Overview of Self-Seeding at X-ray FEL Facilities

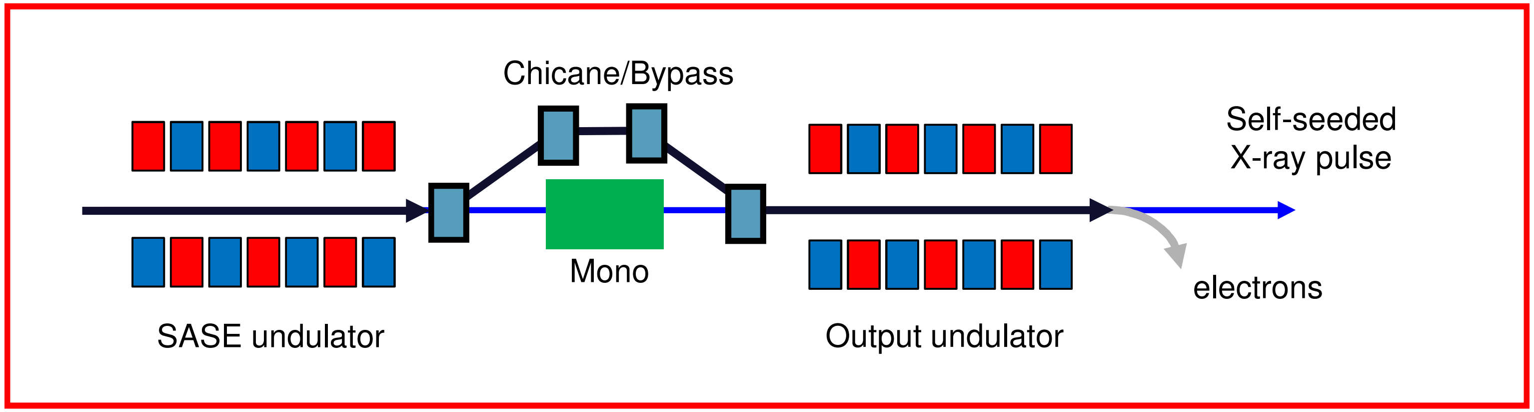
Gianluca Geloni, European XFEL

FUSEE Workshop, Trieste, December 2019

Contents

A short introduction to self-seeding

Method first introduced for soft x-rays [J. Feldhaus, E. Saldin,J. Schneider, E. Schneidmiller, M. Yurkov, Optics Comm. 140, 341 (1997)]: basically an active filter in frequency



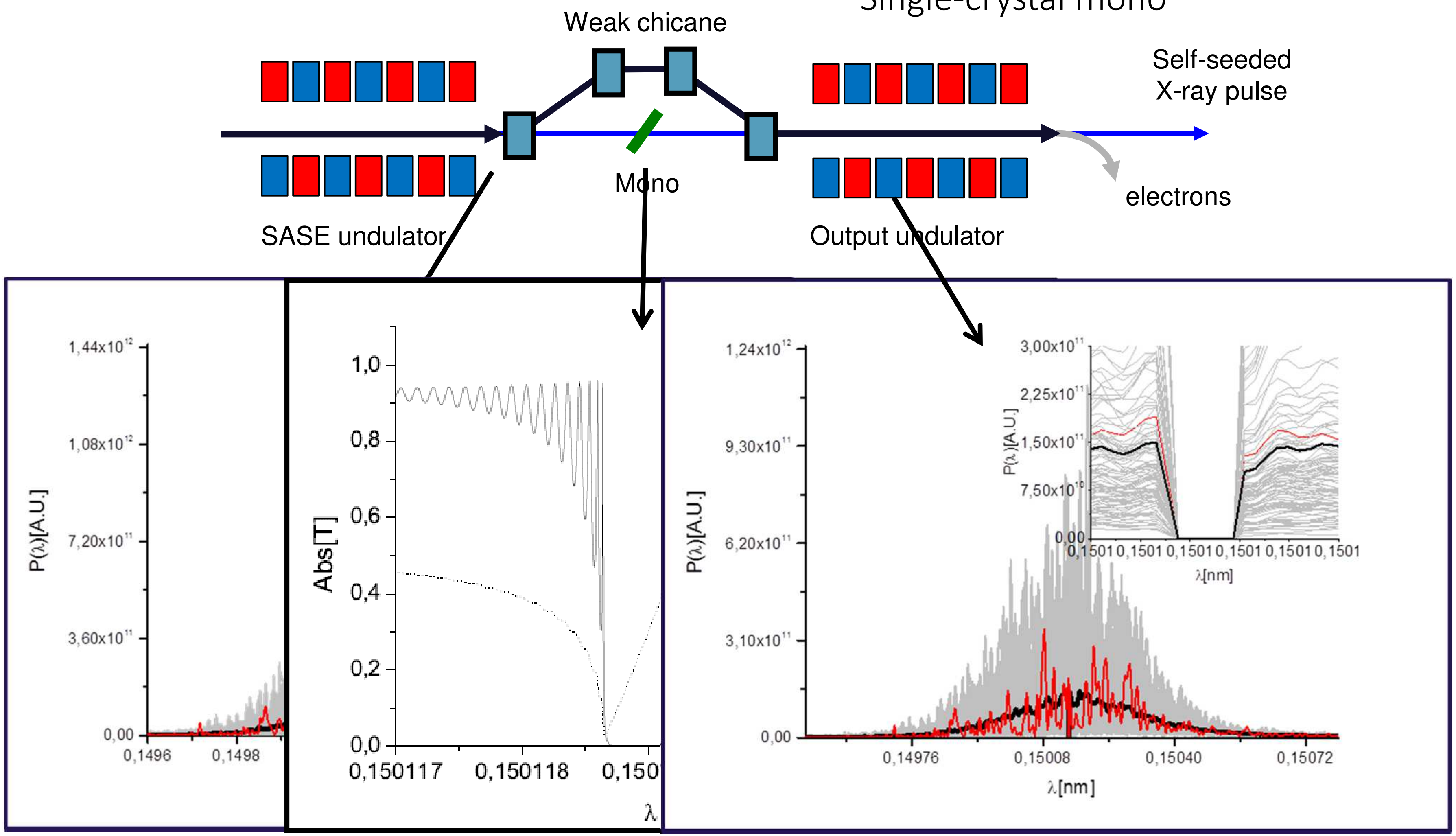
- First part: usual SASE pulse in the linear regime
- Chicane needed for:
  - Creating an offset to insert the monochromator
  - Washing out the electron beam microbunching
  - Acting as a tunable delay line
- The photon pulse from SASE goes through the monochromator
- Photon and electron pulses are recombined

- Independently of Self-Seeding:
  - Chicane for 2 colors...
  - Chicane for autocorrelation...
  - Chicane for DD scan...

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

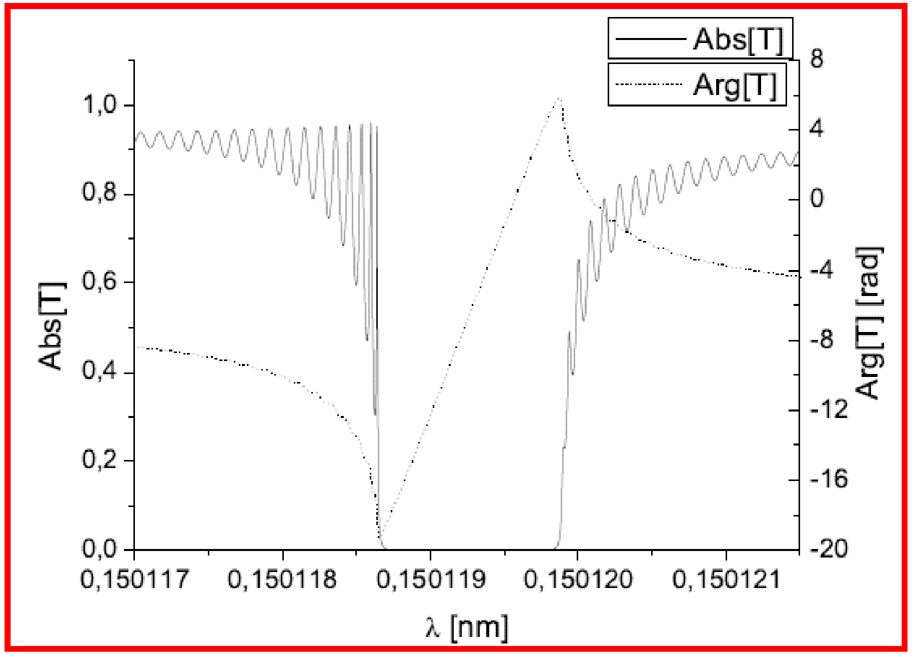
A short introduction to self-seeding

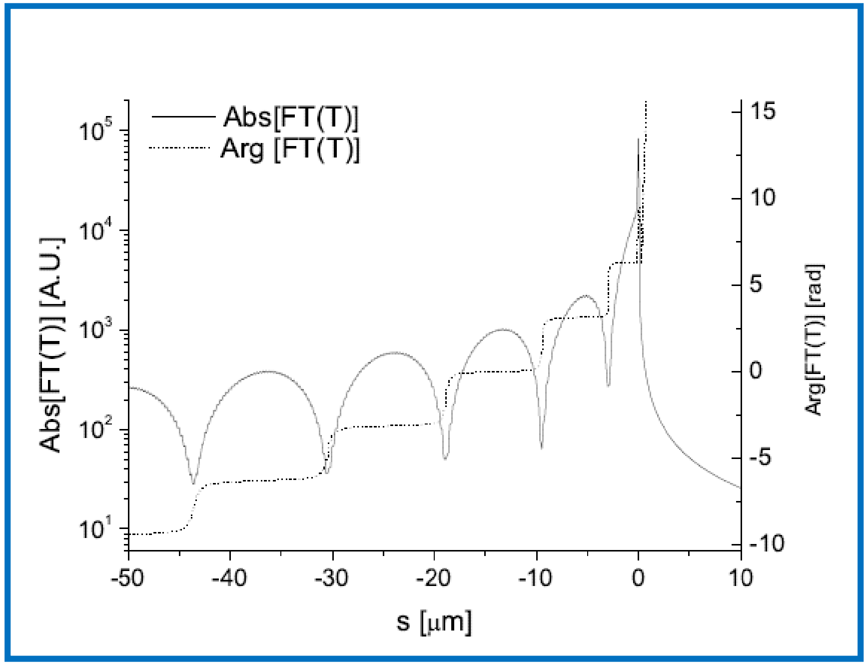
Method made "easy" for HXR
Single-crystal mono



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

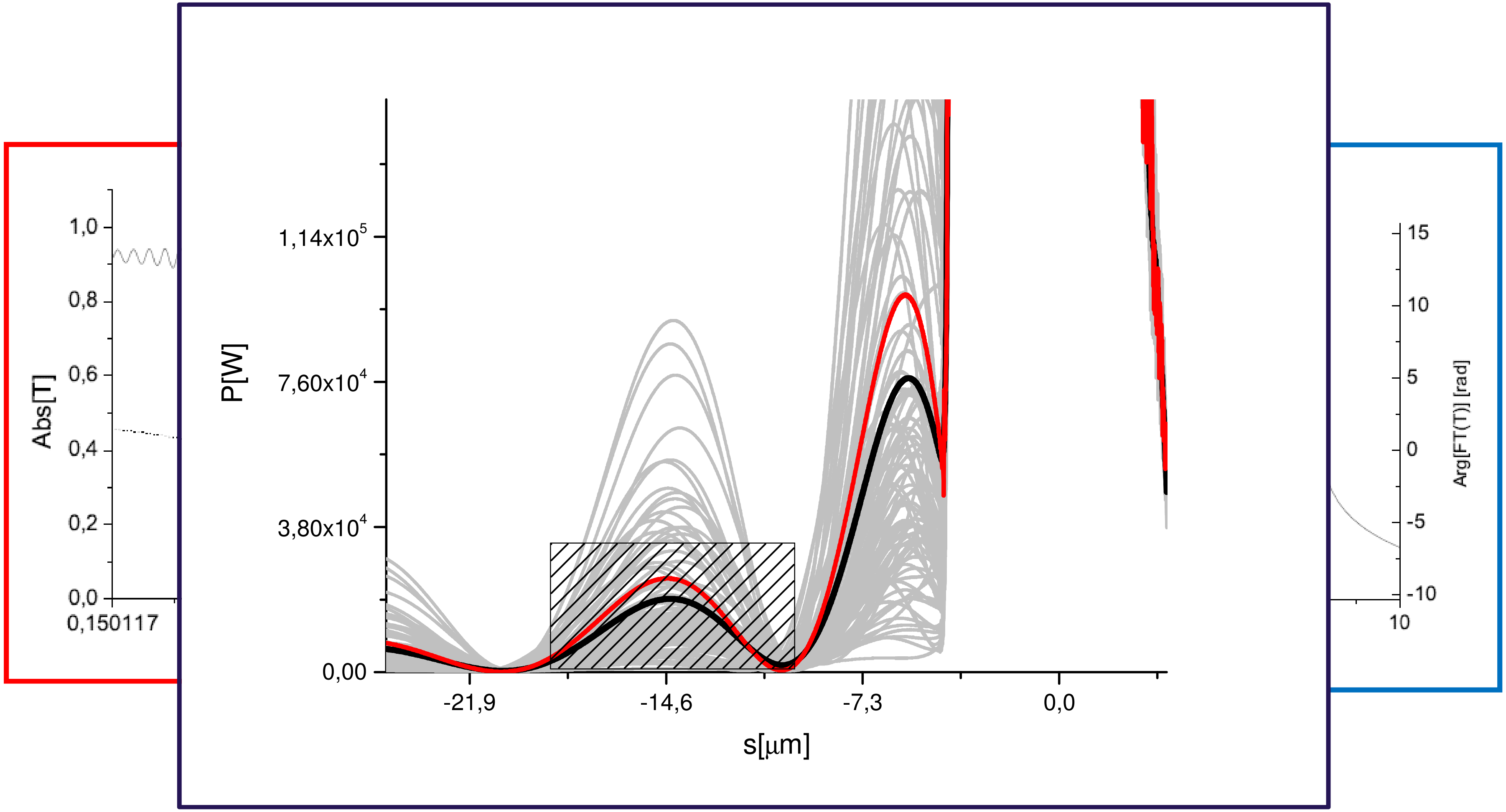
A short introduction to self-seeding





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



Note: notch-shape changes the profile, but not pricipal

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

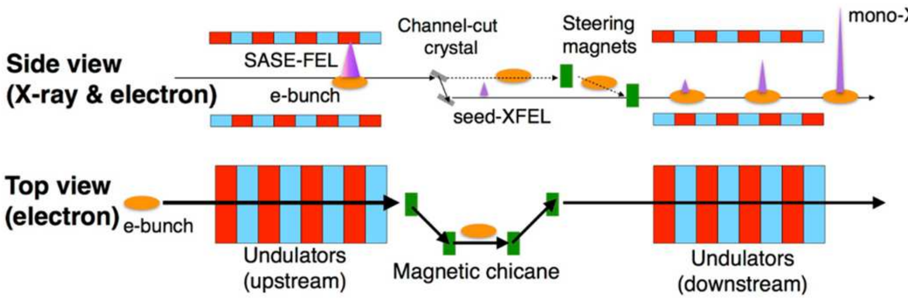
Reflection self-seeding at SACLA

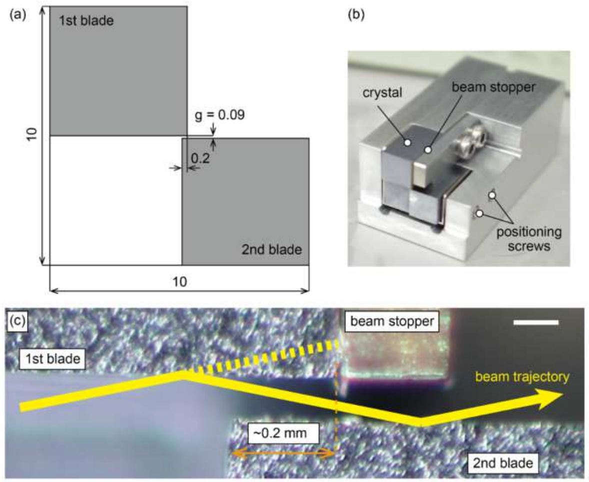
Ichiro Inoue*[1], Taito Osaka[1], Takahiro Inagaki[1], Shunji Goto[1,2], Toru Hara[1], Yuichi Inubushi[1,2], Ryota Kinjo[1], Haruhiko Ohashi[1,2], Takashi Tanaka[1], Kazuaki Togawa[1], Kensuke Tono[1,2], Hitoshi Tanaka[1], and Makina Yabashi[1,2]

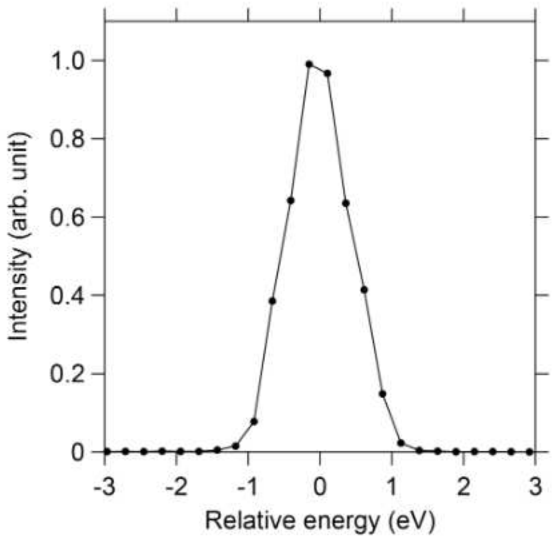
A micro channel-cut crystal X-ray monochromator for a self-seeded hard X-ray free-electron laser

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]

→ Recent reflection-based mono at SACLA





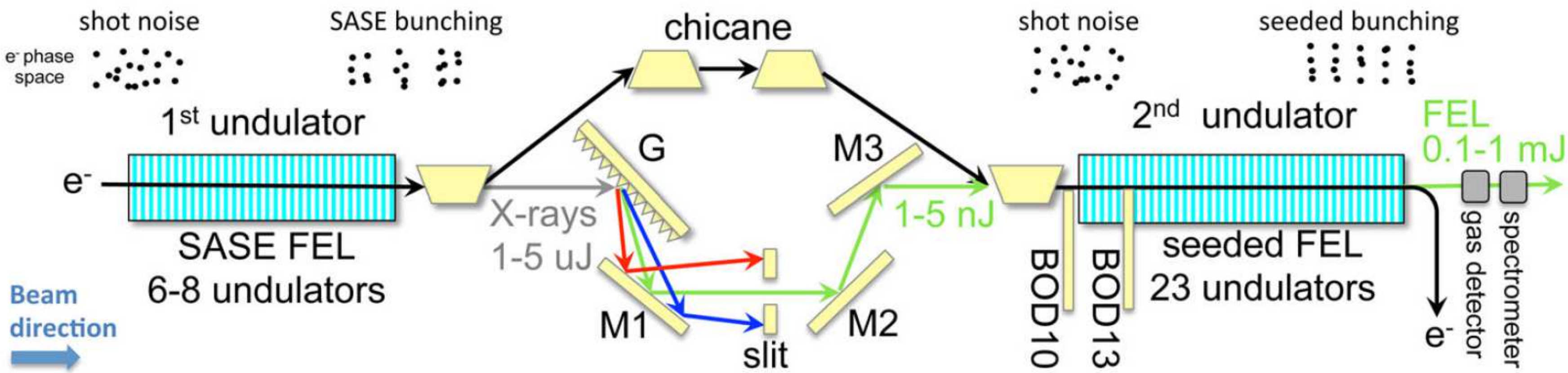


Averaged spectrum of the seed measured with a Si(220) channel-cut crystal. The number of accumulation at each point is 100 shots. The central photon energy is 10 keV

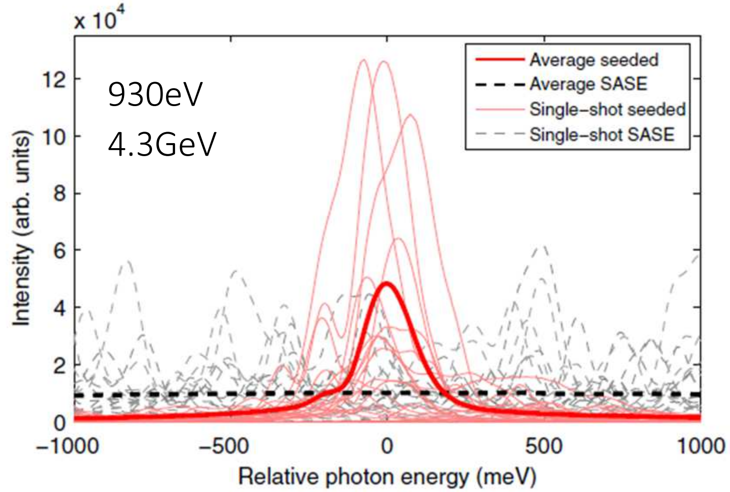
A short introduction to self-seeding

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

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



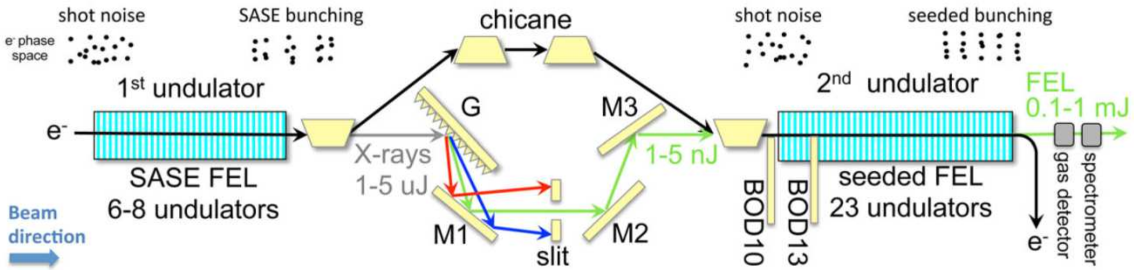
Nominal energy range: 500 eV -1000 eV

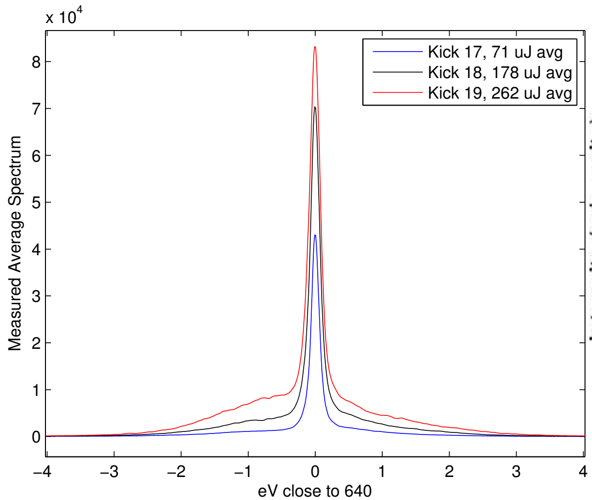


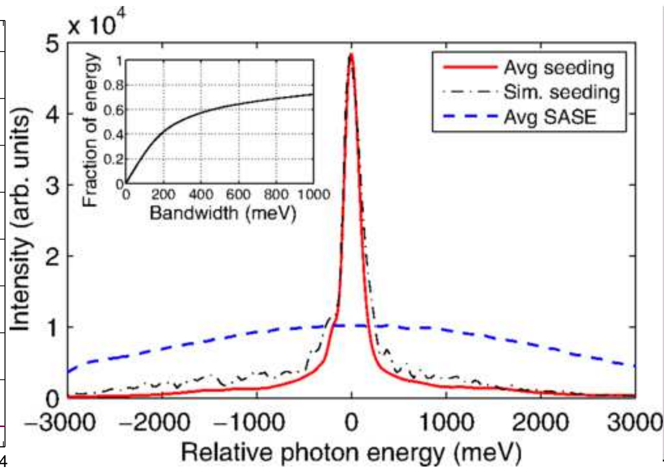
Self-Seeding installations: SXRSS at the LCLS

LCLS Parameters:

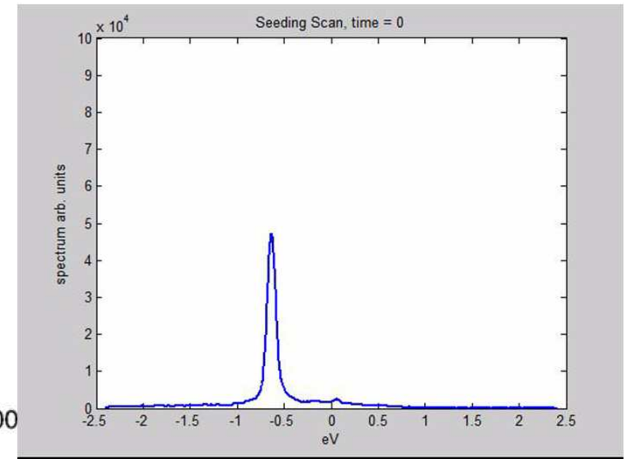
- Electron energy: up to 14 GeV
- Undulator length: 33 segments x3.4m magn. length
- Undulator period: 30 mm
- Peak current: 2-4kA
- Spectral reach: 280eV-12.8keV







10 Shots average

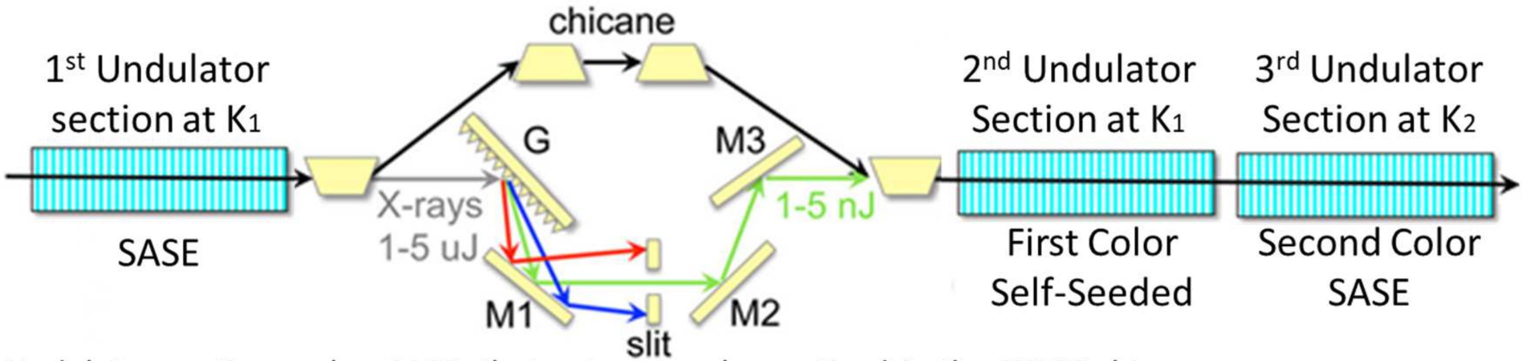


Best SASE reaches a maximum average brightness of ~90k counts on this scale, Best Seeded with a large SASE pedestal reaches an average brightness of ~150k on this scale.

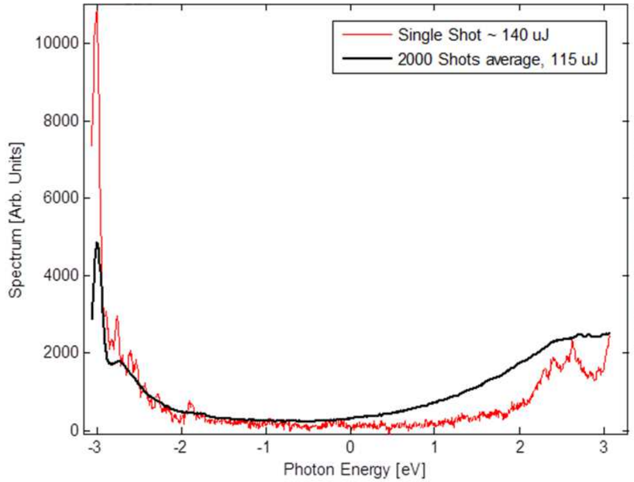
SXRSS scan possible by moving M1 & e-energy

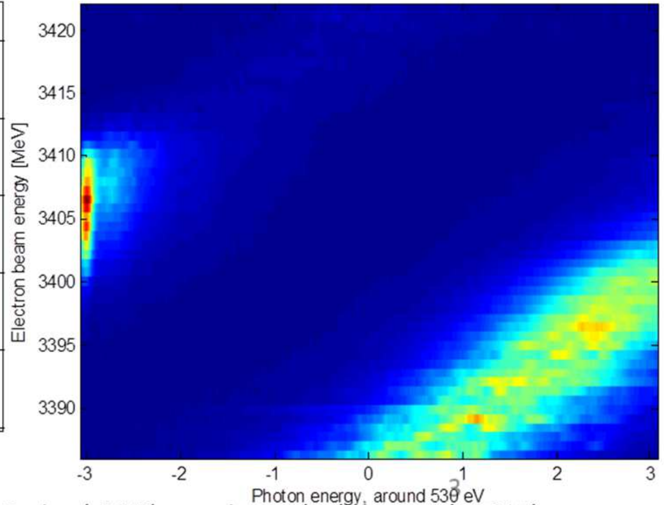
Thanks to A. Lutman for data, slides and discussions

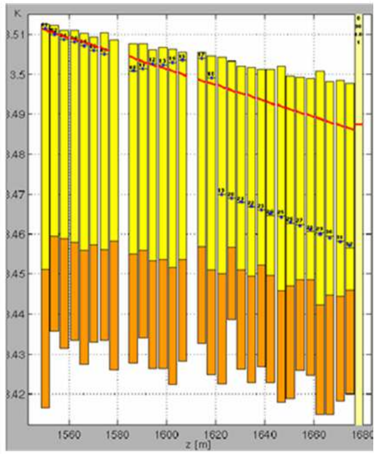
Self-Seeding installations: SXRSS at the LCLS



- 1st Undulator section makes SASE, that gets monochromatized in the SXRSS chicane
- 2nd Undulator section amplifies the seed, should not reach saturation to have second color
- 3rd Undulator section makes SASE at a different color.



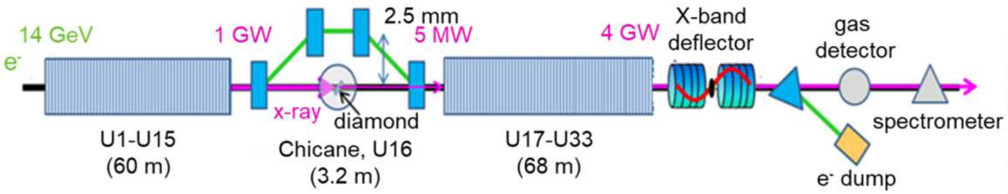




Developed for stimulated resonant inelastic x-ray scattering (sRIXS) experiment (Rohringer July 2015)

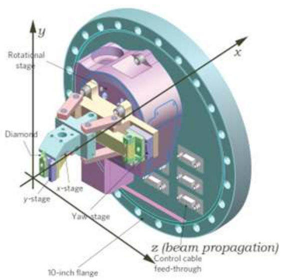
Thanks to A. Lutman for data, slides and discussions

Self-Seeding installations: HXRSS at the LCLS

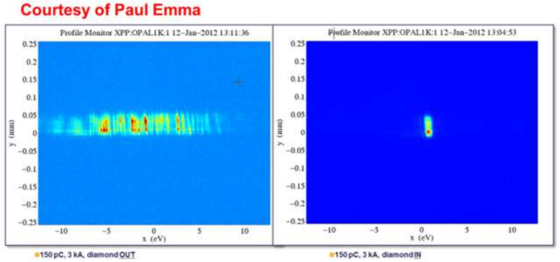


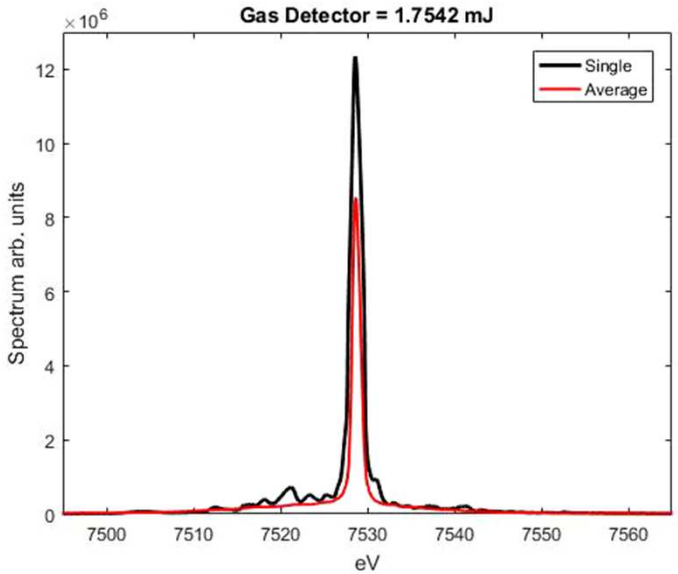
Courtesy of Paul Emma

First experimental verification at the LCLS (Jan 2012): J. Amann, Nature Photonics 6, 693 (2012)

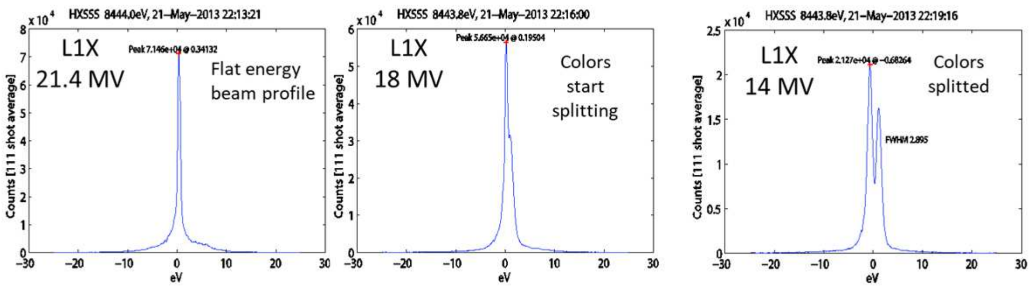


Courtesy of Paul Emma





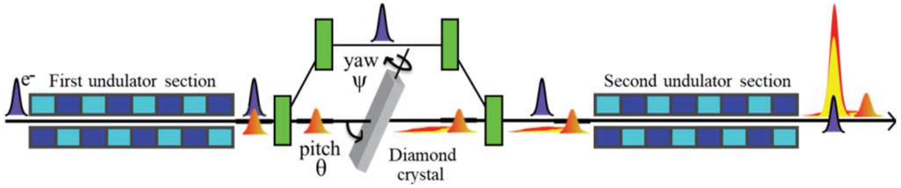
- HXRSS mode between 4.5 keV and 11 keV
- Pulse energy < 400 μJ (average), up to 30 fs
- XTCAV allows diagnosing e-beam long. Phase space
- E-beam manipulation impacts on seeded pulses

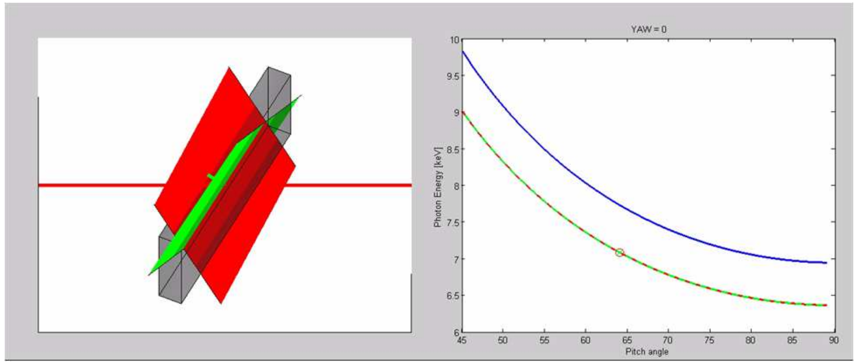


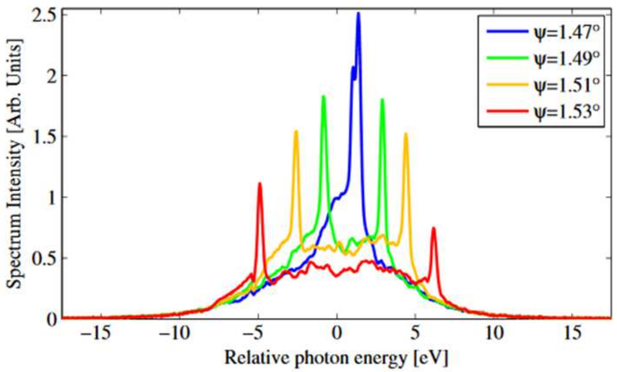
Thanks to A. Lutman for data, slides and discussions

Self-Seeding installations: HXRSS at the LCLS

Multiple colors (within SASE BW)

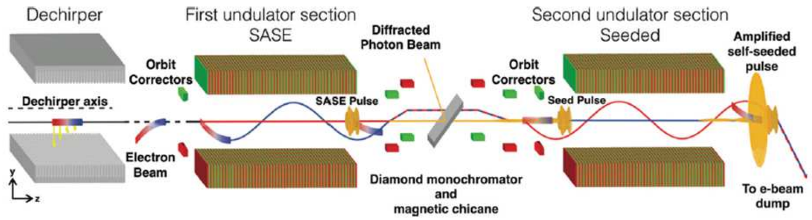


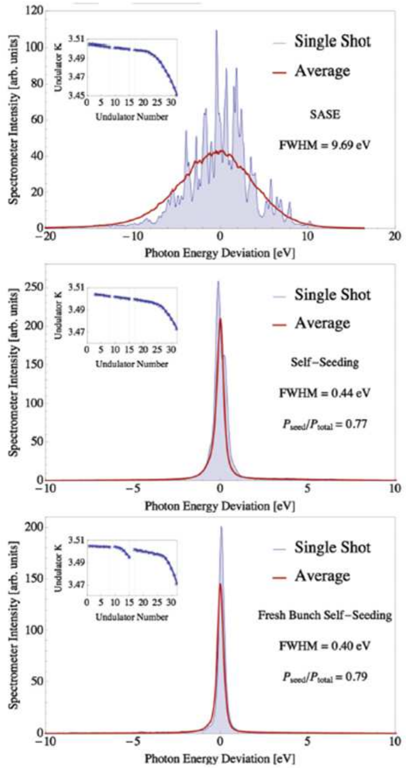




A.A. Lutman et al., PRL 113, 254801 (2014)

Combination with fresh bunch





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

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

- Still B increase for usual self-seeding is 12.5/2.4 = 5.2
- And FBSS can be used at low rep-rate

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

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

C. Emma et al, APL, 2017

Thanks to A. Lutman for data, slides and discussions

Self-Seeding installations: HXRSS at the LCLS

Comparison best seed vs. best SASE ever (6mJ scaled) after a mono with rectangular 1eV BW response function

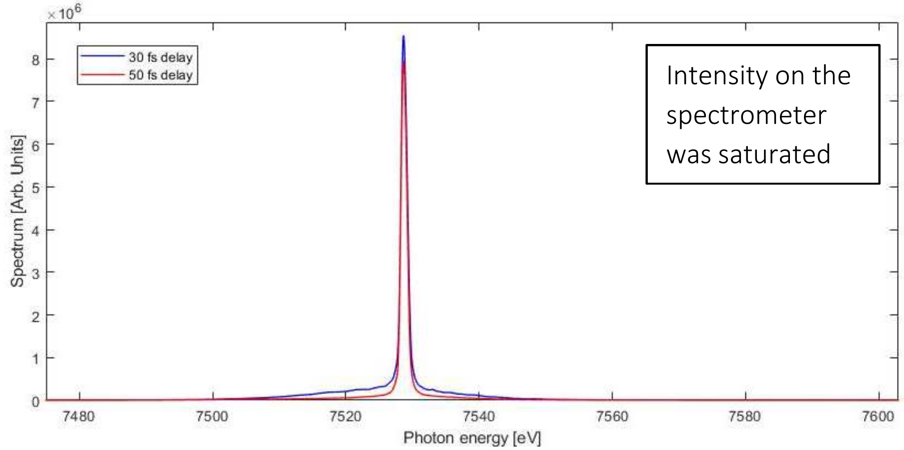
Self-Seeded

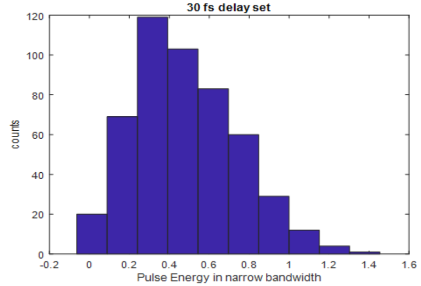
	Average Energy	**Average Energy in 1.088 eV**	Fluctuations	Fluctuations in 1.088 eV	Strongest Shot	**Strongest Shot In 1.088 eV**
50 fs Full set	0.390 mJ	0.255 mJ	55%	58%	1.08 mJ	0.675 mJ
30 fs Full set	0.752 mJ	0.482 mJ	42%	54%	1.80 mJ	1.45 mJ
50 fs Bunch energy filtered	0.49 mJ	0.33 mJ	43%	43%	1.08 mJ	0.675 mJ
30 fs Bunch energy filtered	0.89 mJ	0.57 mJ	33%	45%	1.80 mJ	1.45 mJ

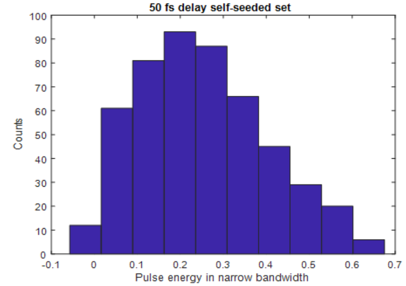
SASE

	Average	Average 1.088 eV	Fluctuations	Fluctuations 1.088 eV	Average x 4 in 1.088 eV
3.7 mJ SET	3.7	0.25 mJ	9%	45-60%	1 mJ
6 mJ SCALED	6	0.4 mJ	9%	45-60%	1.6 mJ

Average x 4 is listed to generally take into account SASE fluctuation within bandwidth.





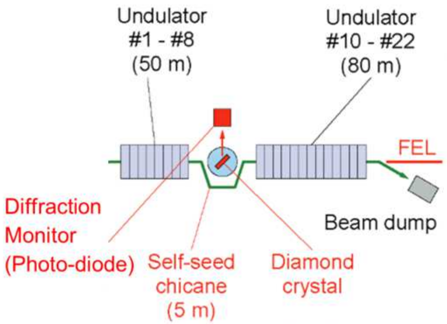


Similar behavior is reported as concerns average and most intense shots

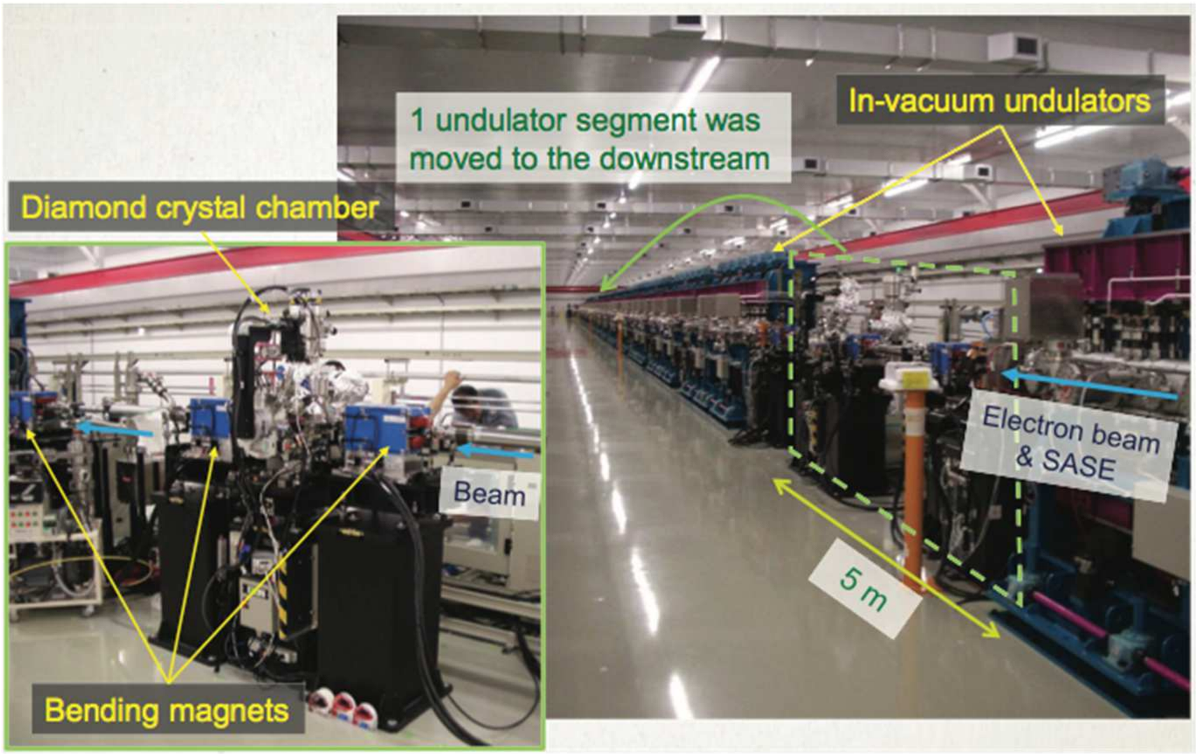
Thanks to A. Lutman for data and discussions

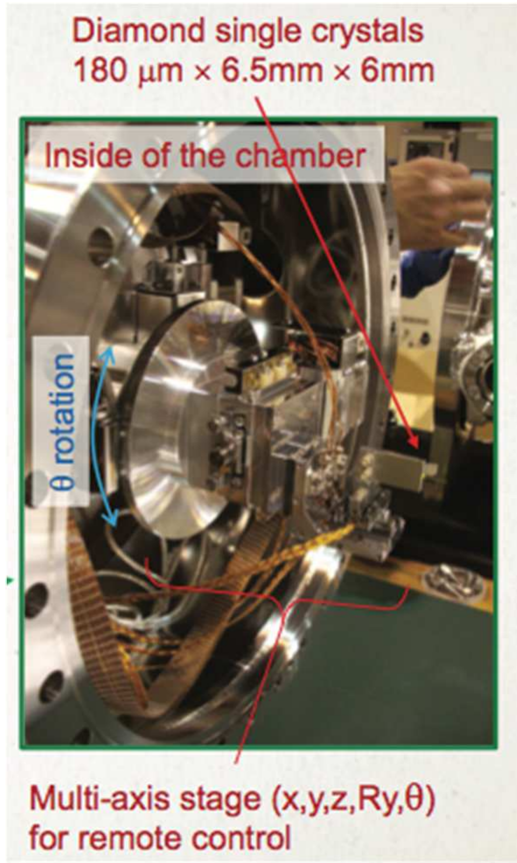
Thanks to A. Lutman for data, slides and discussions

Self-Seeding installations: HXRSS at SACLA (transmission)



- Electron energy: up to 8.5 GeV
- Undulator length: 21 segments x5m magn. Length
- Undulator period: 18 mm (in-vacuum)
- Peak current > 3kA
- Spectral reach: 4 keV- 20 keV

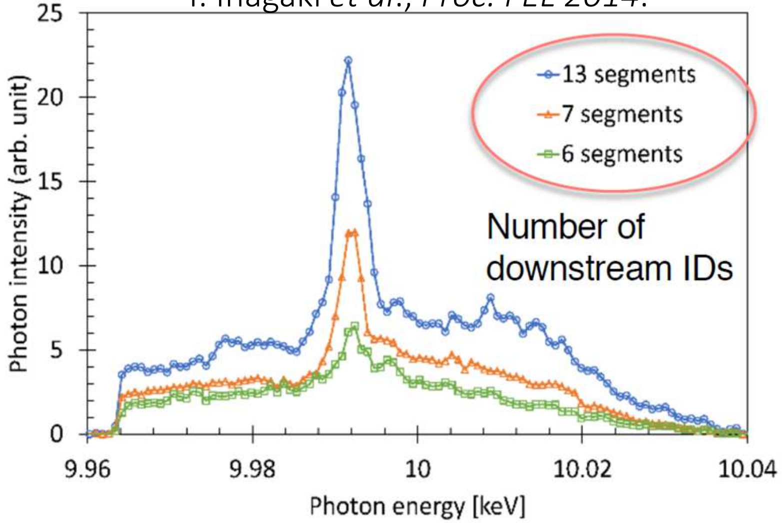




Thanks to T. Tanaka and T. Osaka

Self-Seeding installations: HXRSS at SACLA (transmission)

T. Inagaki *et al*., *Proc. FEL 2014*.



Beam energy	7.8 GeV
Beam charge	340 pC
Undulator K-value	2.1
Photon energy	10 keV
Pulse repetition	10 pps

Spectral brightness was much lower than normal SASE…

Two problems:

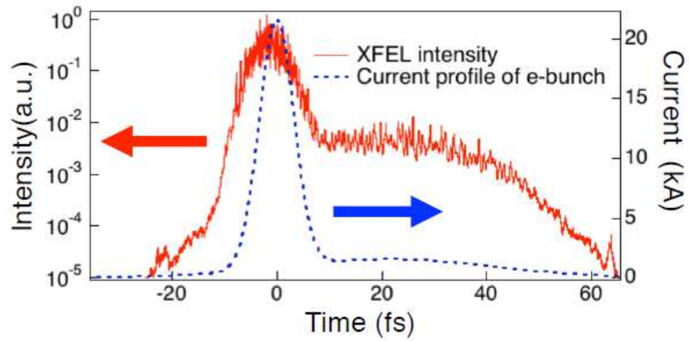
- **Broad SASE background**

  Comparable transmitted SASE tail and monochromatic seed?

- **Transmitted SASE makes the tuning difficult**

  We cannot directly see the seed pulse, such as, intensity, profile, pointing etc.

The electron bunch and XFEL pulse of SACLA has a tail.



I. Inoue et al., *Phys. Rev. Accel. Beams* (2018).

From I. Inoue et al., talk at FEL19

Thanks to T. Tanaka and T. Osaka

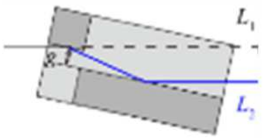
Self-Seeding installations: HXRSS at SACLA (reflection)

µ-Channel-cut monochromator

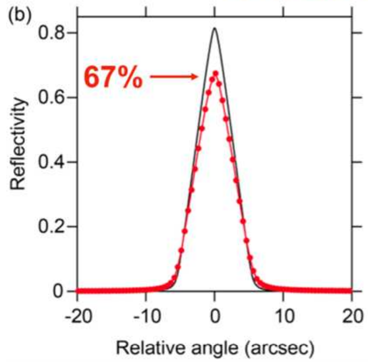
T. Osaka et al., J. Synchrotron Rad. (2019)

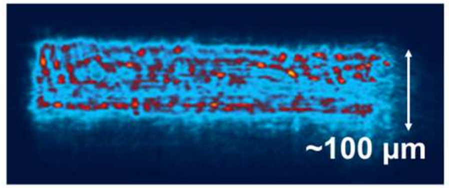
Makina Yabashi

Presented by M. Yabashi at XFEL 3-way meeting in 2011

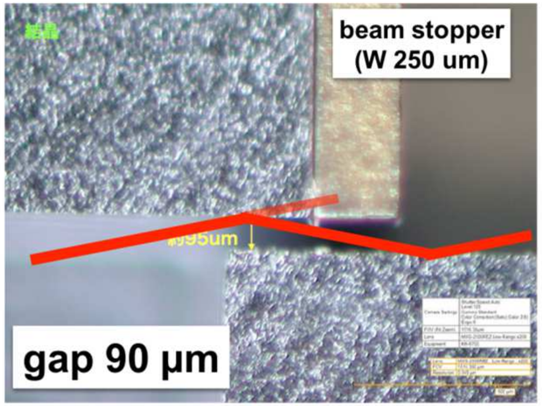


Single 'micro' channel-cut crystal (g ~ 100 µm)





- Clean monochromatic seed w/o SASE contamination
- High conversion efficiency from SASE to seed
- Cooling capability



Diffraction plane: Si(111) (⊿E/E ~ 1.3e-4)
Channel width: 90 µm
Energy range: >4.5 keV in design
Optical delay: 120 fs @10 keV
Beam offset: <180 µm
Spatial acceptance: ~100 µm (V) x 500 µm (H)

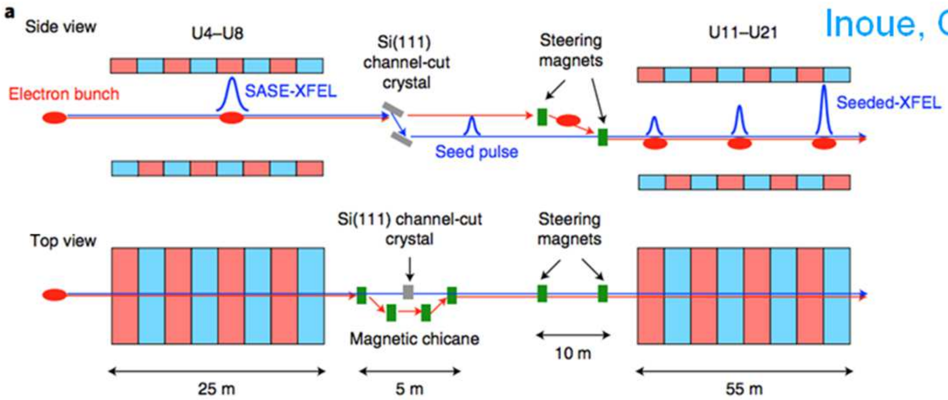
Spatial acceptance is large enough for incident SASE beam (~50 µm FWHM)

Thanks to T. Tanaka and T. Osaka

Self-Seeding installations: HXRSS at SACLA (reflection)

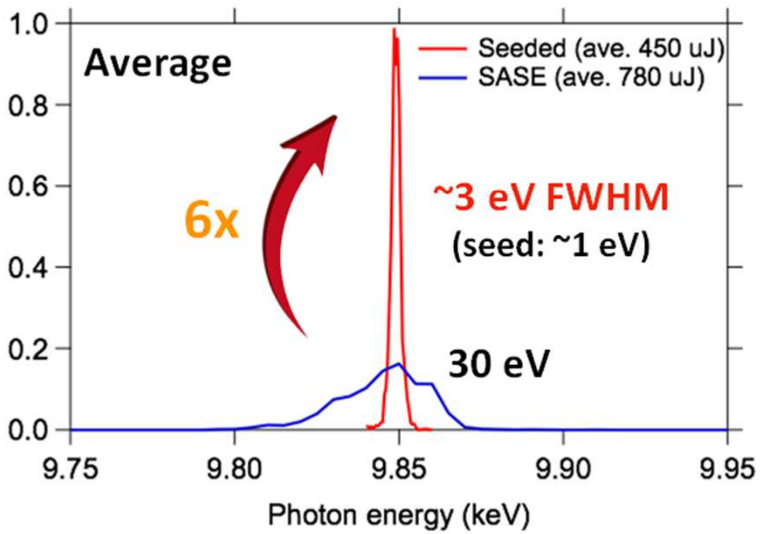
Early commissioning results

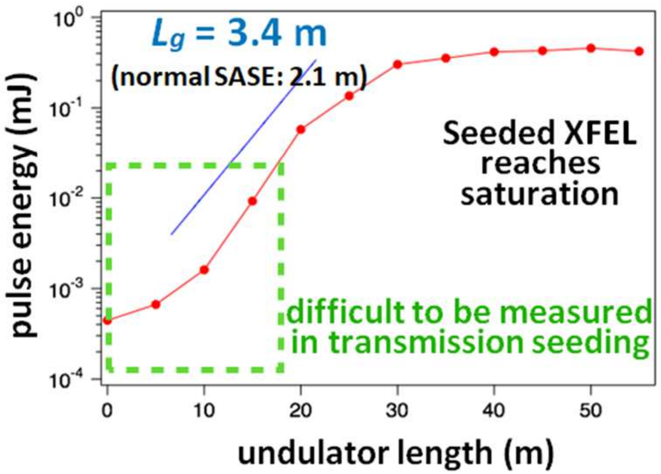
Inoue, Osaka et al., Nat. Photon. (2019)



Accel. parameters (same as usual)

- E-beam energy: **7.8 GeV**
- E-bunch duration: **~10 fs**
- E-beam charge: **270 pC**
- K-value: **2.1**
- Photon energy: **9.85 keV**



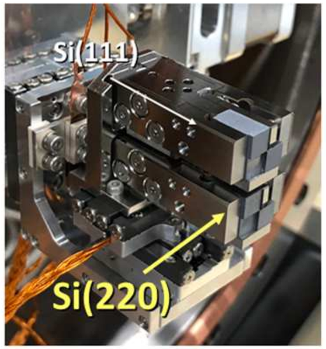


Thanks to T. Tanaka and T. Osaka

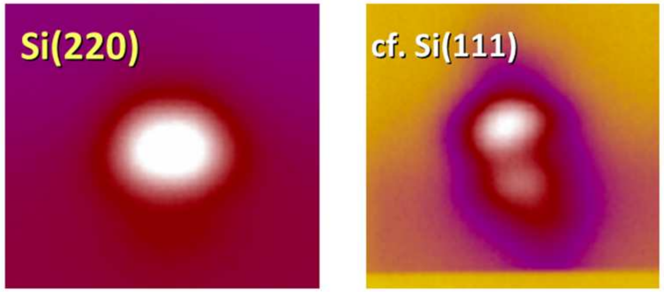
Self-Seeding installations: HXRSS at SACLA (reflection)

Recent status of reflection self-seeding

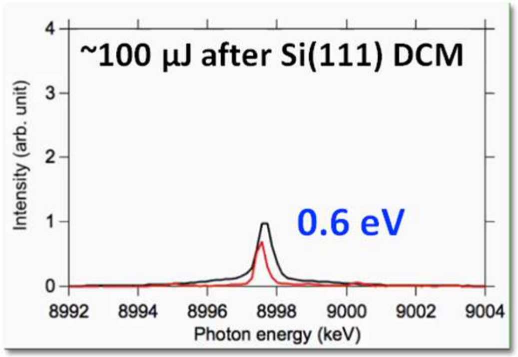
Smaller chirp in the e-beam
Narrower BW with Si(220)



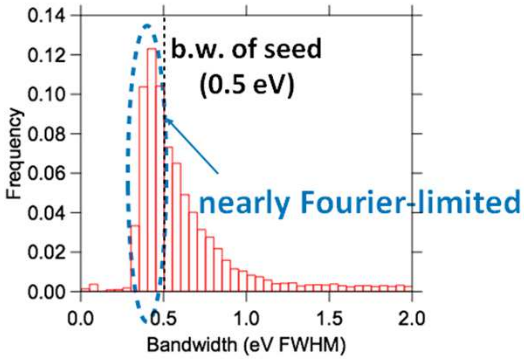
Osaka et al., in preparation



Average profiles of seeds

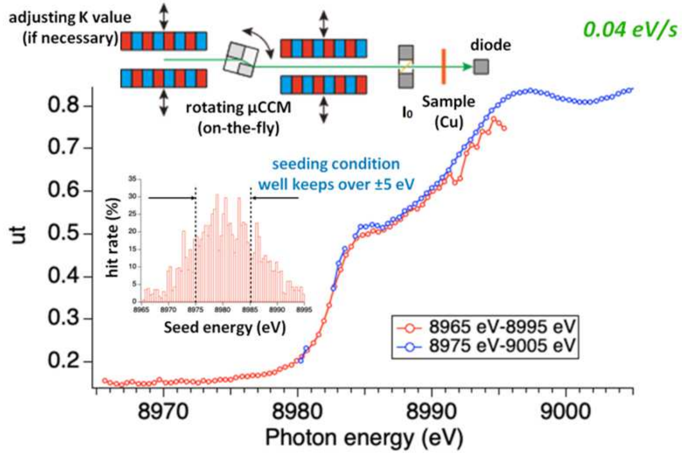


Single-shot spectra



Histogram of bandwidth

Energy scan capability



Thanks to T. Tanaka and T. Osaka

Self-Seeding installations: HXRSS at PAL

Undulator Line	HX1	SX1
Photon energy [keV]	2.0 ~ 14.5	0.25 ~ 1.25
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	energy	gap
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0
No. of undulators	20	7

Main parameters

e^- Energy	11 GeV
e^- Bunch charge	150 - 220 pC
Slice emittance	< 0.4 mm mrad
Peak current	> 3 kA
Repetition rate	60 Hz
FEL photon energy	2 ~ 14.5 keV (HX) 0.25 ~ 1.25 keV (SX)
FEL intensity	> 1 mJ (HX), > 0.2 mJ (SX)
duration	5 – 35 fs
SX line switching	DC magnet (to be changed to Kicker by 2020)

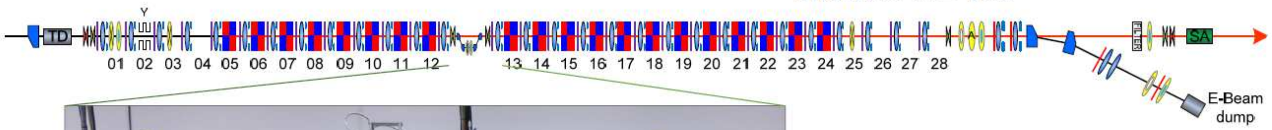
Small e-energy Jitter: 0.012% rms

Configuration: 8+12

Self seeding system

Hard X-ray Undulator (HX1)

Undulator K = 1.87

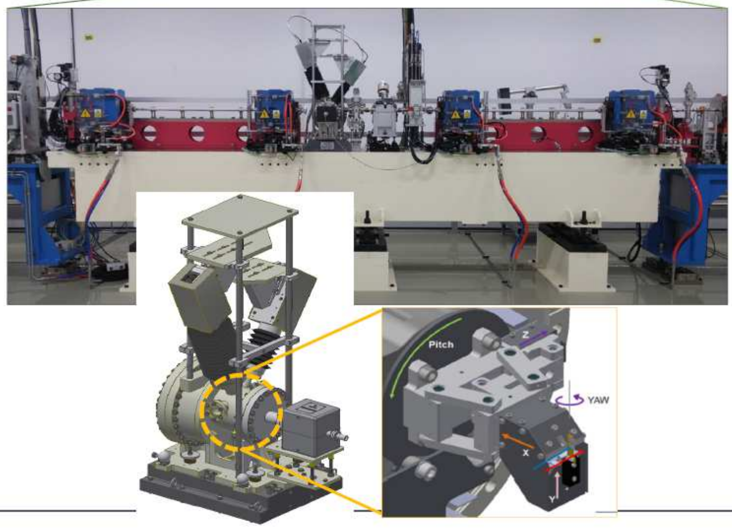


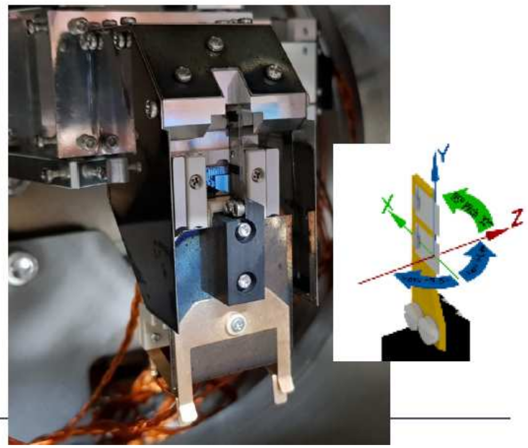
Diamond (400) : Photon energy: 7~10 keV

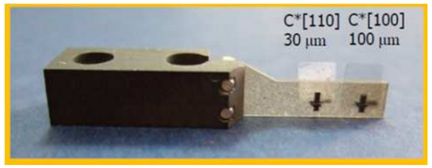
C(400), E_c=8.3 keV, η=0°, θ=56°

Diamond (220) : Photon energy: 5~7 keV

C(220), E_c=5.0 keV, η=0°, θ=79.48°







From Chang-Ki Min Talk at FEL19 TUB03

Thanks to Heung-Sik Kang for data, slides and discussions

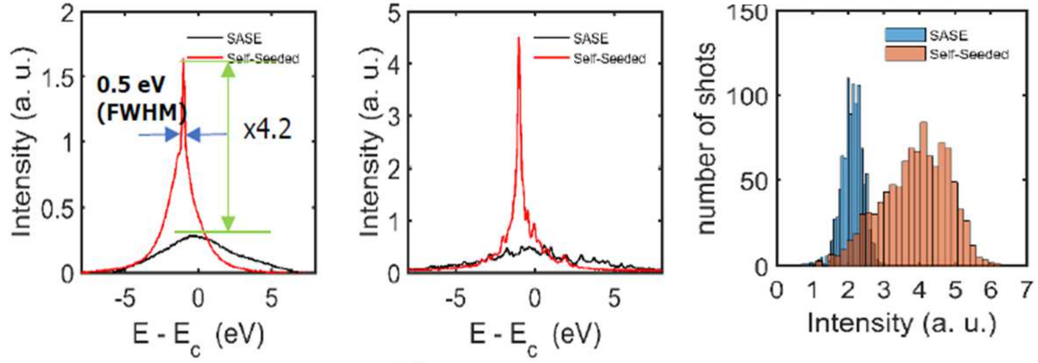
Self-Seeding installations: HXRSS at PAL **From Chang-Ki Min Talk at FEL19, TUB03**

Seeding at 3.5 keV – 30µm crystal

Pitch angle: 89.5 deg [11-1]

FEL energyL 400 mJ seeded– 1 mJ SASE

BW (FWHM): 0.5 eV seeded (ave) – 6.5 eV SASE

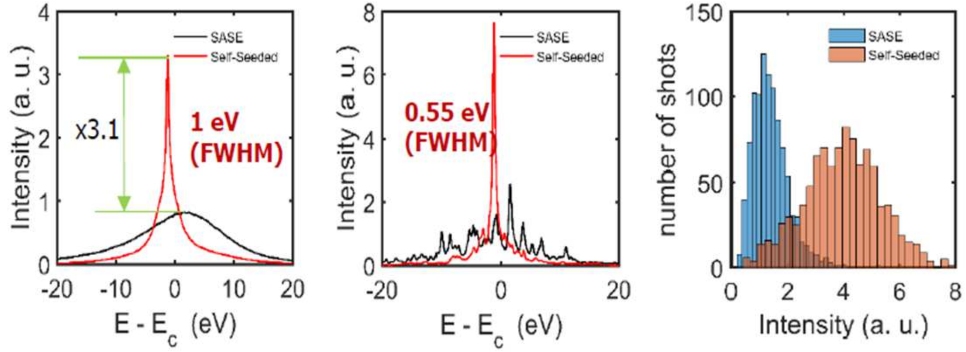


Seeding at 14.4 keV – 100µm crystal

Pitch angle: 46.63 deg [440]

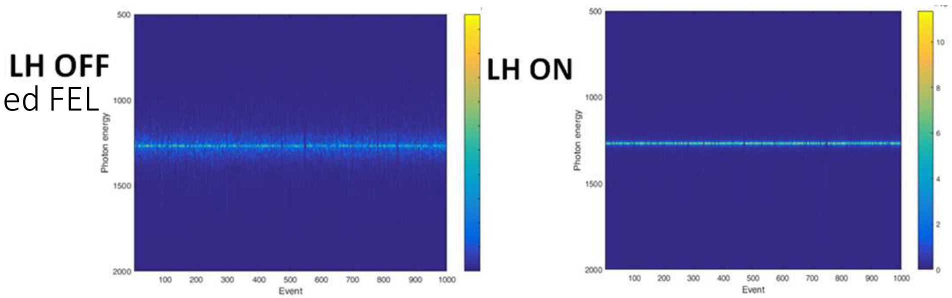
FEL energyL 400 mJ seeded– 1 mJ SASE

BW (FWHM): 1 eV seeded (ave)– 18 eV SASE



PAL seeds between 3.5 and 14.4 keV

LH improves spectral purity and brightness of seeded FEL (increase up to a factor 3)



Courtesy H.-S. Kang

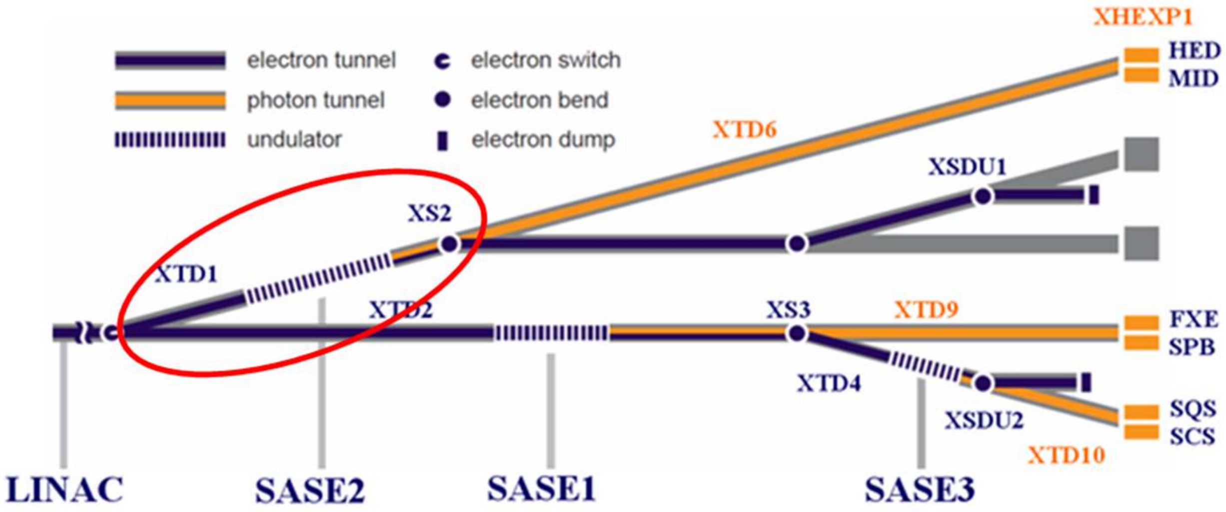
Thanks to Heung-Sik Kang for data, slides and discussions

Self-Seeding installations: HXRSS at PAL

Courtesy H.-S. Kang

Thanks to Heung-Sik Kang for data, slides and discussions

HXRSS at the European XFEL



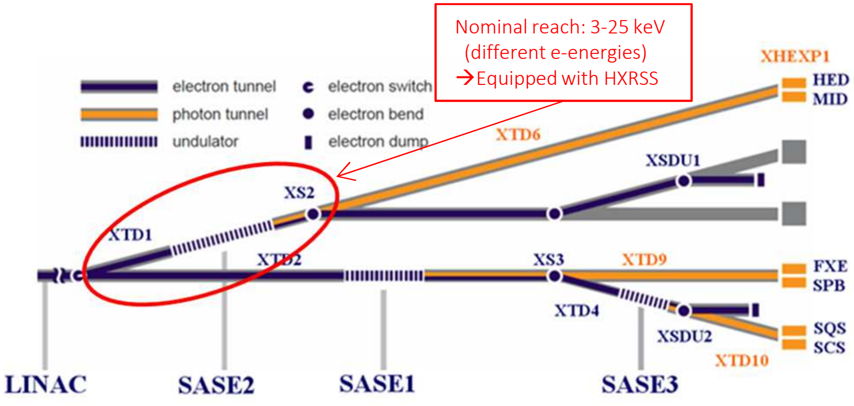
- Nominal electron energy points: 8.5 GeV, 12 GeV, 14 GeV and 17.5 GeV
- HXR undulators (SASE1, SASE2)

  -period: 40mm

  -length: 35 segments x5m magnetic length each

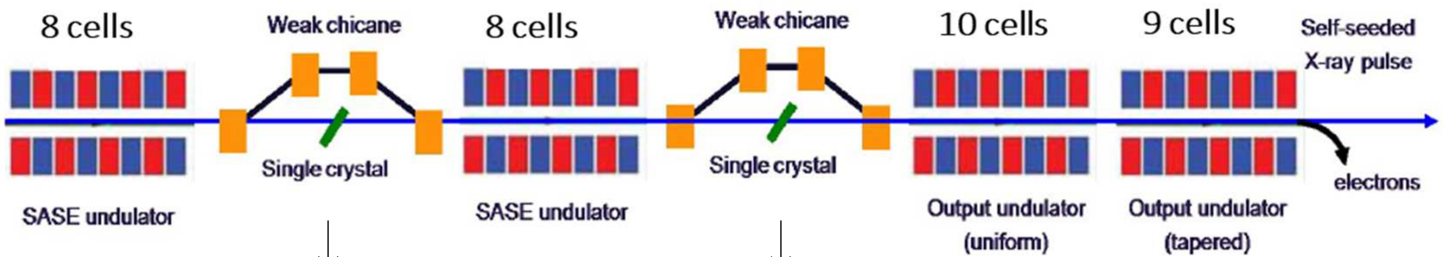
  -Nominal Spectral reach: 3.0keV – 25keV (at different electron energies)

HXRSS at the European XFEL



Long undulators (175m magnetic length at SASE2)
→ Tapering

High repetition-rate. Overall, more pulses but:
Larger heat-load. For example HXRSS:
→ ω-shift beyond Darwin width (conservative)
→ Spectrum broadening
Two sources:
→ SR
→ FEL-based : depends heavily on photon energy



SASE
-"large" BW σ_{SASE}
- Power P

Seeded
-"narrow" BW σ_{seed}
- Power P

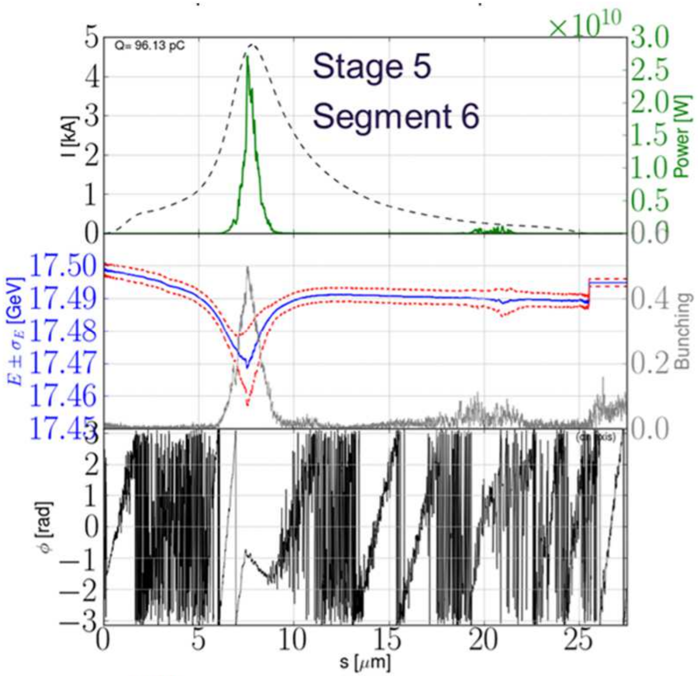
Larger spectral density (seeded signal) Compared to one-chicane

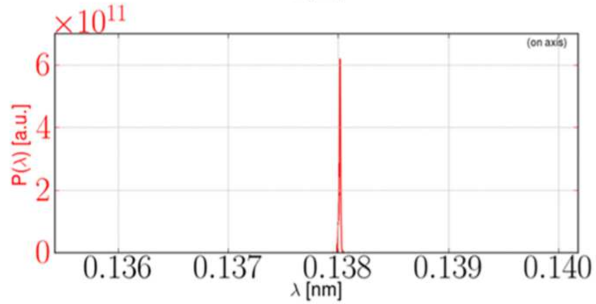
$$\frac{S_2}{N_2} \simeq \frac{S_1}{N_1}\frac{\sigma_{SASE}}{\sigma_{seed}}$$

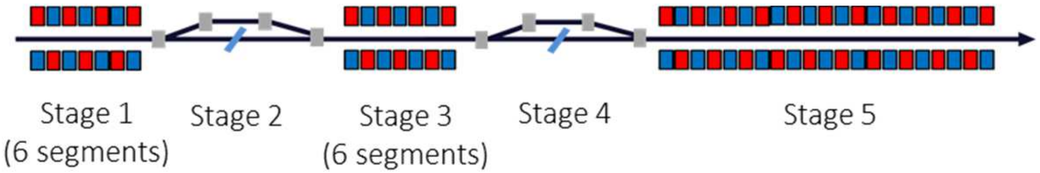
HXRSS at the European XFEL

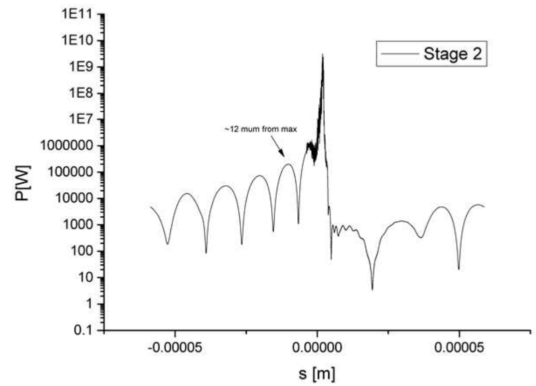
One example for 17.5GeV 100pC electron beam

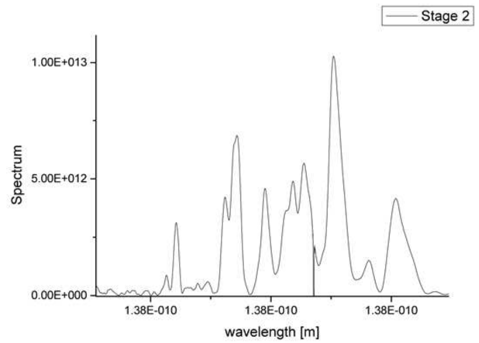
C004 symmetric, 100mum

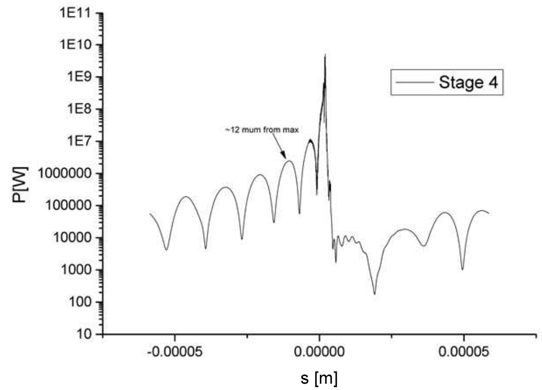


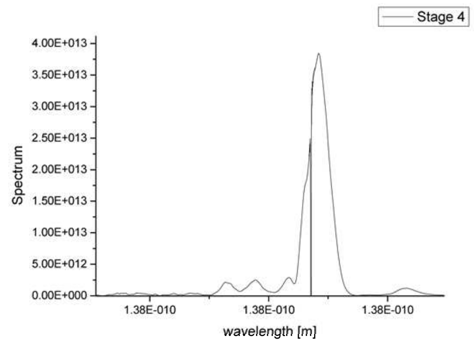




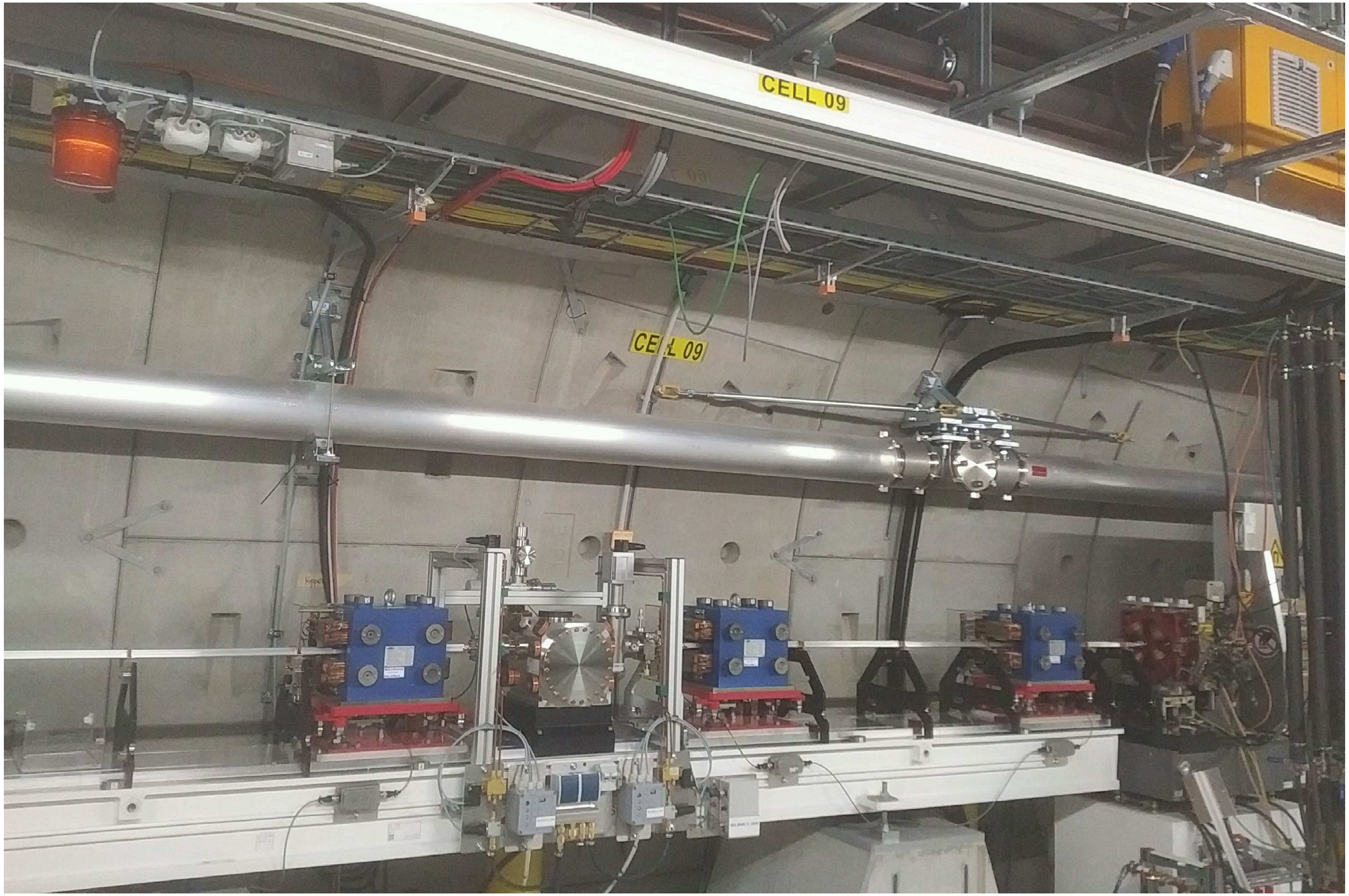






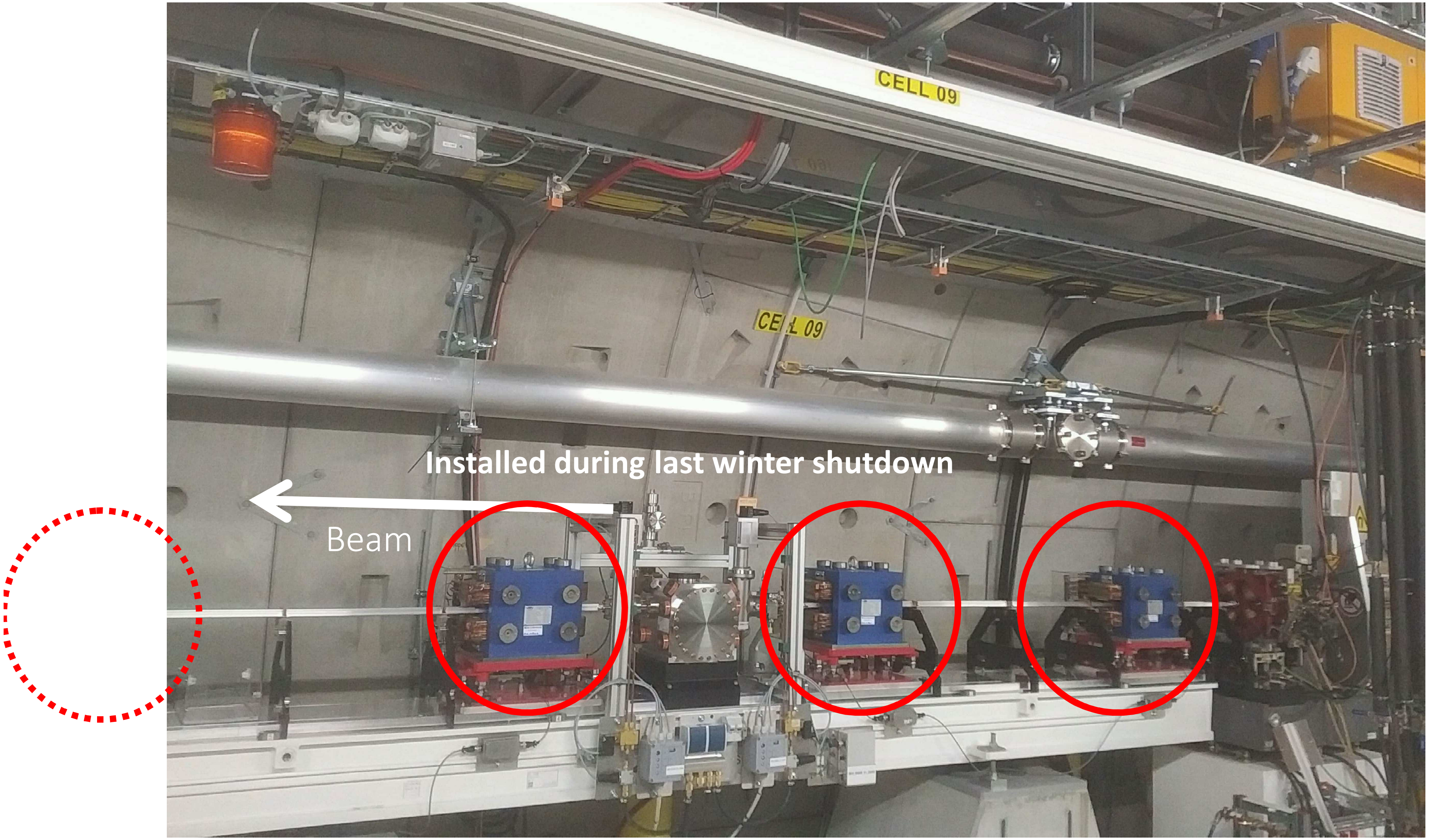


HXRSS at the European XFEL

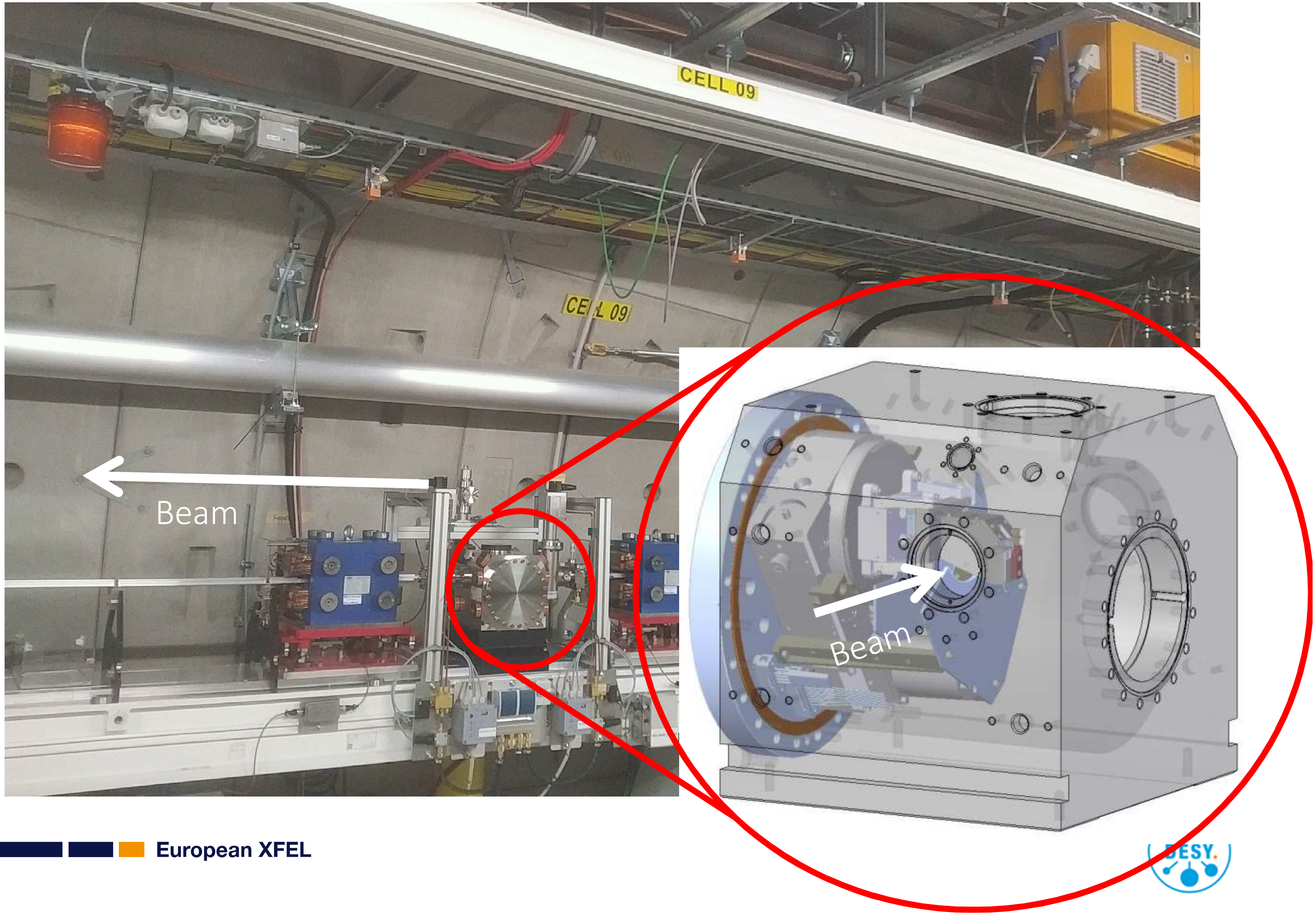


HXRSS at the European XFEL

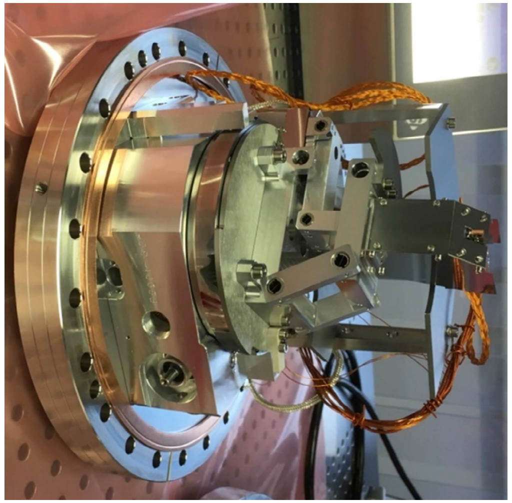
HXRSS at the European XFEL

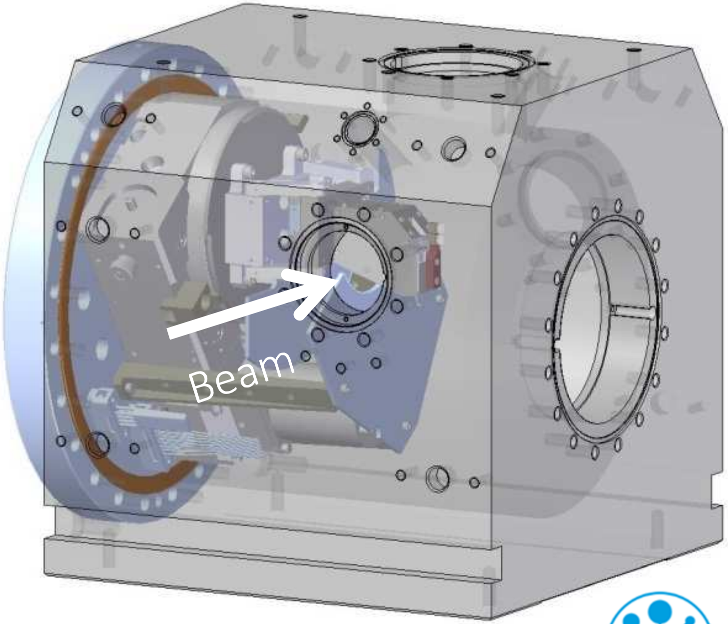


HXRSS at the European XFEL

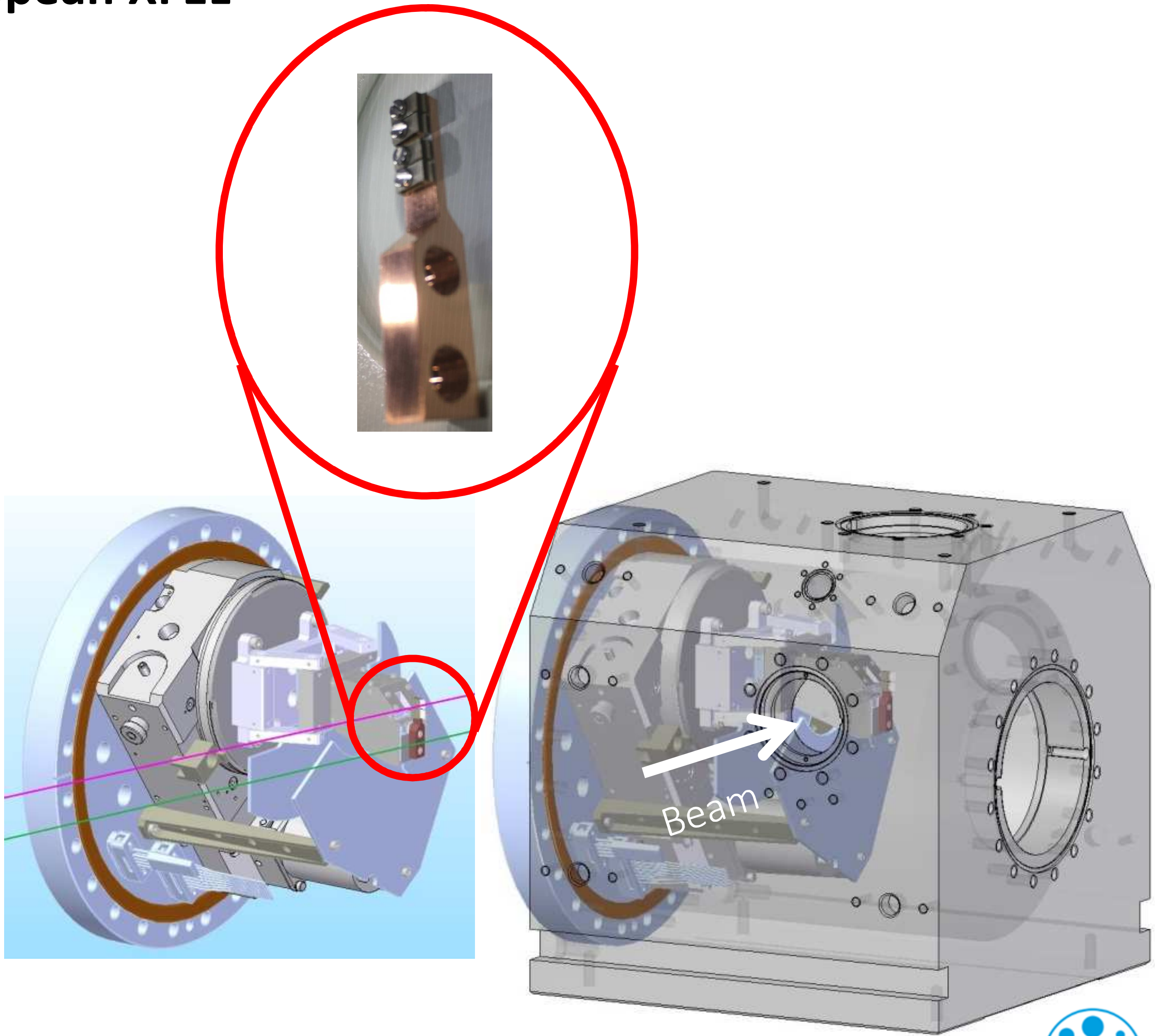


HXRSS at the European XFEL

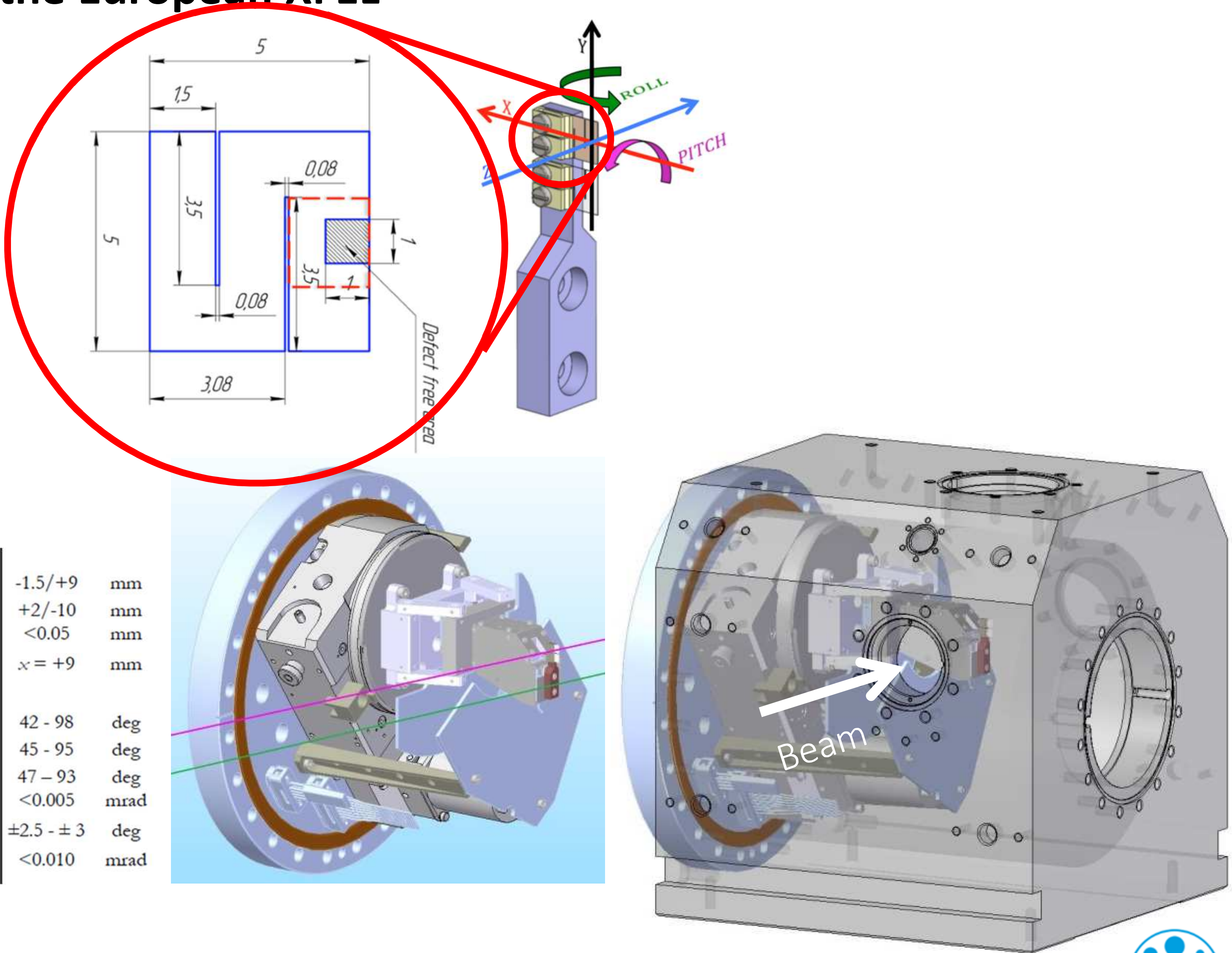




HXRSS at the European XFEL



HXRSS at the European XFEL

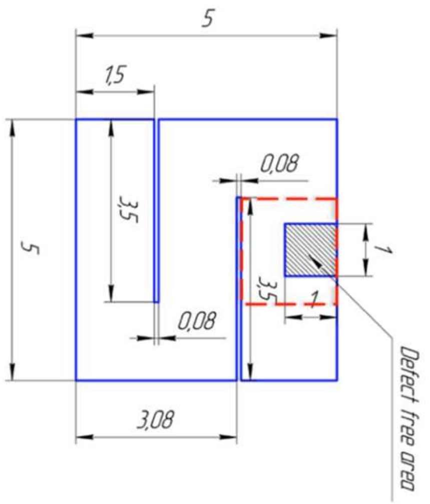


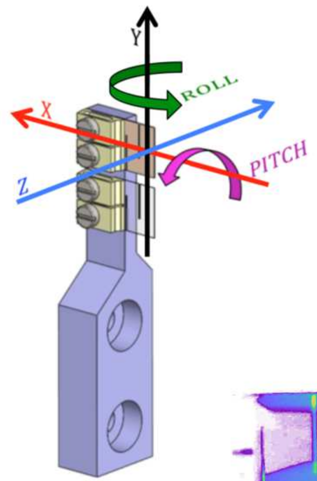
x position control range	-1.5/+9	mm
y position control range	+2/-10	mm
x and y position settability (rms)	<0.05	mm
crystal extraction position (approx).	$x = +9$	mm
crystal pitch angle hard limit range	42 - 98	deg
crystal pitch angle limit switch range	45 - 95	deg
crystal pitch angle operation range	47 – 93	deg
pitch angle settability (rms)	<0.005	mrad
crystal yaw angle control range	±2.5 - ± 3	deg
crystal yaw angle settability (rms)	<0.010	mrad

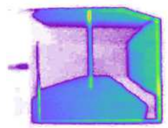
HXRSS at the European XFEL

Mono. #1:
105µm <100>
110µm <111>

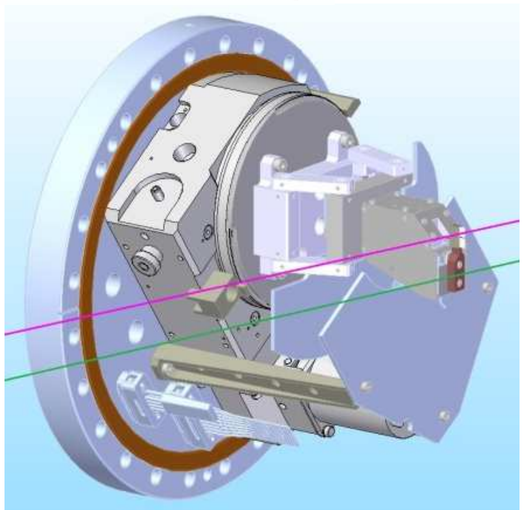
Mono. #2:
105µm <100>
42µm <111>







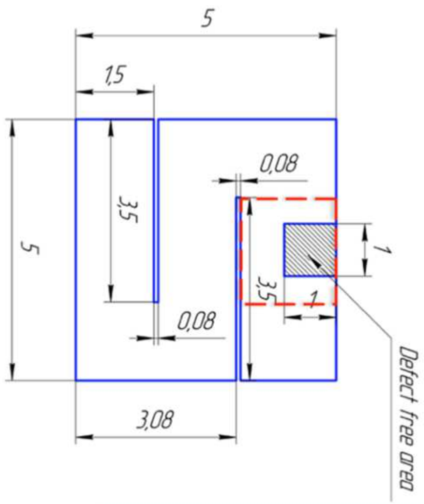
x position control range	-1.5/+9	mm
y position control range	+2/-10	mm
x and y position settability (rms)	<0.05	mm
crystal extraction position (approx).	x = +9	mm
crystal pitch angle hard limit range	42 - 98	deg
crystal pitch angle limit switch range	45 - 95	deg
crystal pitch angle operation range	47 – 93	deg
pitch angle settability (rms)	<0.005	mrad
crystal yaw angle control range	±2.5 - ± 3	deg
crystal yaw angle settability (rms)	<0.010	mrad



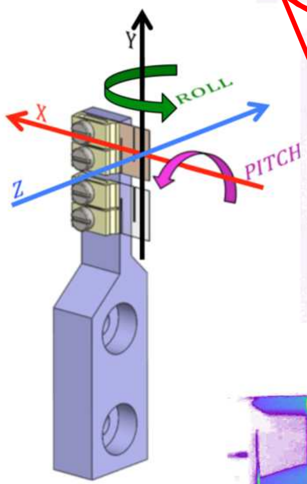
HXRSS at the European XFEL

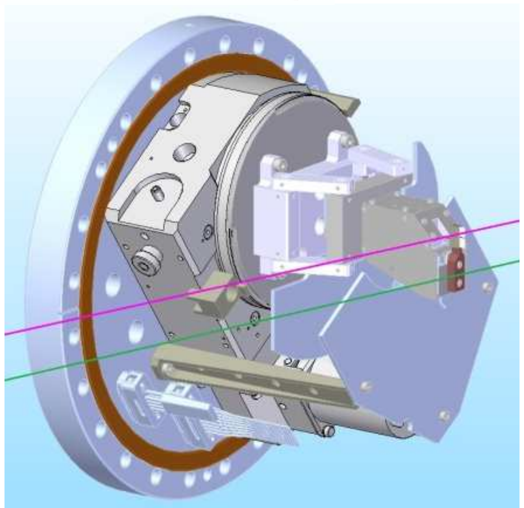
Mono. #1:
105µm <100>
110µm <111>

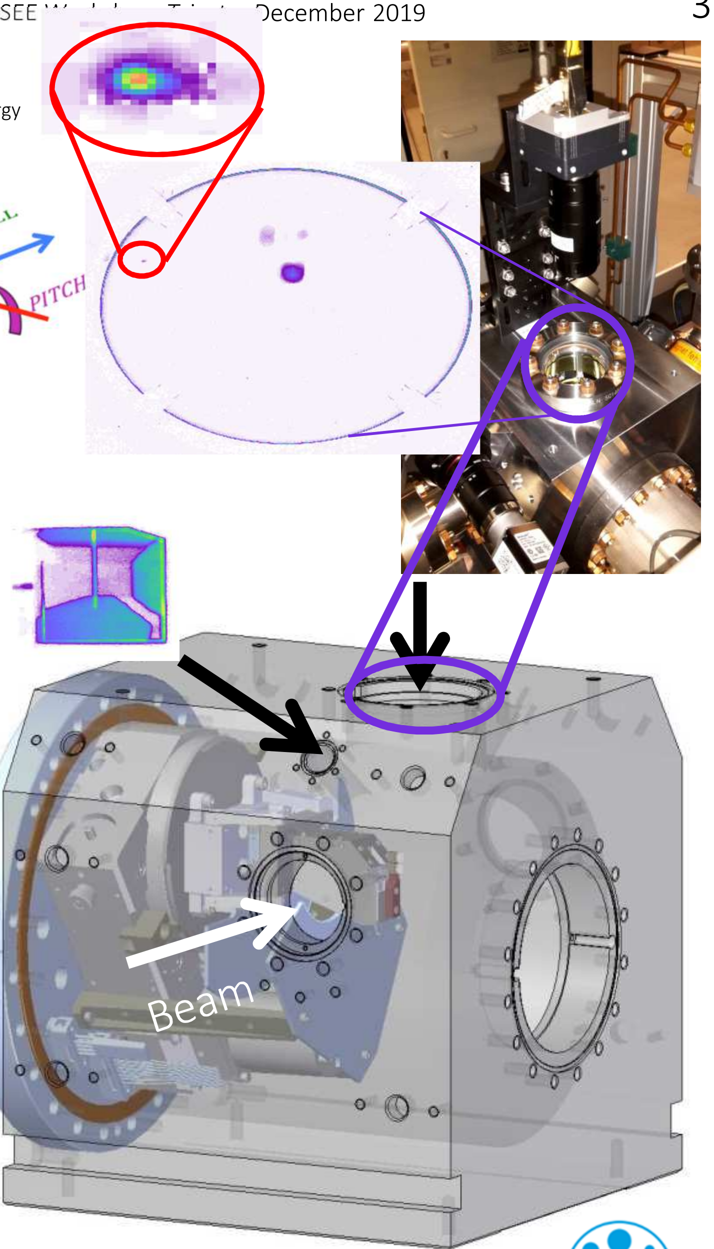
Mono. #2:
105µm <100>
42µm <111>



C(004), 100um,
pitch ~59deg
8keV photon energy



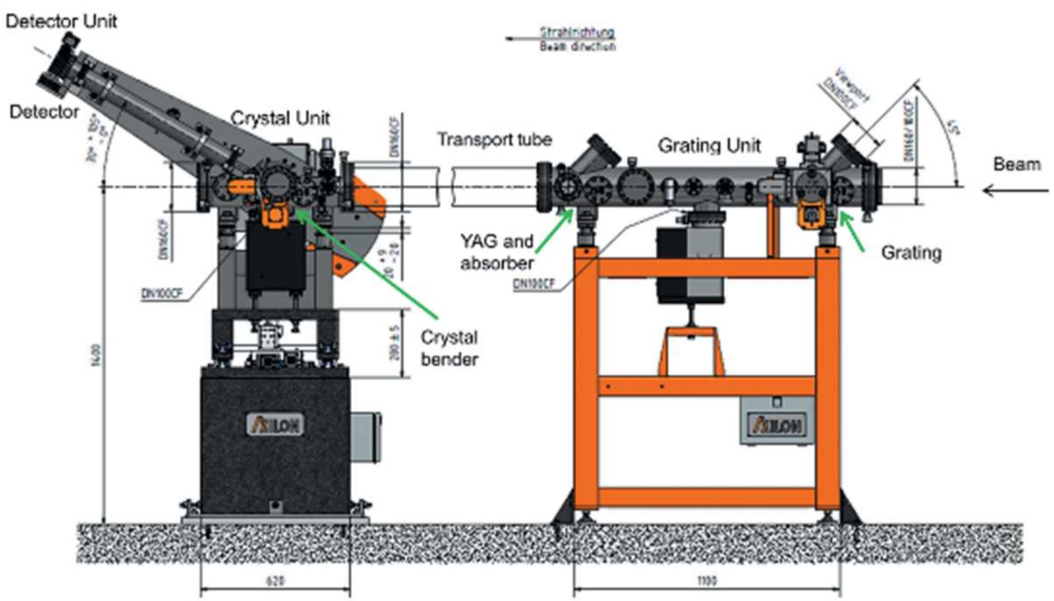




x position control range	-1.5/+9	mm
y position control range	+2/-10	mm
x and y position settability (rms)	<0.05	mm
crystal extraction position (approx).	$x = +9$	mm
crystal pitch angle hard limit range	42 - 98	deg
crystal pitch angle limit switch range	45 - 95	deg
crystal pitch angle operation range	47 – 93	deg
pitch angle settability (rms)	<0.005	mrad
crystal yaw angle control range	±2.5 - ± 3	deg
crystal yaw angle settability (rms)	<0.010	mrad

HXRSS at the European XFEL

High Resolution hard X-ray single-shot spectrometer available



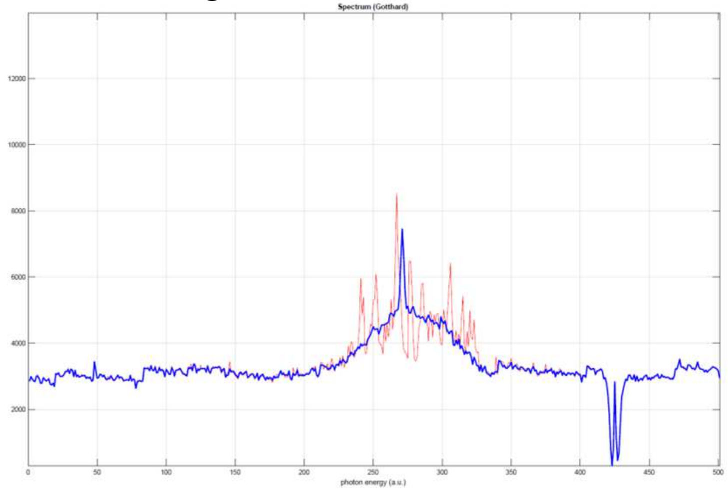
HIREX spectrometer at SASE1 from J. Gruenert et al, JSR 26, 1422 (2019)

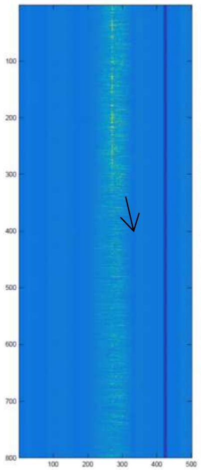
A similar unit is available at SASE2

HXRSS at the European XFEL

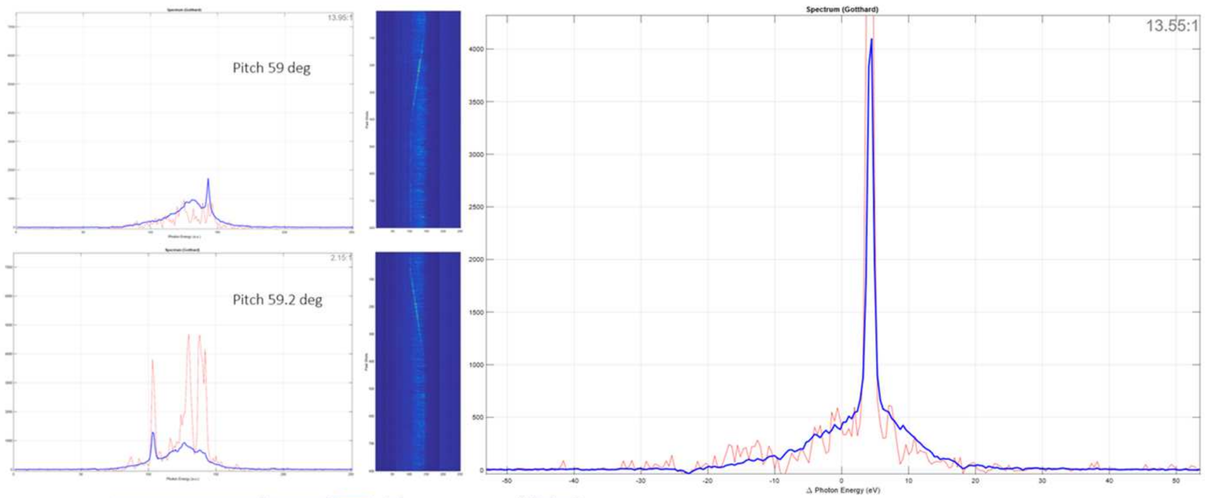
September: 8 keV, C(004), 100um. First HXRSS try (spectrometer available)

First seeding indications, chicane around 25fs delay





After optimization (orbit, LH, phase shifters...)



- First observation of self-seeding at SASE2 in the linear regime
- **Only a few microjoules**

HXRSS at the European XFEL

Many people involved in different ways from different facilities…

Suren Abeghyan, Ulrike Boesenberg, Sara Casalbuoni, Wolfgang Freund, Jan Gruenert, Suren Karabekyan, Andreas Koch, Naresh Kujala, Daniele La Civita, Gianluca Geloni, Theophilos Maltezopoulos, Marco Ramilli, Svitozar Serkez, Harald Sinn, Liubov Samoylova, Roman Shayduk, Vivien Sleziona , Patrick Thiessen, Takanori Tanikawa, Sergey Tomin, Maurizio Vannoni, Mikhail Yakopov, Angel Rodriguez-Fernandez, Alexey Zozulya (EuXFEL), Frank Brinker, Winni Decking, Wolfgang Freund, Nina Golubeva, Marc Guetg, Wolfgang Hillert, Evgeny Negodin, Dirk Winfried Lipka, Raimund Kammering, Vitali Kocharyan, Lars Froelich, Shan Liu, Matthias Scholz, Evgeni Saldin, Dirk Winfried Lipka, Torsten Wohlenberg (DESY), Vladimir Blank, Sergey Terentiev (TISNUM), J. Anton, S. Kearney and D. Shu (ANL)

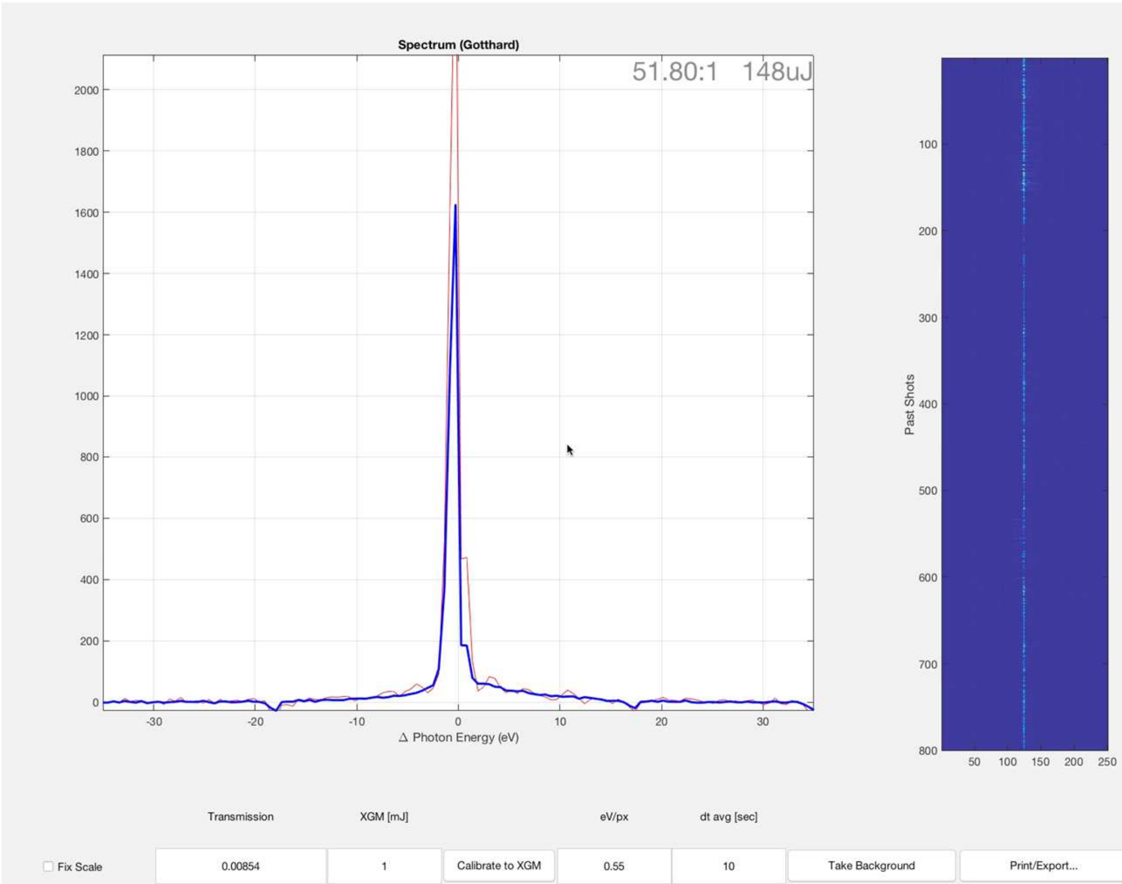
…apologies if I forgot somebody…

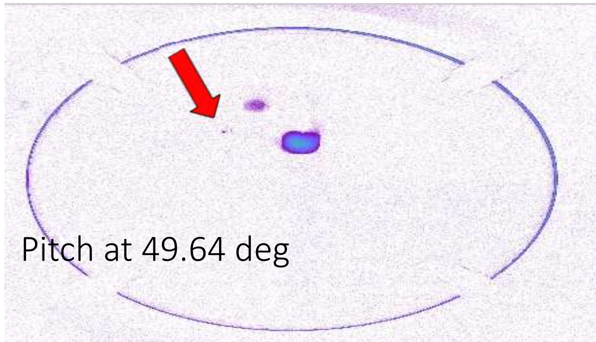
…and special thanks to Alberto Lutman (SLAC) for making available his calibration tool.

HXRSS at the European XFEL

October: 9 keV, C(004), 100um. Best seeded beam up to now

Chicane at about 15fs delay

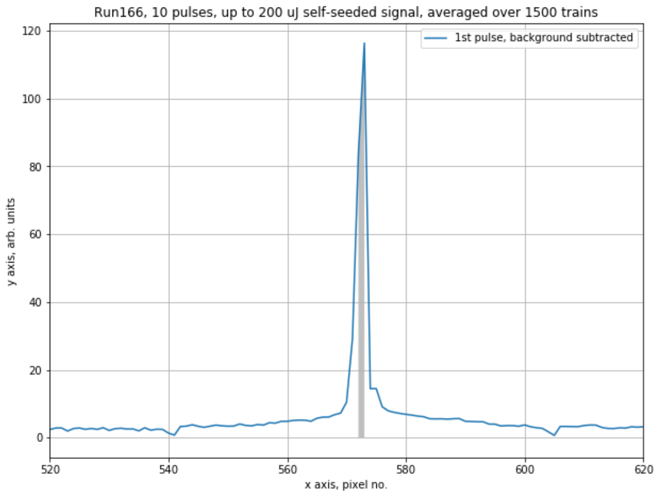




Up to ~200 μJ

(XGM data after low-λ contamination check)

FWHM BW < 1eV

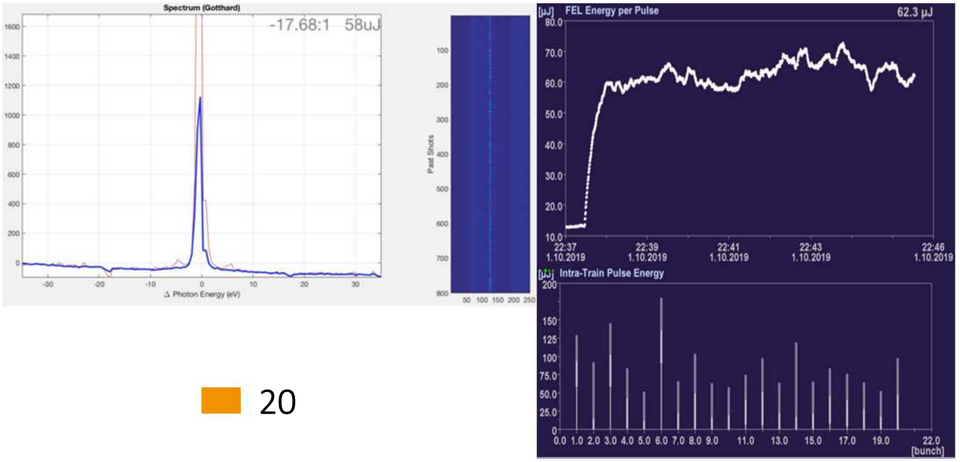


1 pixel = 0.55 eV

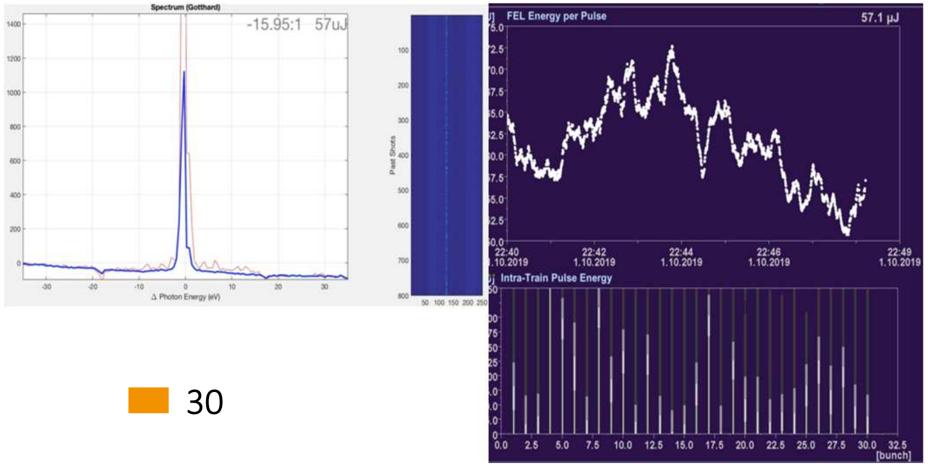
HXRSS at the European XFEL

October: 9 keV, C(004), 100um. Best seeded beam up to now

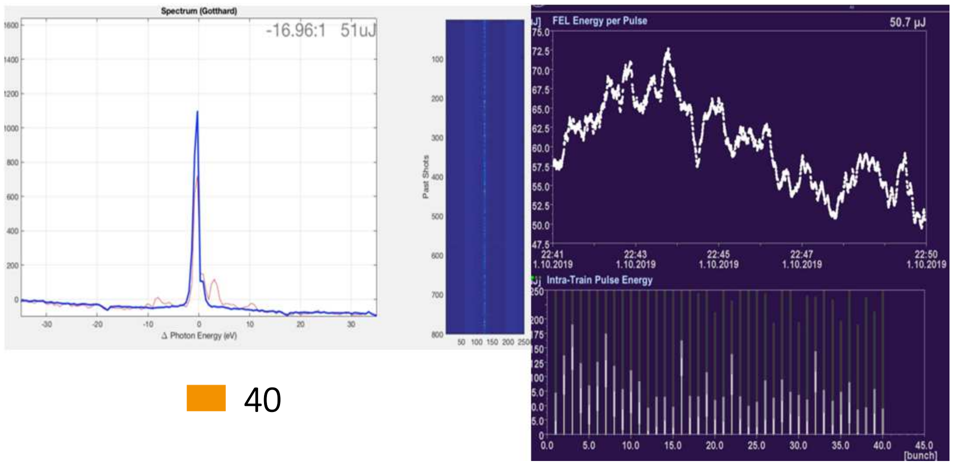
A first attempt to go to higher rep-rate. 10 → 50 bunches/train (10 trains/second)



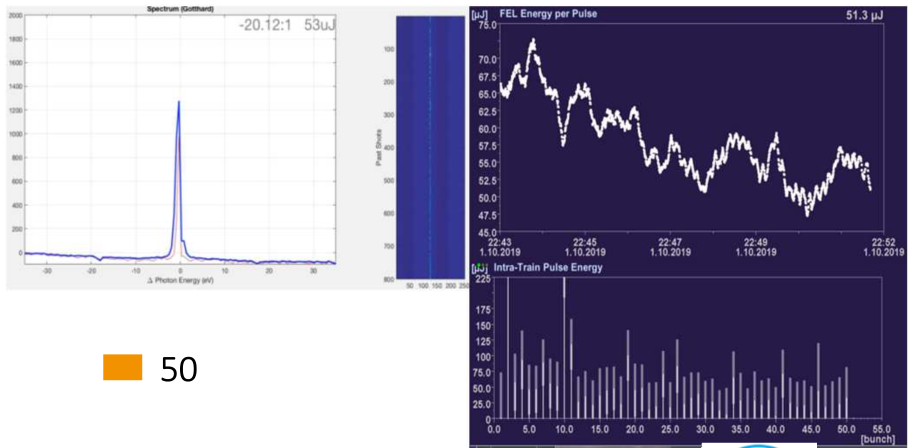
20



30



40



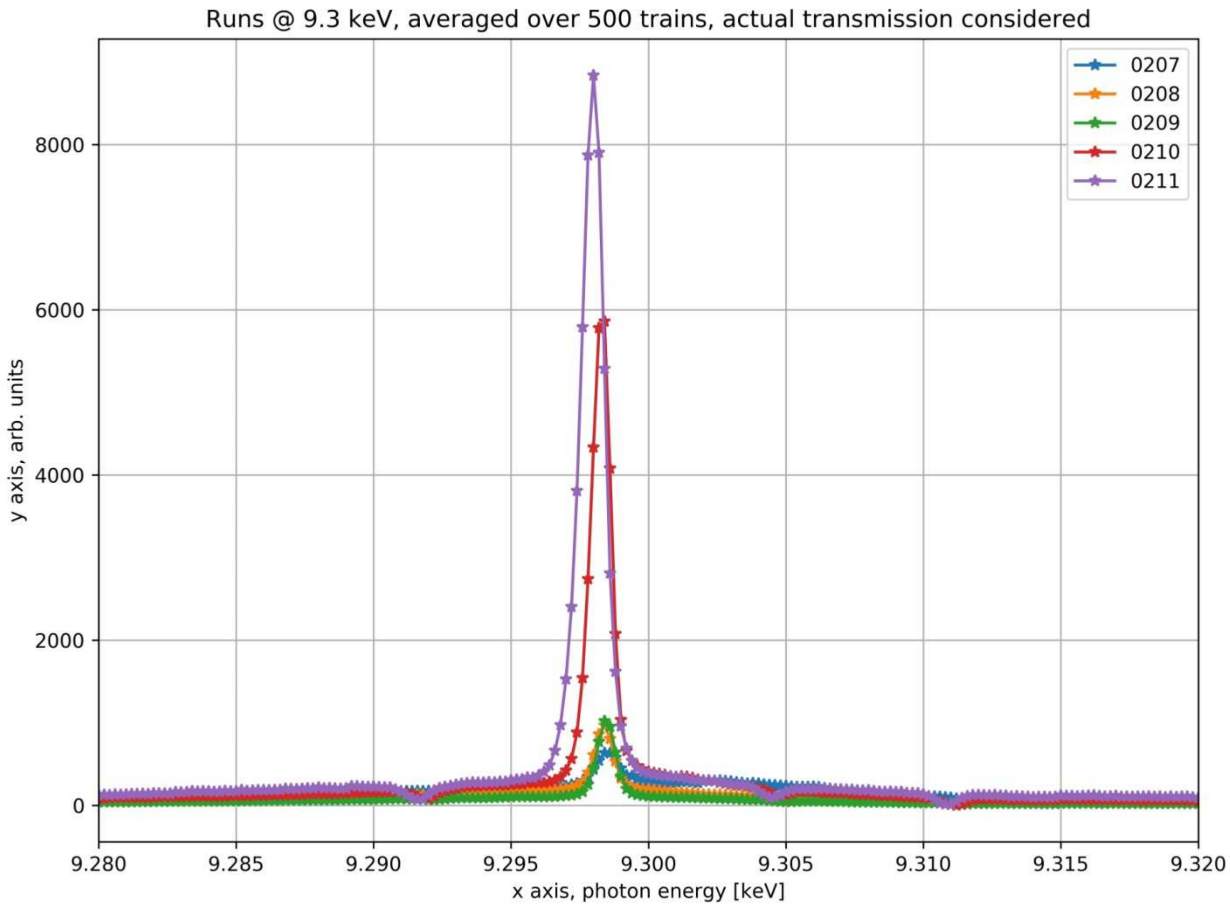
50

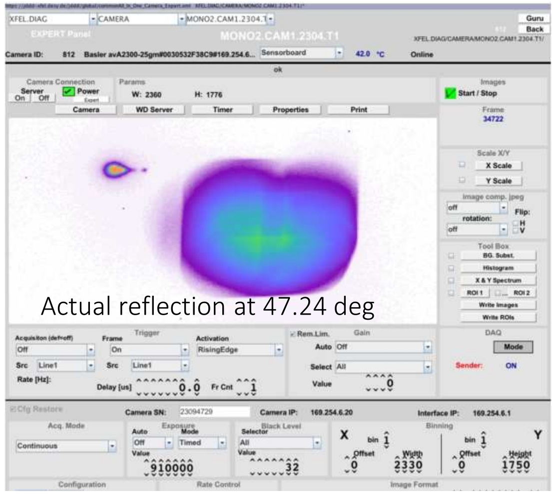
HXRSS at the European XFEL

November: 9.3 keV, C(-3-33), 100um.

Extremely bad SASE conditions: max 35uJ from XGM (run 211)

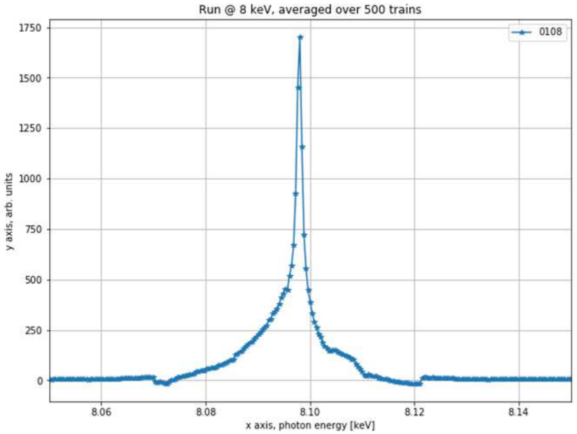
Si(440) mounted → better resolution: run 210 – FWHM = 0.6 eV; run 211 – FWHM = 0.8 eV

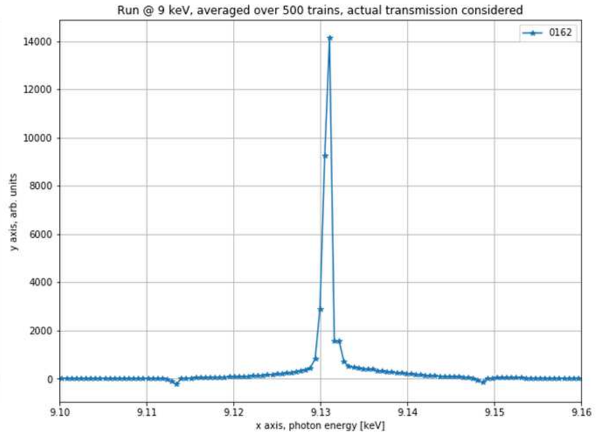


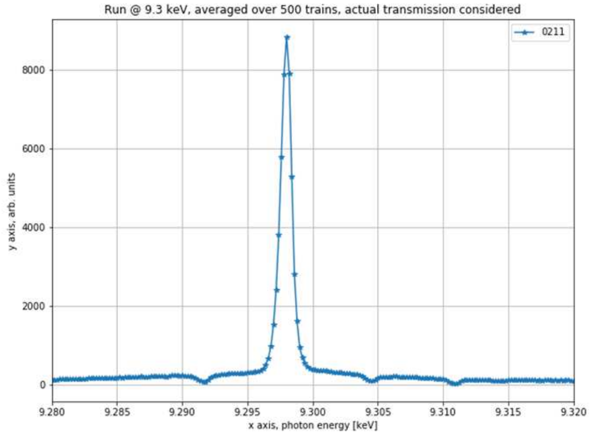


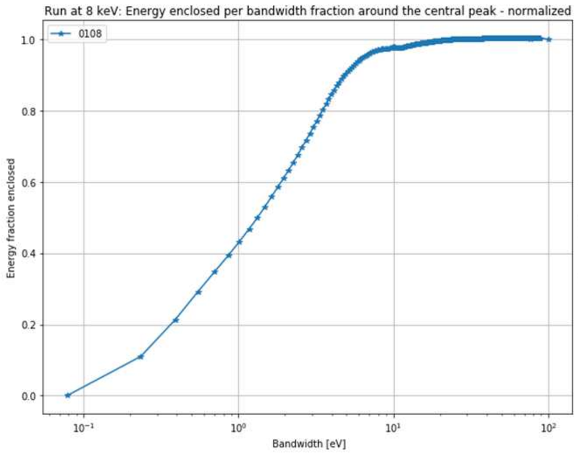
HXRSS at the European XFEL

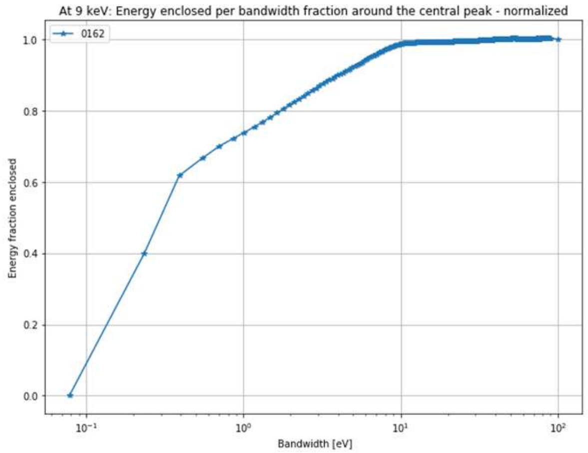
Data analysis by V. Sleziona

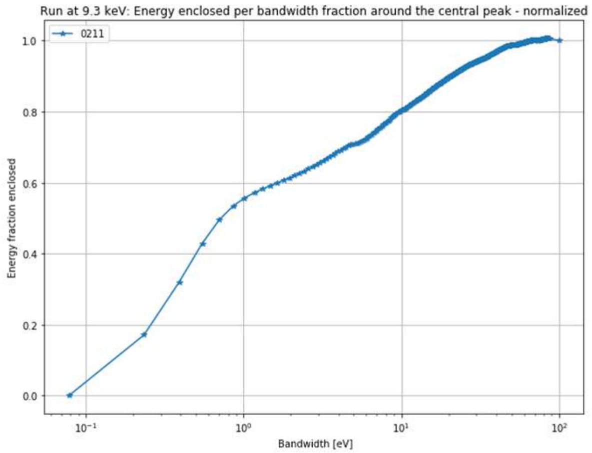












Average XGM value ~ 7uJ
(still in the XGM noise for that day settings)

Average XGM value ~ 155uJ

Average XGM value ~ 33uJ

Outlook and Conclusions

- 1x operating SXRSS system (LCLS)
- 4x operating HXRSS system (LCLS, SACLA, PAL, EuXFEL)
- Did not discuss about systems under considerations
- …Nor possible schemes e.g. for shorter wavelengths, seeding + harmonics

- **These devices rely on magnetic length & e-beam quality extra-budget**

- EuXFEL only started the commissioning
    - Robust (even with bad SASE), and clean pulses
    - Unicity of EuXFEL:
        - High rep rate
        - Second chicane
        - Long undulators → effective tapering possibilities

The End…

Thanks for your attention!