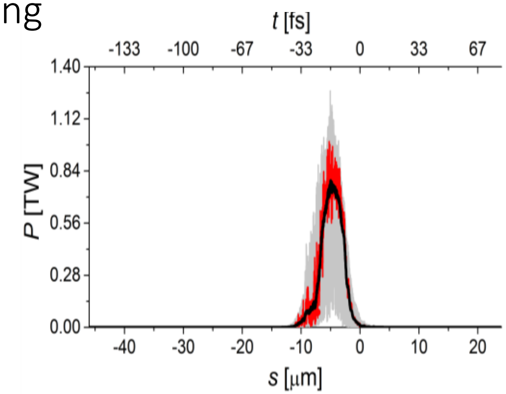


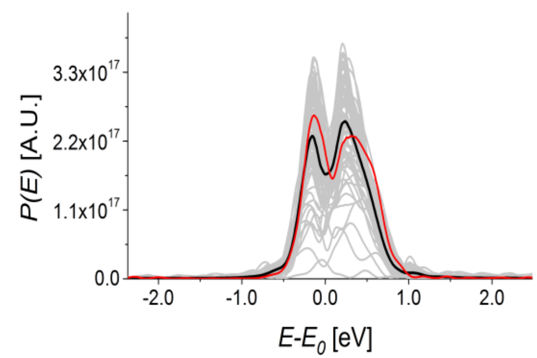
Application: Ultra-High Resolution Inelastic X-ray Scattering (UHRIXS)

Combination of high rep-rate HXRSS and Tapering

- Tapering: increases power
- HXRSS: decreases bandwidth
- Figure of merit for IXS: spectral flux

Standard mode of operation at 250pC





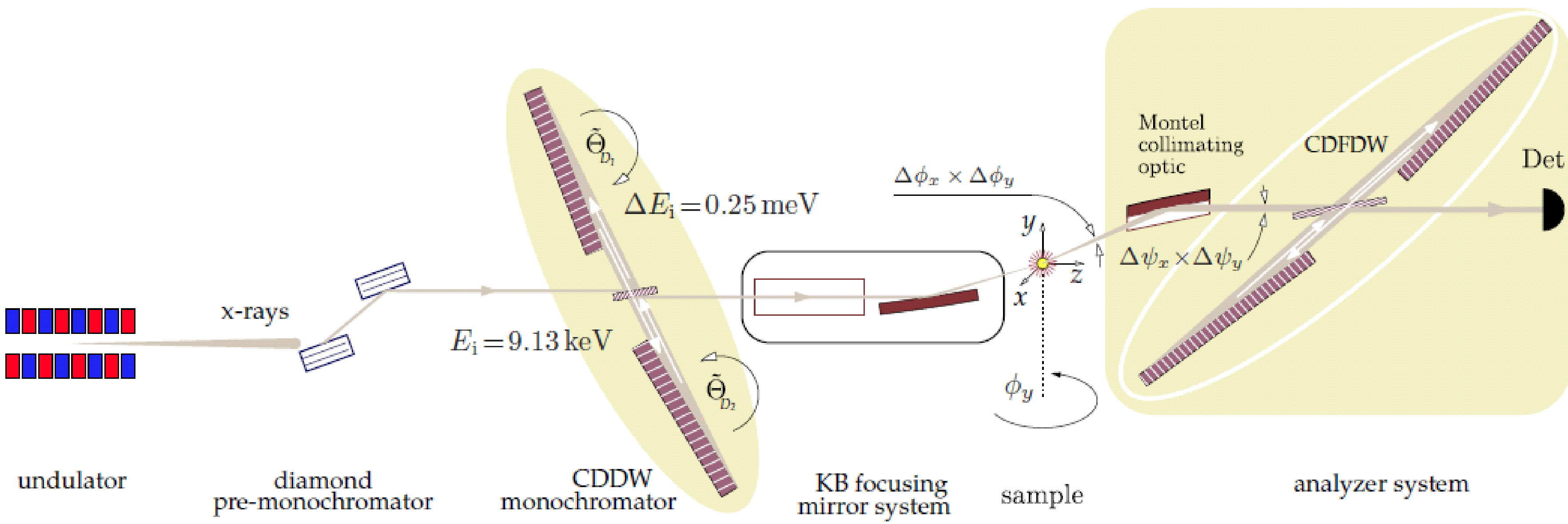
	Intensity, [Ph/ pulse]	Photon pulse BW	Photon Flux, [Ph/s/meV]
w/o HXRSS	7e11	$\Delta\lambda/\lambda$~1.2e-3 or ~12eV	**1.5e12**
w/ HXRSS	7e12	$\Delta\lambda/\lambda$~1e-4 or ~940meV	**2.1e14**

J. Synchrotron Rad. 23 (2016)

HXRSS – mid energy: one possible application

UHRIX: Ultra-High-Resolution IXS Spectrometer

Joint R&D Effort of APS and DLS



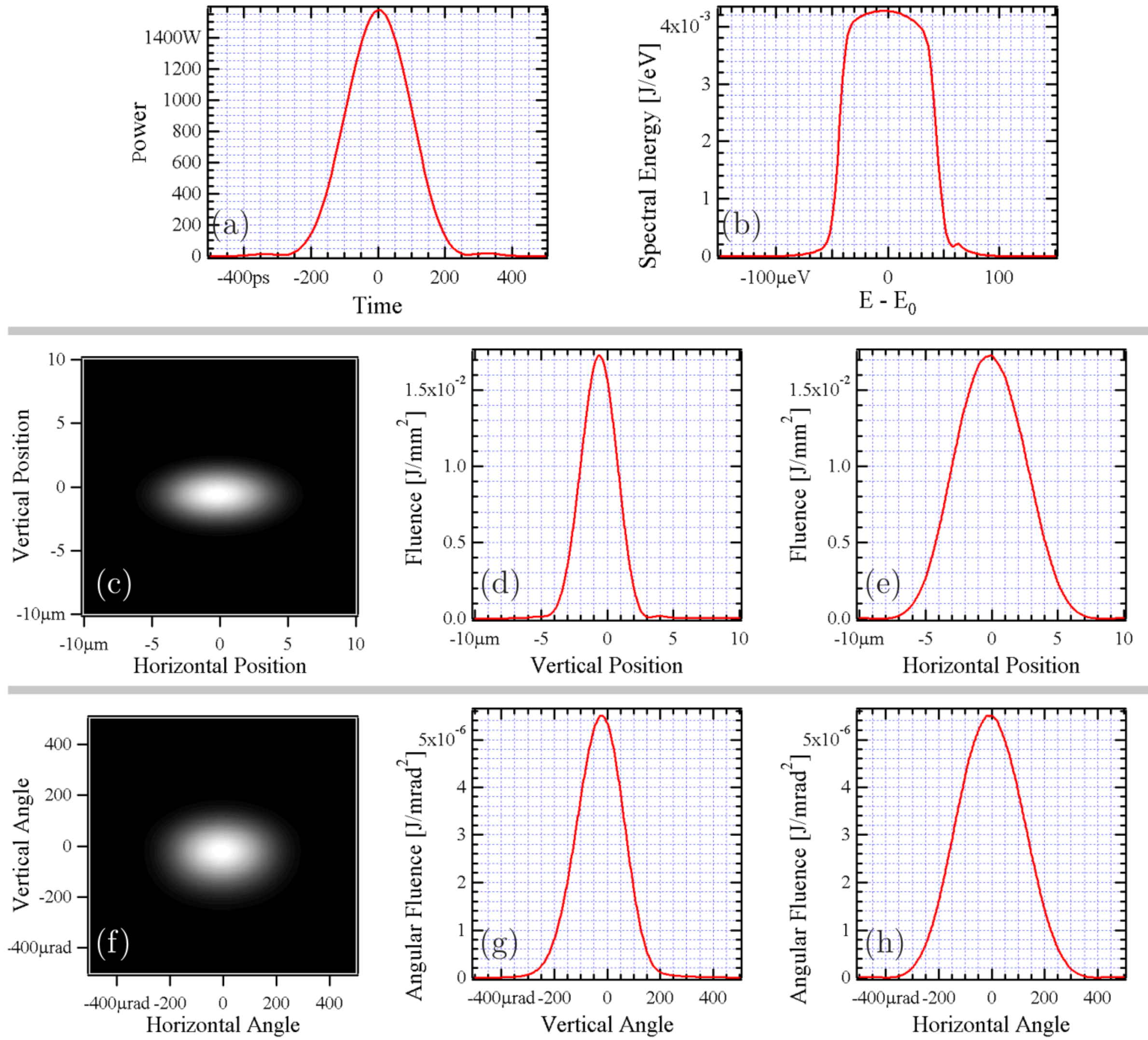
Courtesy of Y. Shvyd'ko, ANL, APS

21

HXRSS – mid energy: one possible application

The spectral flux from the XFEL undulator can be transported to the sample through the UHRIX X-ray optics with a ~30% efficiency

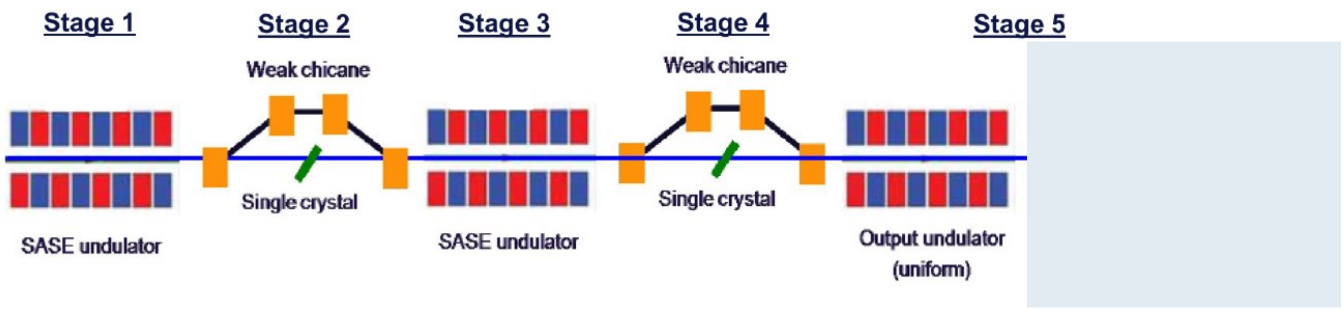
→ **7e12 ph/s in 90 meV** BW at the sample



SRW simulations by Oleg Chubar (BNL)

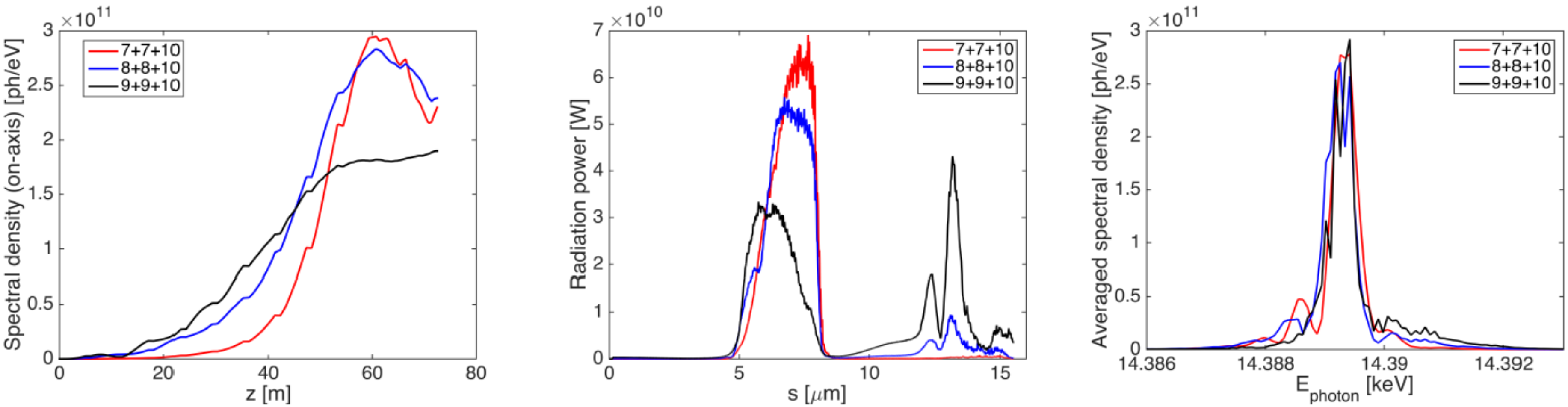
HXRSS – high-energy

S. Liu, S. Serkez, G. Geloni et al., In preparation



Chicane position → Study up to saturation

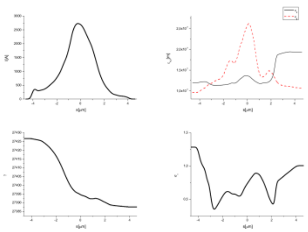
Nominal (separate tolerance studies vs. emittance and energy spread)

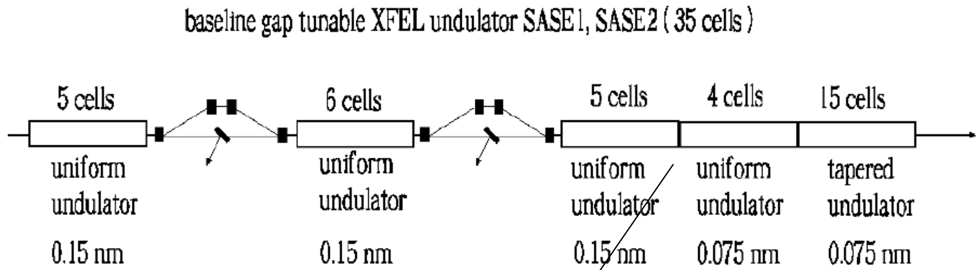


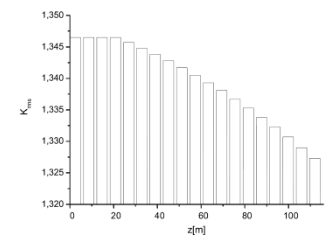
Our suggestion: 7+7 → 8+8 for safety

Harder X-rays@SASE1/2

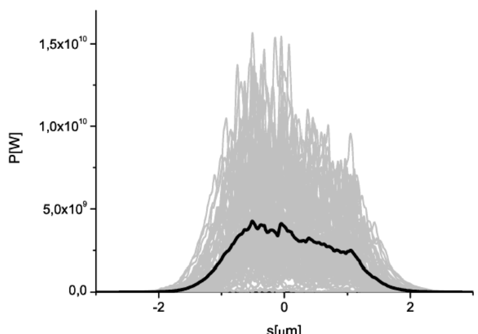
Example – HXRSS + Second harmonic (G. Geloni, V. Kocharyan, E. Saldin: DESY 11-124, 2011)

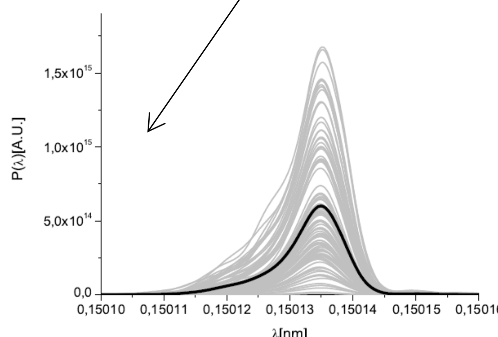




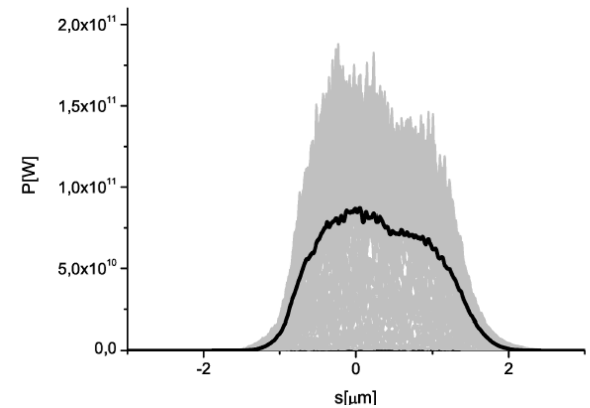


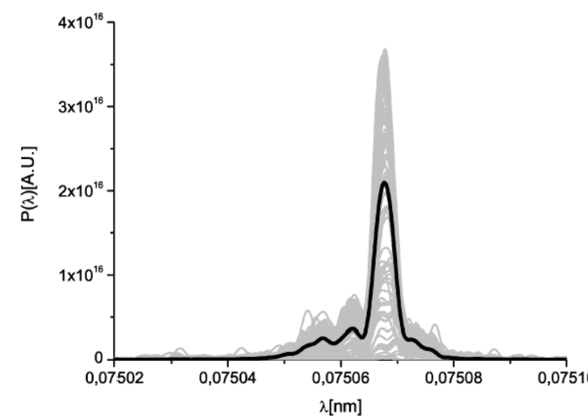
low-charge (0.03 nC) mode of operation
at electron beam energy 14 GeV



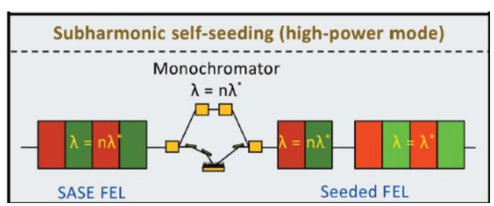


(1 cell before saturation)



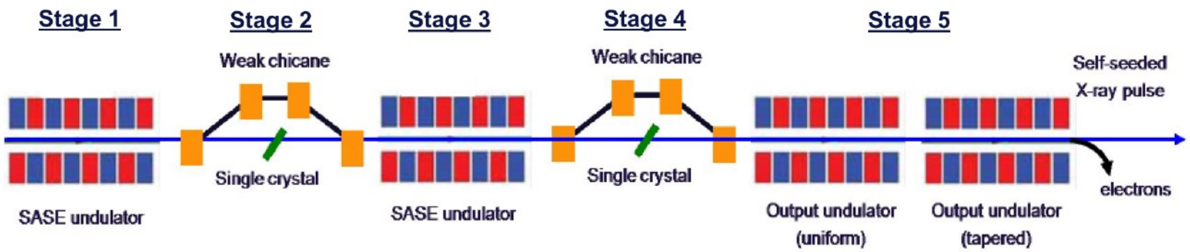


Related approach:
Prat&Reiche,
J. Synchrotron Rad. (2018). 25, 329–335

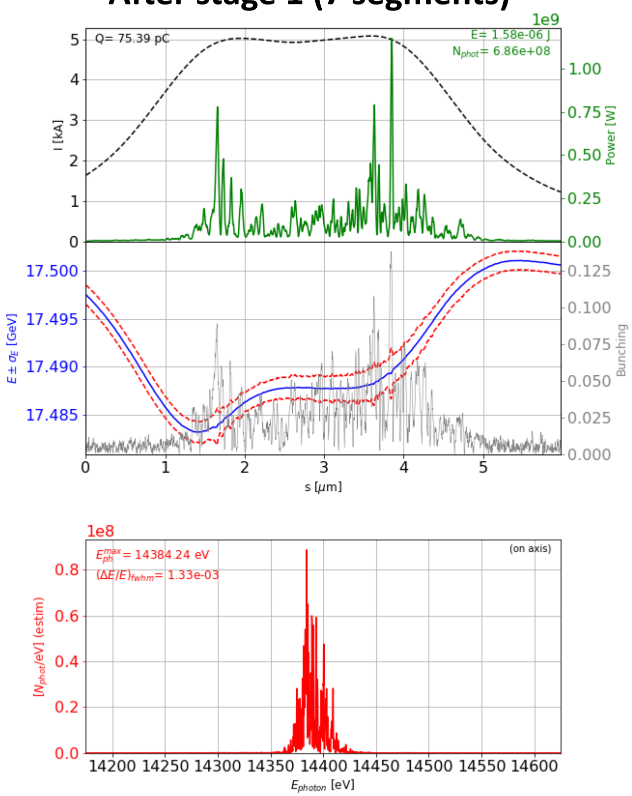


Harder X-rays@SASE1/2

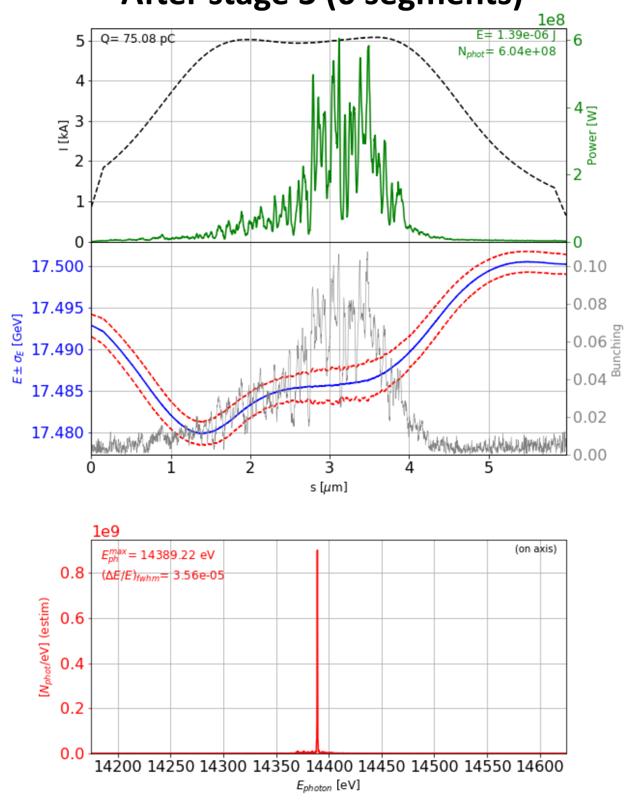
How far can we push this?



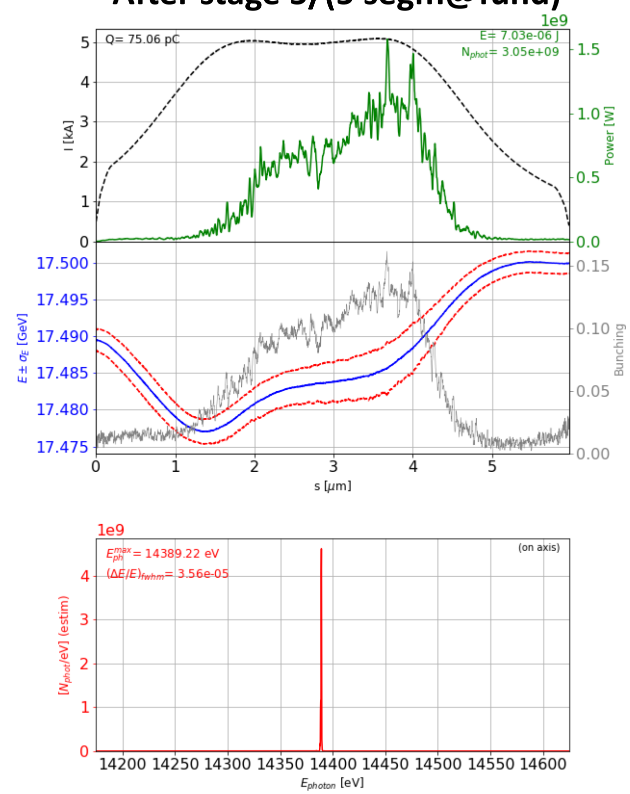
After stage 1 (7 segments)



After stage 3 (6 segments)

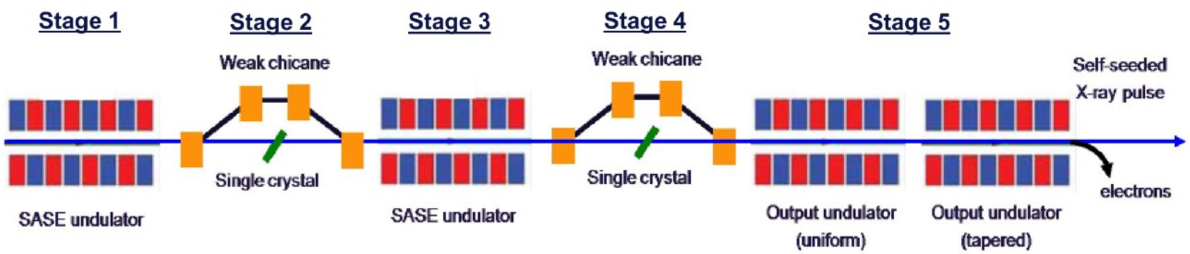


After stage 5/(5 segm@fund)

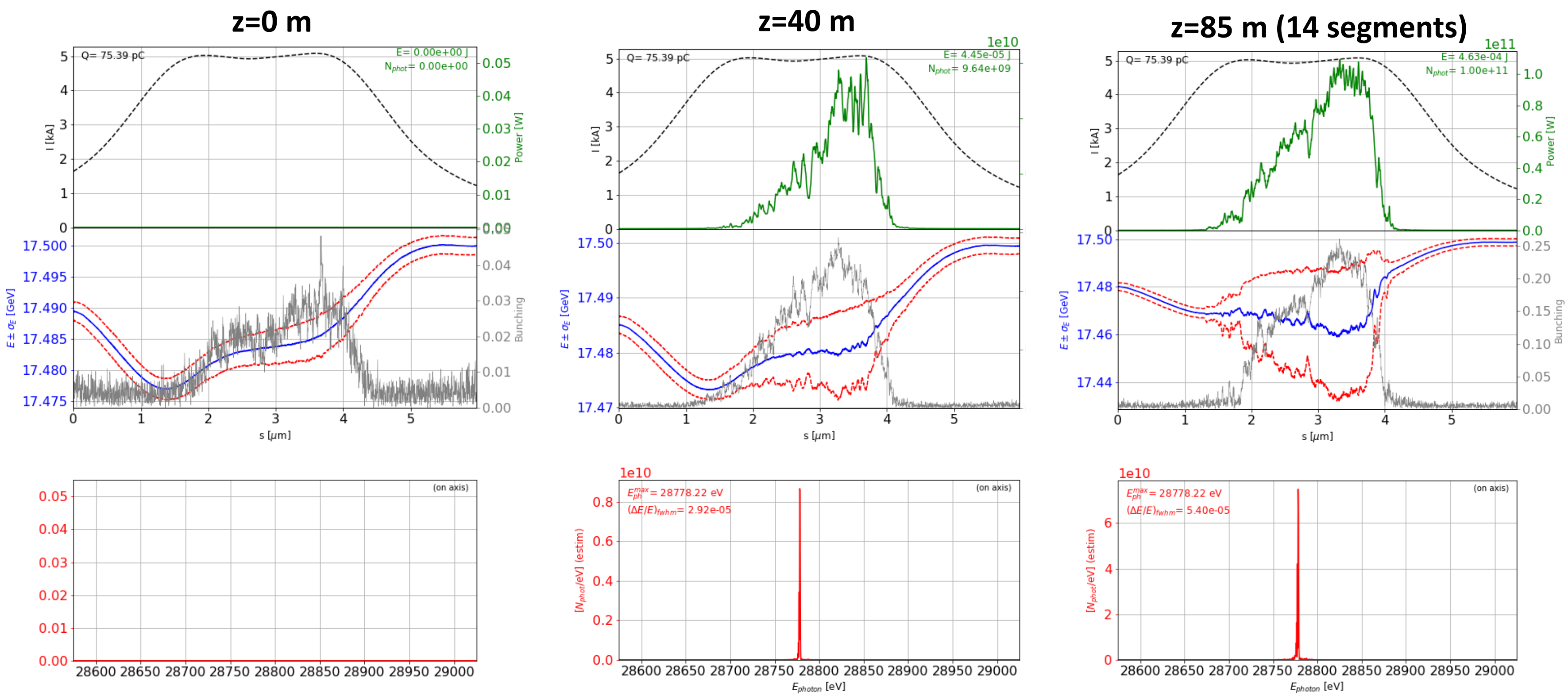


Harder X-rays@SASE1/2

How far can we push this? Second harmonic…

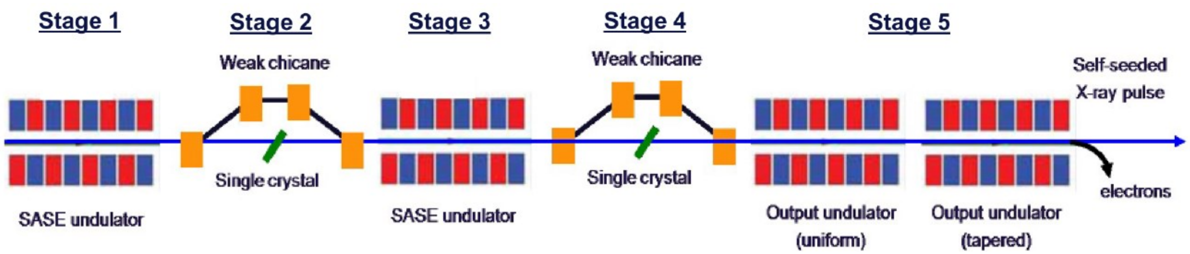


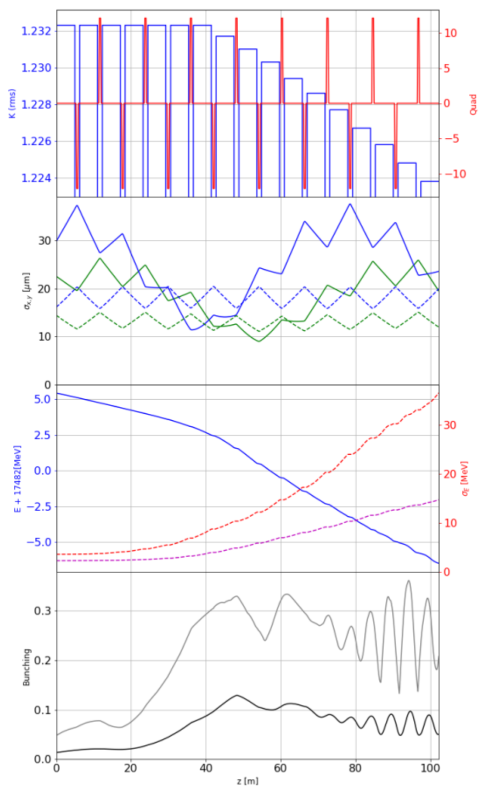
Stage 5/2nd harmonic

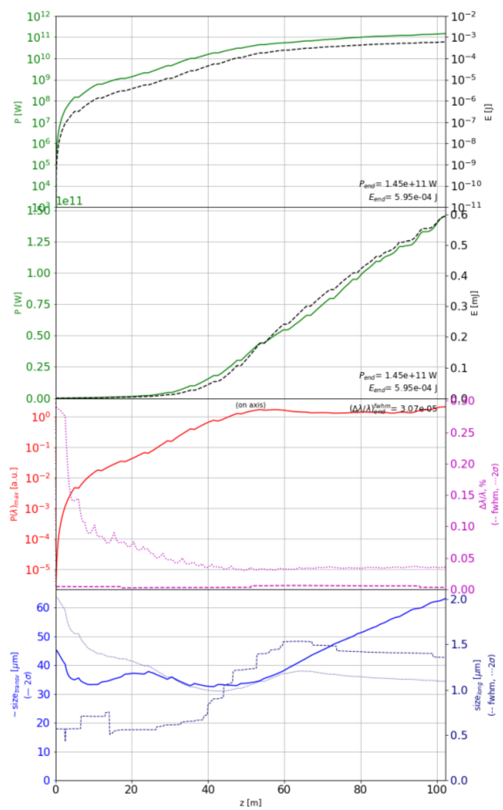


Harder X-rays@SASE1/2

How far can we push this? Second harmonic…







→Tapering not fully optimized

→ Power ~100GW level – BW ~5e-5

→ It could go on for longer undulator

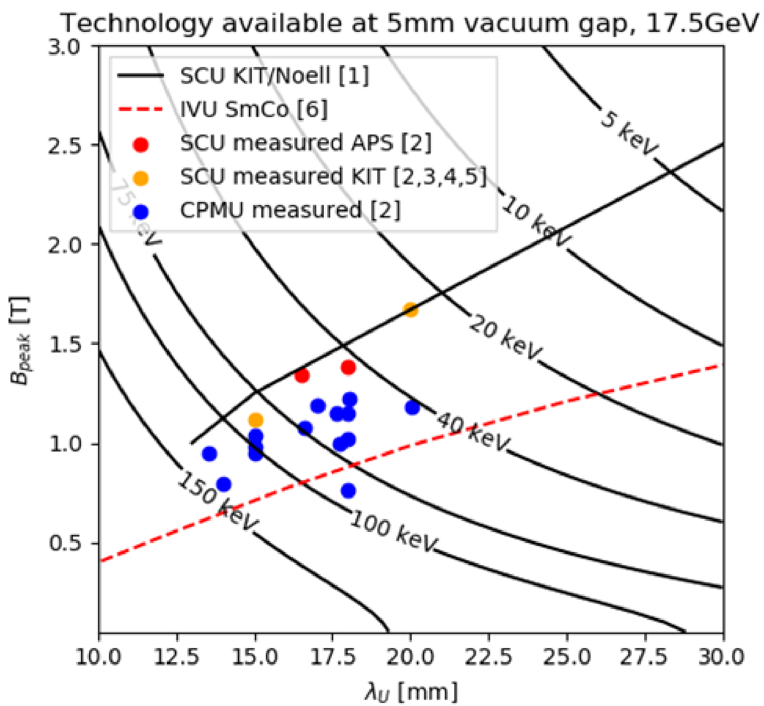
Self-seeding and mid-term additions

HXRSS/SXRSS are relatively small additions that can be fit to virtually any mid-term upgrades

Combination with Super-X using period doubling:

λ_w can change from 15mm → 30 mm and B_{max} would increase to cover down to SXR.

Undulator technologies



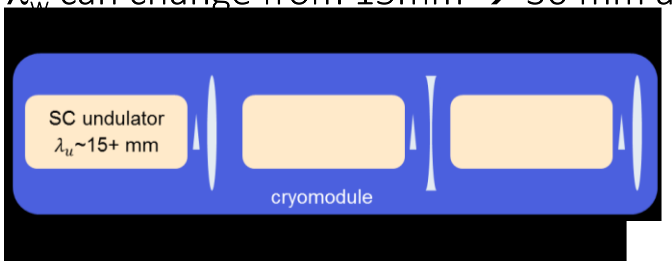
- [1] M. Turenne, C. Boffo, S. Casalbuoni, private communication
- [2] J. Bahrdt and E. Gluskin, "Cryogenic permanent magnet and superconducting undulators," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 907, no. March, pp. 149–168, Nov. 2018.
- [3] S. Casalbuoni, et. al., "Magnetic Field Measurements of Full-Scale Conduction-Cooled Superconducting-Undulator-Coils," IEEE Trans. Appl. Supercond., vol. 28, no. 3, pp. 3–6, 2018.
- [4] S. Casalbuoni, et.al., "Characterization and long term operation of a novel superconducting undulator with 15 mm period length in a synchrotron light source," Phys. Rev. Accel. Beams, vol. 19, no. 11, p. 110702, Nov. 2016.
- [5] S. Casalbuoni, et.al., "Superconducting Undulators: From Development towards a Commercial Product," *Synchrotron Radiat. News*, vol. 31, no. 3, pp. 24–28, May 2018.
- [6] R. Dejus, M. Jaski, and S. H. Kim, "On-axis brilliance and power of in-vacuum undulators for the Advanced Photon Source.," Argonne, IL (United States), Nov. 2009.

Self-seeding and mid-term additions

HXRSS/SXRSS are relatively small additions that can be fit to virtually any mid-term upgrades

Combination with Super-X using period doubling:

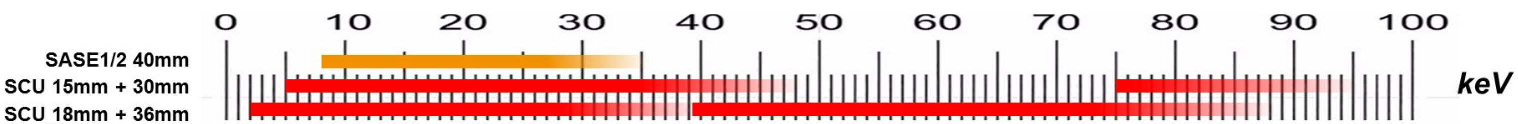
λ_w can change from 15mm → 30 mm and B_{max} would increase to cover down to SXR.



SASE2: 175m [mag. Length]/ 40mm = 4375 periods

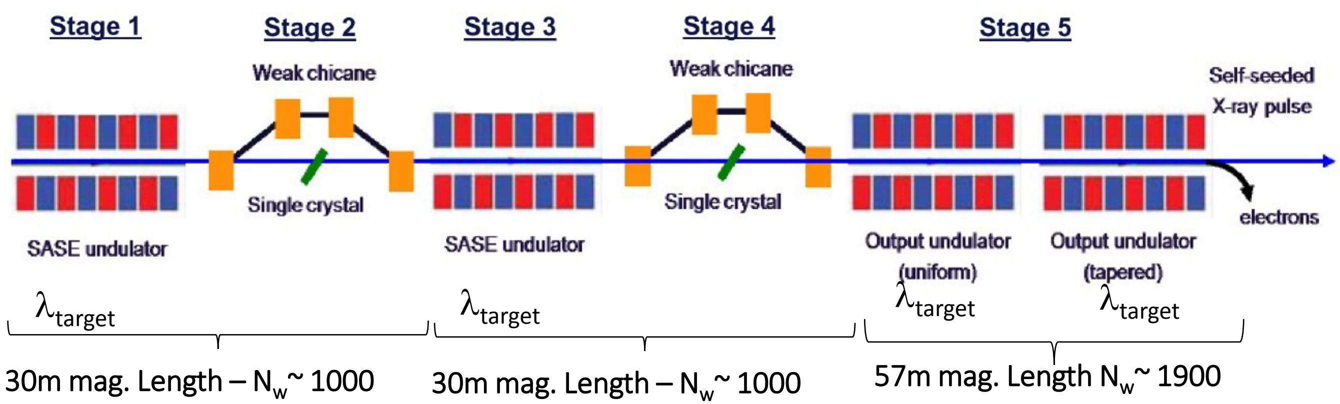
Super-X: 117m [mag. Length]/ 30mm = 3900 periods

→ Comparable length @ 30mm (10% shorter for Super-X)



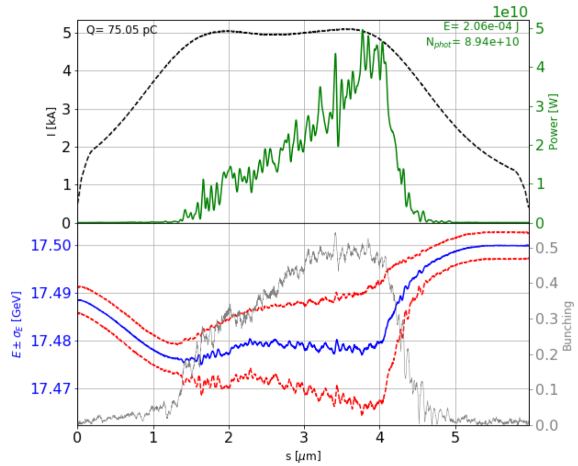
(1) Seeding directly up to 14.4 keV would become possible

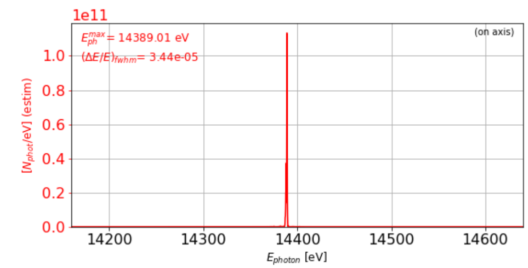
8 SASE2 segments → 40m [mag. Length] / 40mm x 30mm = 30m [mag. Length] for Super-X



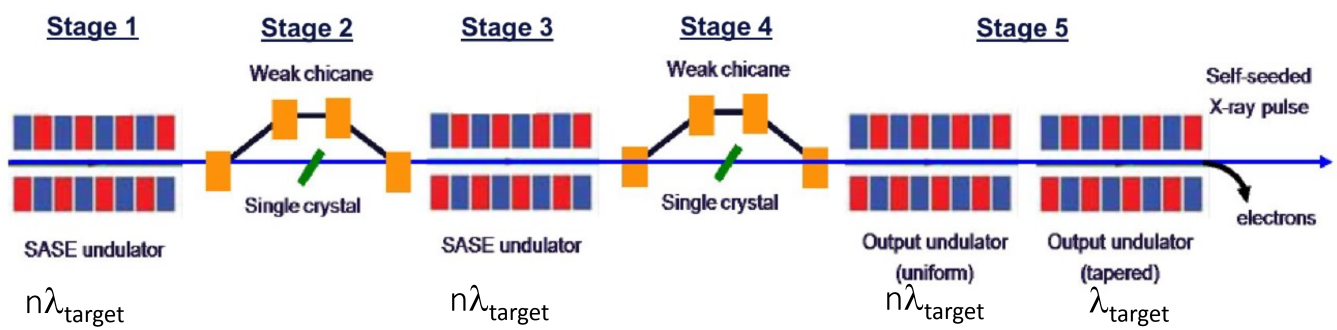
Self-seeding and mid-term additions

(1) Seeding directly up to 14.4 keV would become possible (cont'd)→ 36m+32m+50m (physical lengths)





(2) Seeding at the second subharmonic would also be feasible



30m mag. Length – N_w~ 1000

30m mag. Length – N_w~ 1000

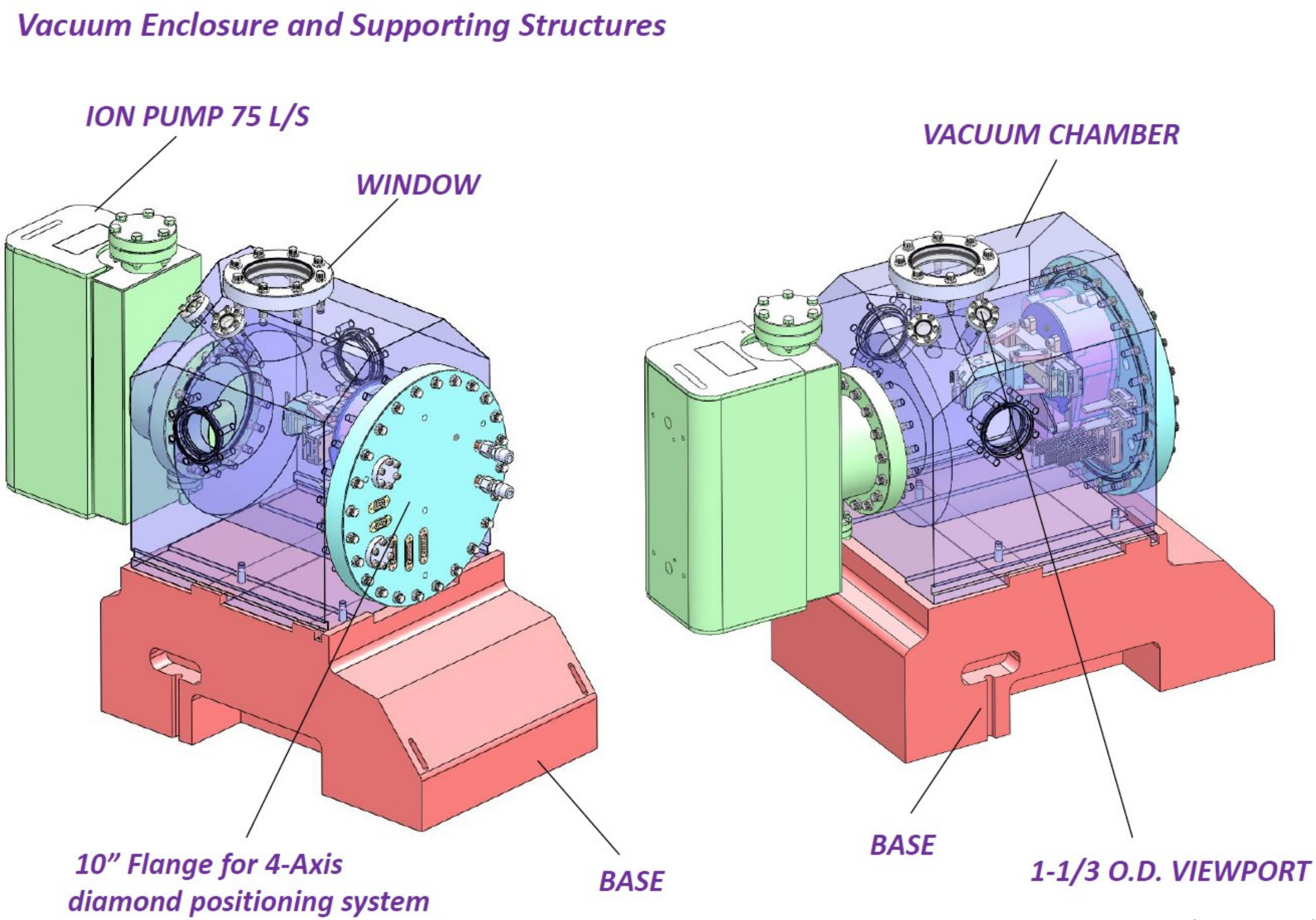
57m mag. Length N_w~ 1900

European XFEL implementation at SASE2 in 2019: Chicanes

- 8 r
- C c

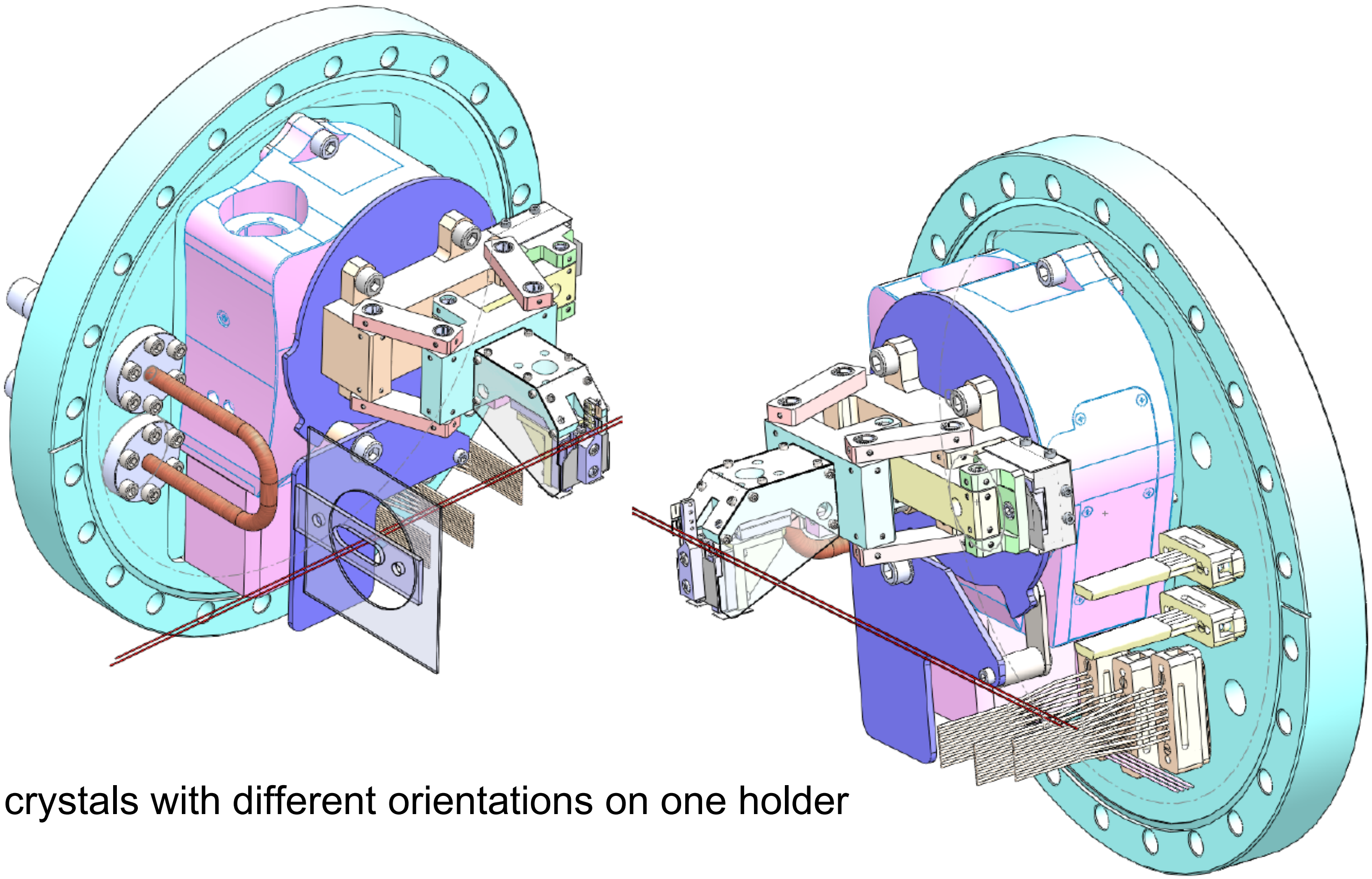
ugust 2017

Monochromator design



By D. Shu (Argonne)

Monochromator design

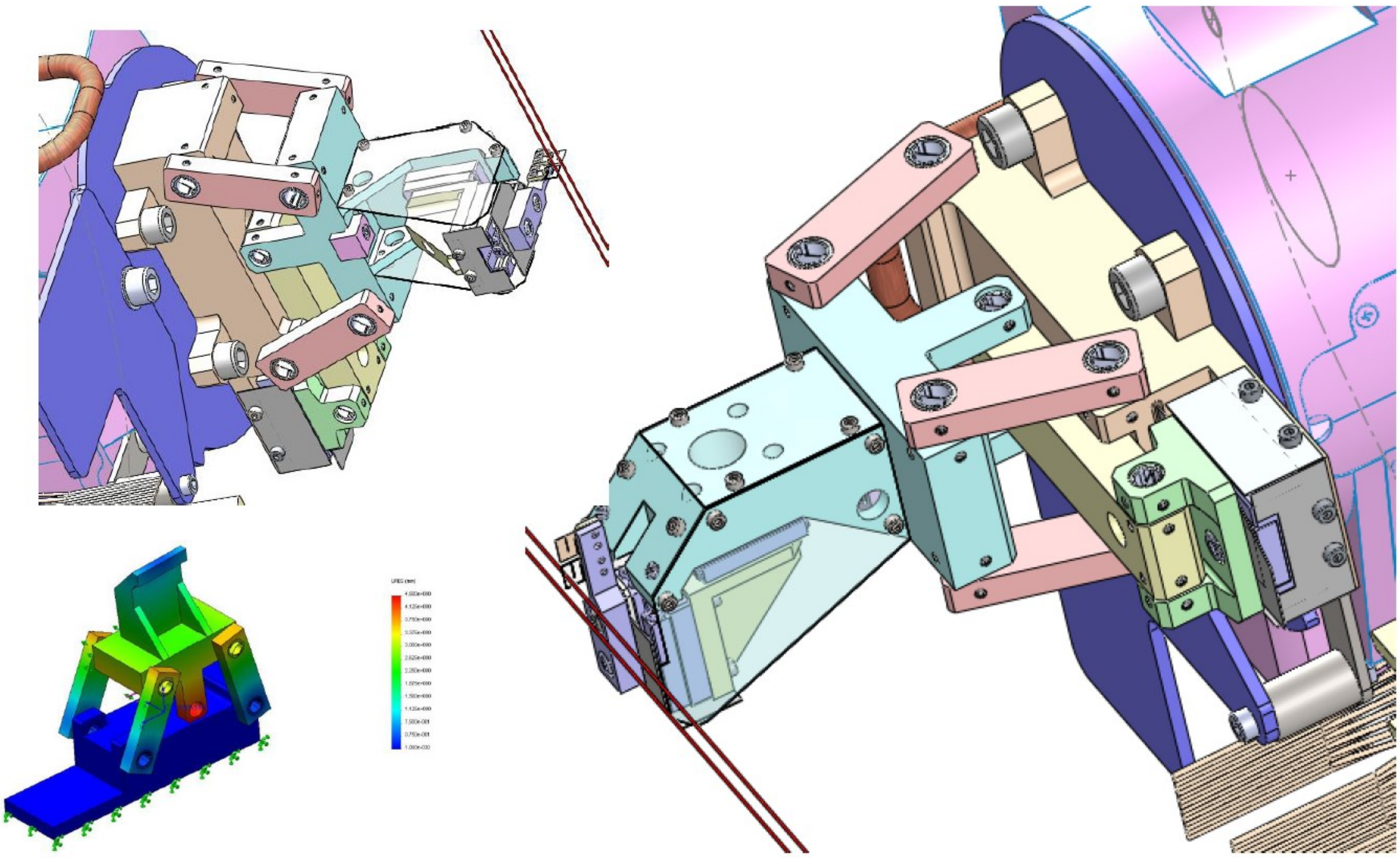


Two crystals with different orientations on one holder

By D. Shu (Argonne)

Mo

X, Y, and Tip-Tilt Stages for Diamond Crystal Positioning



By D. Shu (Argonne)

Conclusions

- HXRSS at SASE2 (2019) → experimental evaluation of performance (e.g. impact of muBI etc) - For now: simulations based on s2e e-beams
- Energy ranges:
  - 0.3 keV – 1keV SXRSS
  - (also external seeding – but different properties)
  - 1keV-3keV : no self-seeding
  - 3keV-15 keV HXRSS
  - up to about 30 keV HXRSS + harmonics

Self-seeding is a relatively simple addition to any mid-term strategy. In particular, if Super-X will be implemented with period doubling then

→Seeding up to >14.4 keV

→Seeding + Harmonics

The end

Thank you and Merry X-mas!!