Operation Status and Future Perspective of Warm XFEL

Hitoshi Tanaka, RIKEN SPring-8 Center

1. Warm XFEL in the world
2. Warm vs. cold
3. Status of each warm XFEL
4. Future directions
5. Summary

Acknowledgments

The speaker likes to thank the following persons for their providing presentation material and cooperation;

Axel Brachmann (SLAC)

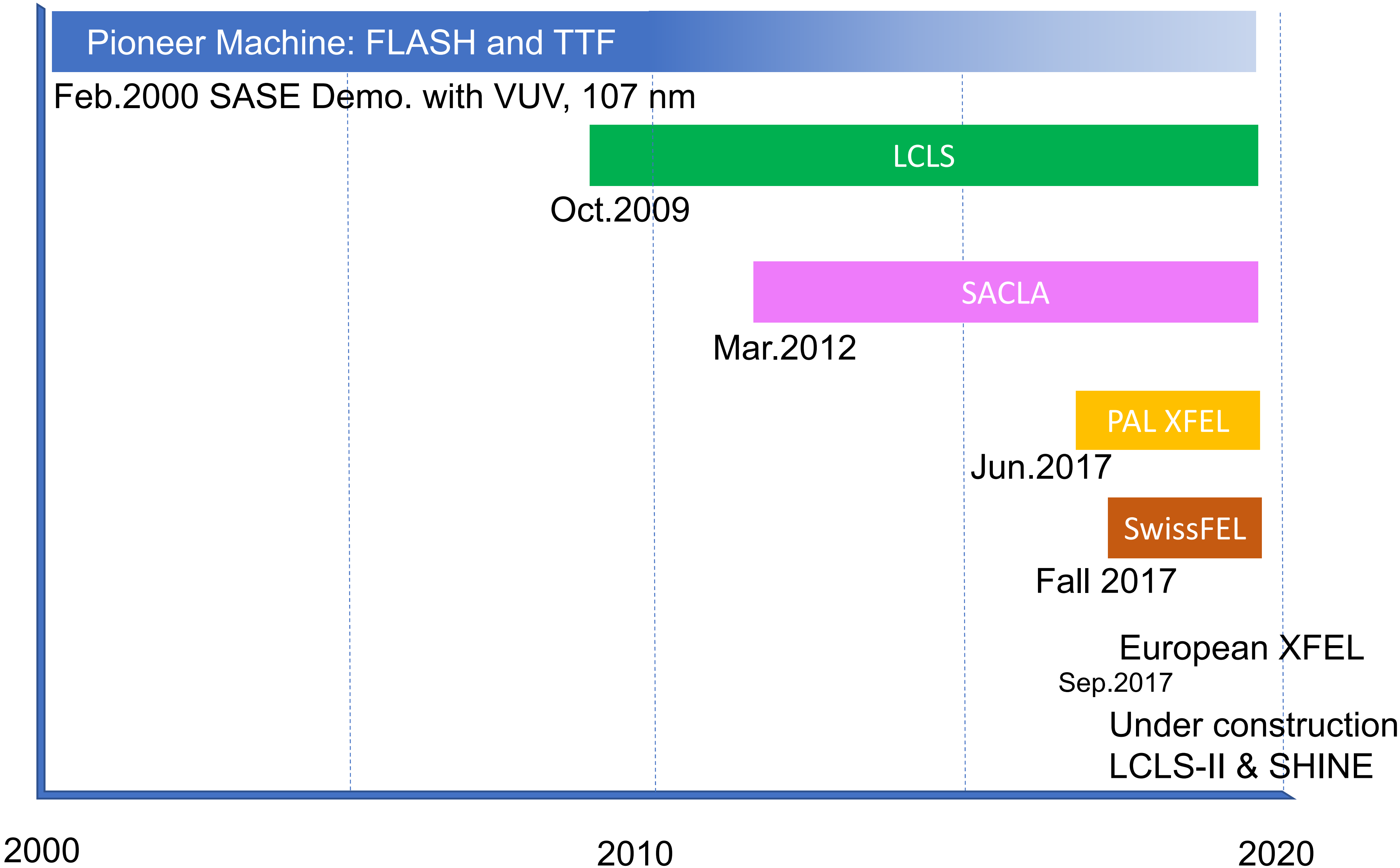
Heung-Sik Kang (PAL)

Löhl Florian (PSI)

Schietinger Thomas (PSI)

Toru Hara (RIKEN/SACLA)

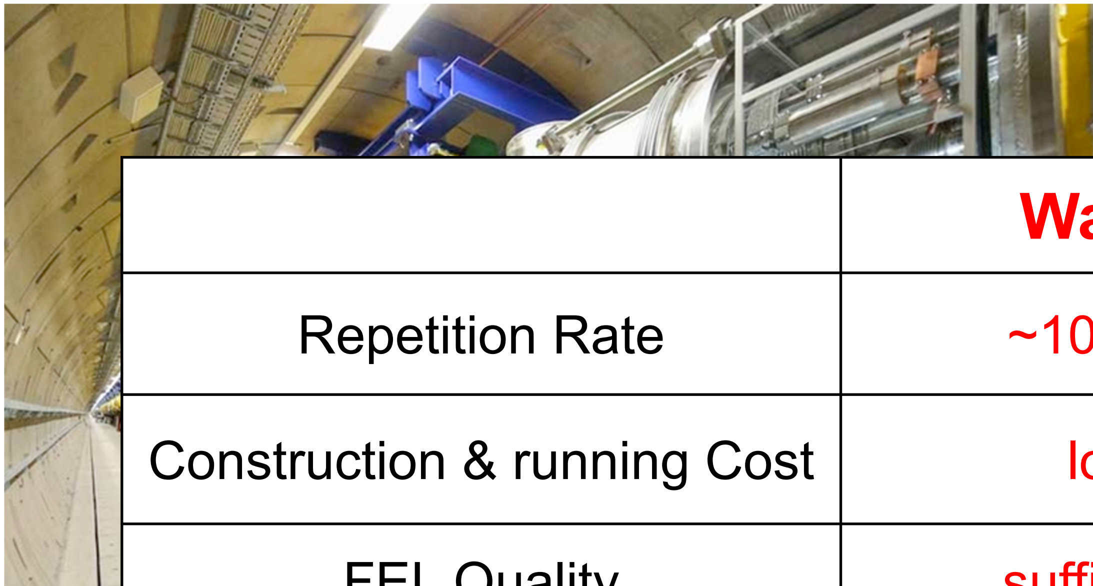
XFEL development



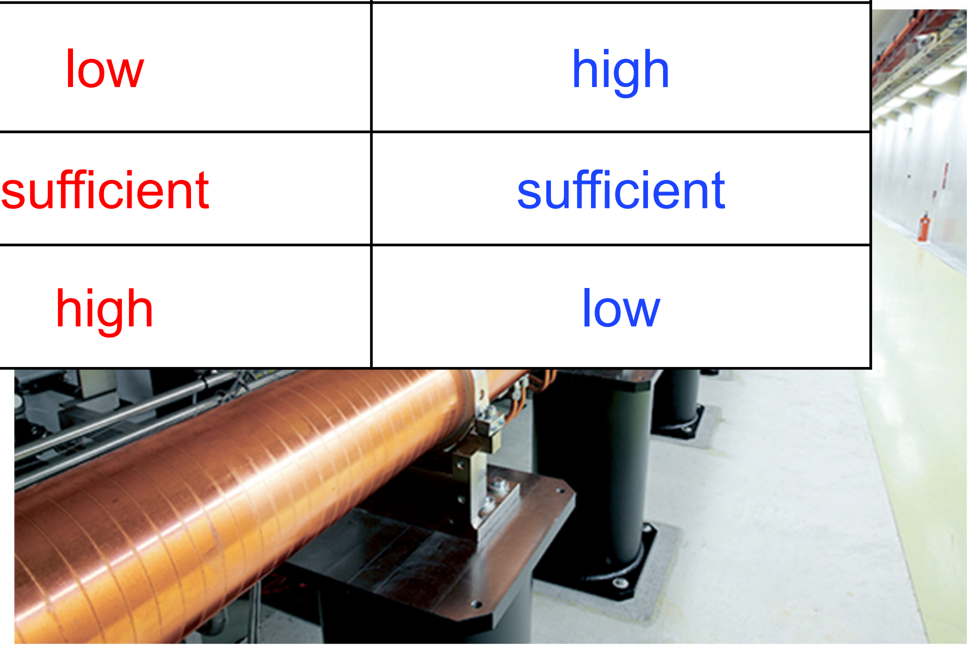
Simple comparison

	E-gun	Main RF	Max. energy (GeV)	Max. photon energy (keV)	Pulse energy@ 10keV(mJ /pulse)	Rep. rate (Hz)	Size (km)	BLs	Budget (M$)
LCLS	Cu photo RF	S-band	17	12.8	2	120	2.2	1	~615
SACLA	Thermionic	C-band	8	20	0.7	60	0.7	2+1	~380
PAL XFEL	Cu photo RF	S-band	11	14.5	2	60	1.1	1+1	~400
SwissFEL	CsTe2-Cu photo RF	C-band	6.2	12.4	0.74	100	0.72	1+1	~280

2. Warm vs. cold



	Warm	**Cold**
Repetition Rate	~100 Hz	~MHz
Construction & running Cost	low	high
FEL Quality	sufficient	sufficient
Technological maturity	high	low



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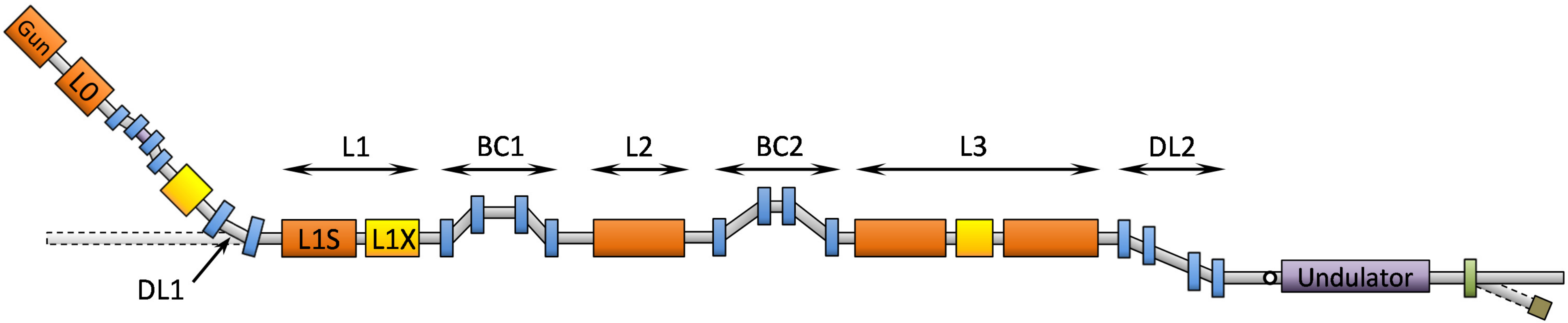
LCLS Accelerator and FEL Systems

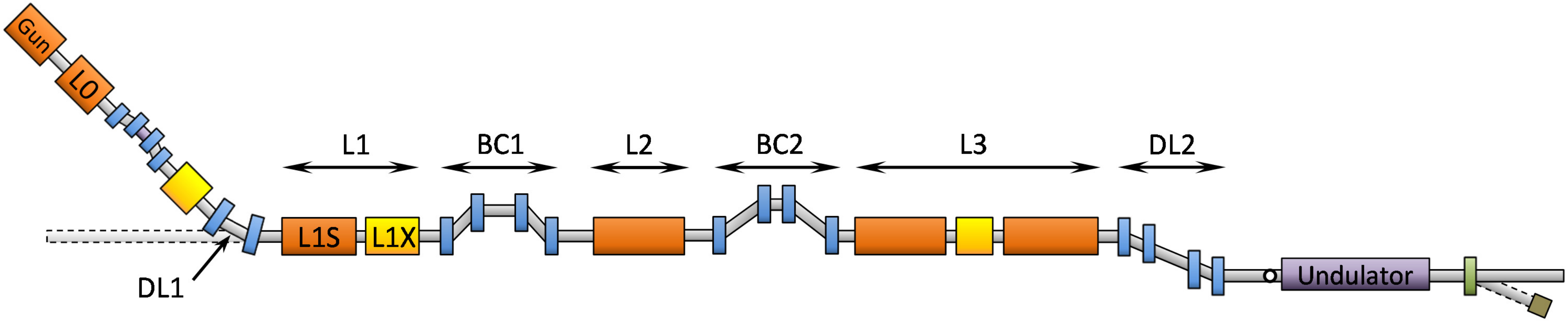
LCLS provided by Axel Brachmann



System	Parameters
LINAC	1 km , S-band, Normal Conducting
Electron beam energy	2.5 GeV → 17 GeV
Repetition rate	120 Hz
Bunch Charge	few pC → 1 nC; ~ 180 nC is standard
Bunch length	0.5 ~ 100 fs
Undulators	~ 100 m, K = 3.51, fixed gap
Photon Energy	250 eV → 12.8 keV
Photon Pulse Energy	up to 6 mJ
Photon Bandwidth	.1-.2 % for SASE, few eV or <1 eV for seeded beams

LCLS provided by Axel Brachmann

LCLS Accelerator and FEL Systems



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Full set of parameters at: https://lcls.slac.stanford.edu/parameters

Variety of Dual-Pulse & Dual-Energy Modes are now part of routine operation

LCLS provided by Axel Brachmann

HARD X-RAYS

Technique	Pulse Separation	Min Pulse Duration	Energy Separation	Max Energy/Pulse	Mode	Comments
Twin Bunches						Requires long setup (laser stacker/injector tune).
Two SASE Pulses	0 - 125 fs	~ 10 fs	0.2-3%	2 mJ (30 fs duration)	SASE	1st/probe pulse always higher photon energy
Twin bunches + V slotted foil	+/- 50 fs	~5-10 fs	~3%	50 uJ	SASE	
Twin bunches + HXR Self-Seeding	0-100 fs	~ 10 fs	~1 %	150 uJ per pulse	SEEDED	Both colors or a single color can be seeded. Requires longer setup time (hours).
Double Slotted Foil	7-20 fs	~ 10 fs	+/-1.5%	100-300 uJ	SASE	Minimally invasive, faster setup than twin bunches. Delay/energy separation not independent, minor tuning needed between changes.
Two bucket (ns spacing)	350 ps increments, +/- 38 ns	20 fs	~ 2%	1-2 mJ (40 fs duration SASE)	SASE SEEDED	Under development

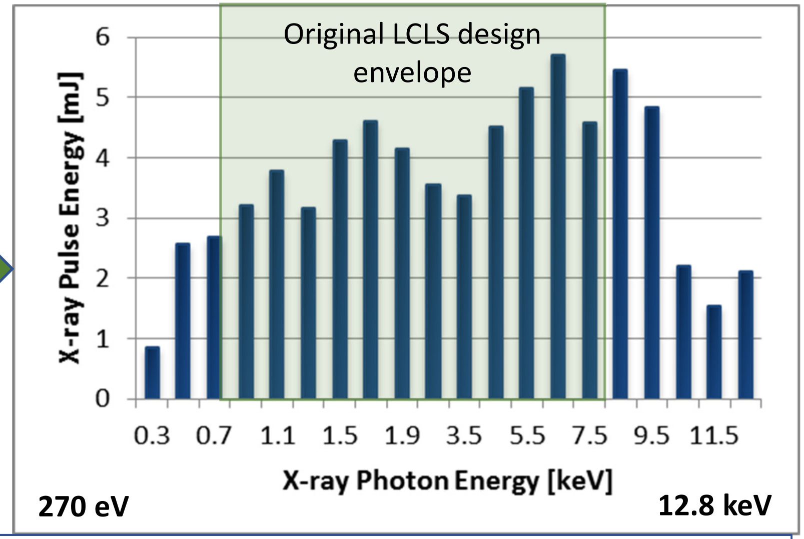
For detailed information and trade-off decisions, contact the Instrument Scientist!

Table is posted on LCLS FAQ page, Answer to Question 20
https://portal.slac.stanford.edu/sites/lcls_public/Lists/machine_faq/FAQ.aspx

Pulse Energy and Energy Reach

Routine pulse energy approximately **doubled** in last 3 years.

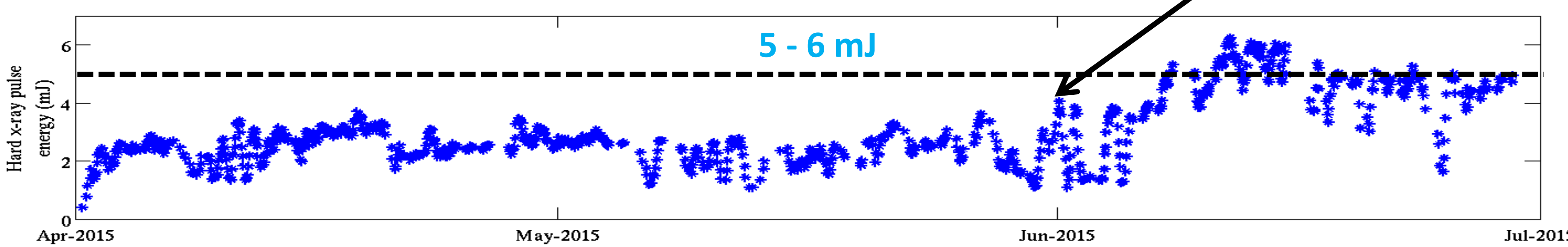
Many small improvements, with a step-function due to 'Horn-Cutting'



'Horn-Cutting' flat energy profile of electron bunch leads to improved matching of electron-bunch / lattice → improved beam transport and emittance preservation.

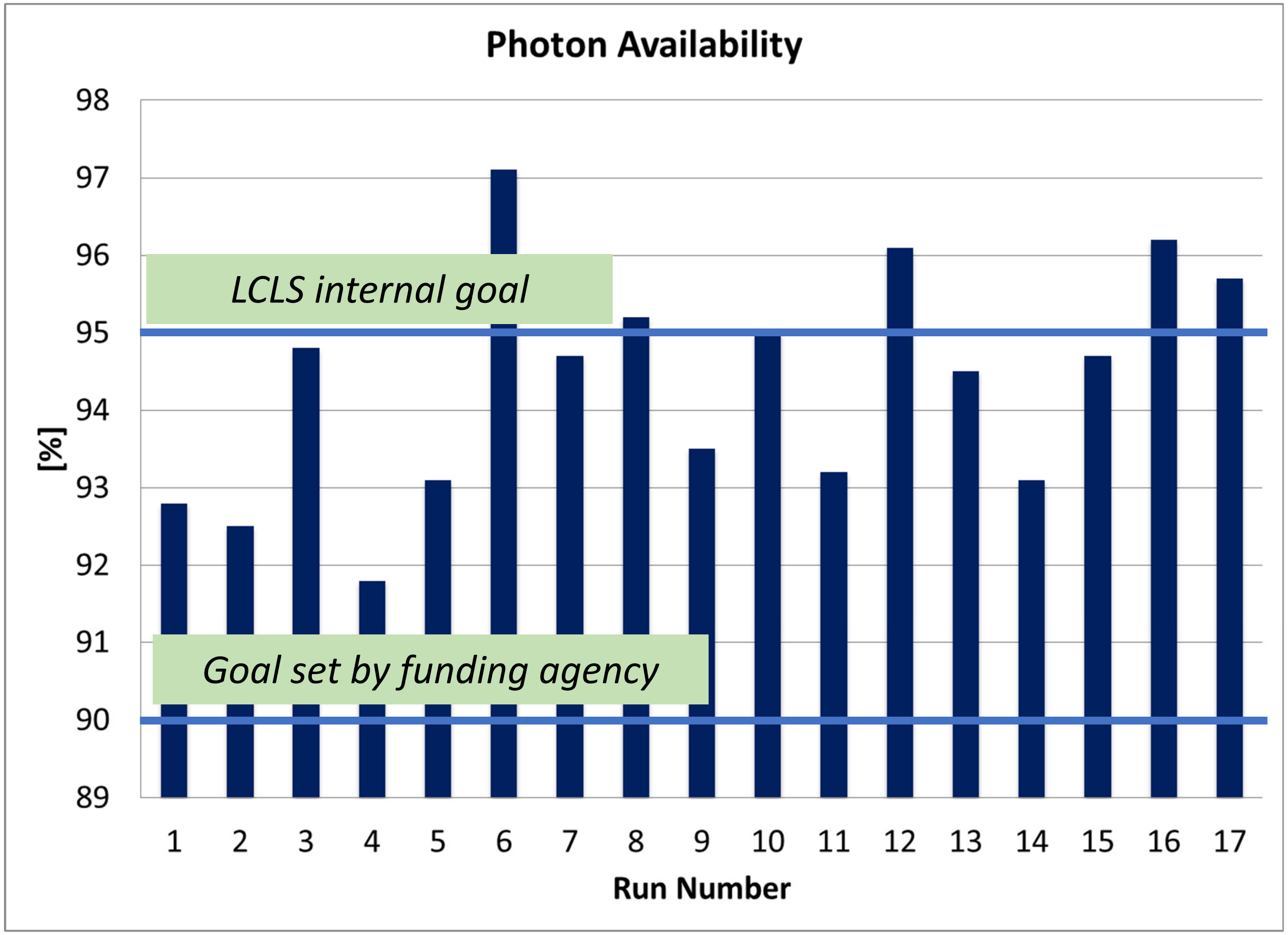
HXR gas detector history

Started collimation



History of LCLS Photon Beam Availability

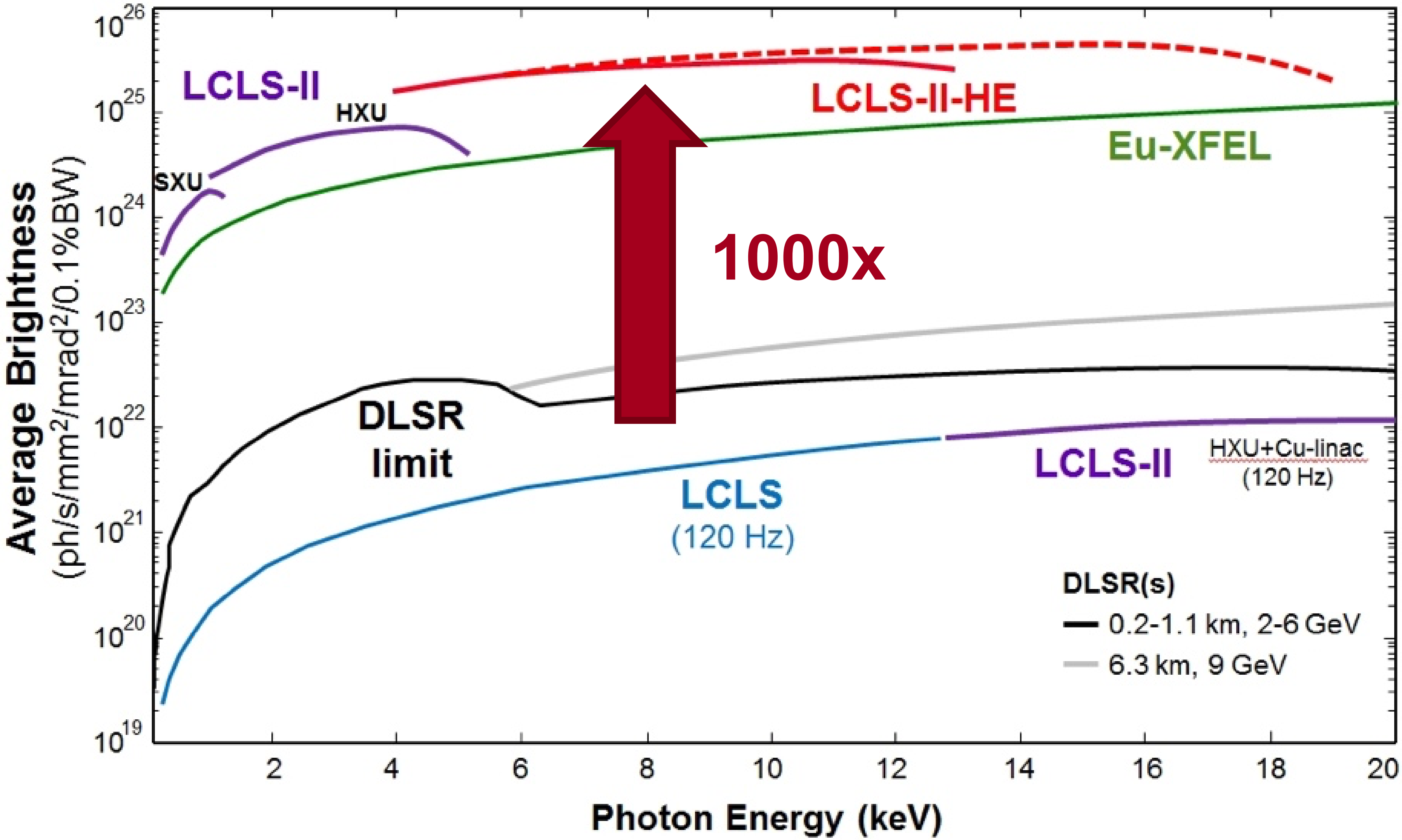
LCLS provided by Axel Brachmann



- Reported metric is photon beam availability at the transport shutter to x-ray instruments
- Electron availability typically ~ 1% higher
- ‘Mission Readiness’ program addressed obsolescence issues for the ~ 60 year old LCLS accelerator systems

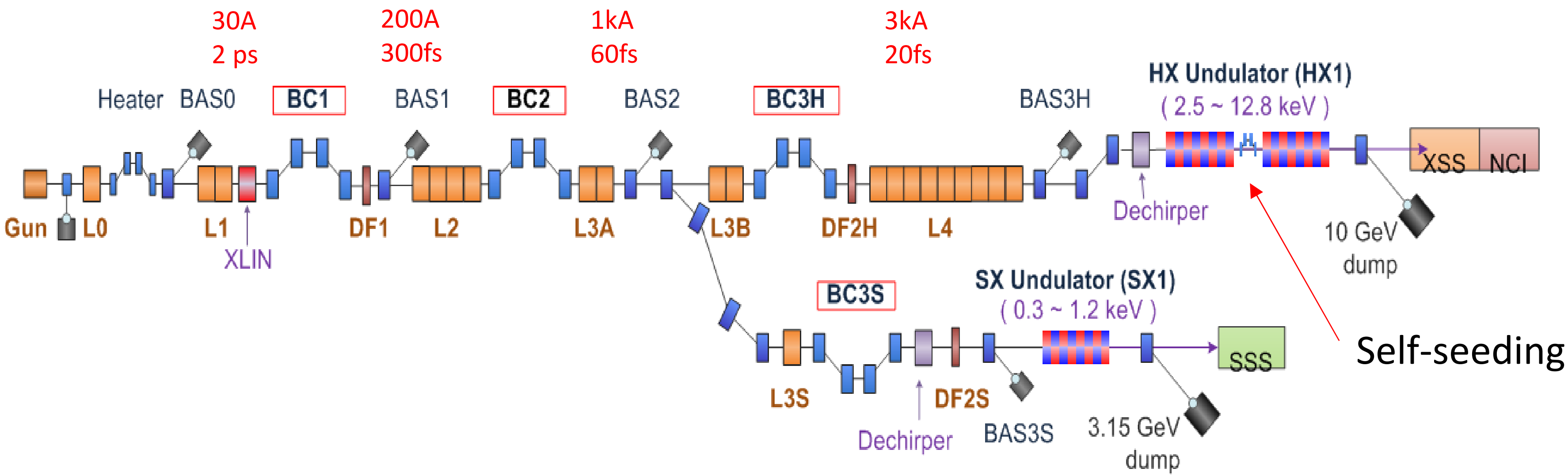
LCLS provided by
Axel Brachmann

Performance of LCLS FEL's



PAL-XFEL Parameters

PAL XFEL provided by H. S. Kang



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)

Undulator Line	HX1	SX1
Photon energy [keV]	2.0 ~ 14.5	0.25 ~ 1.25
Operation mode	SASE / self-seeding	SASE
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

Operation parameters

- Gun 33.7
- L1 -10.5
- X-linearizer -180.0
- L2 -19.6
- L3 -3.0
- L4 -2.0
- BC1 4.97° (-66.7 mm)
- BC2 3.3° (-46.9 mm)
- BC3 1.6° (-11.6 mm)

※ **3-BC improves FEL power stability and phase tolerance by reducing CSR.**

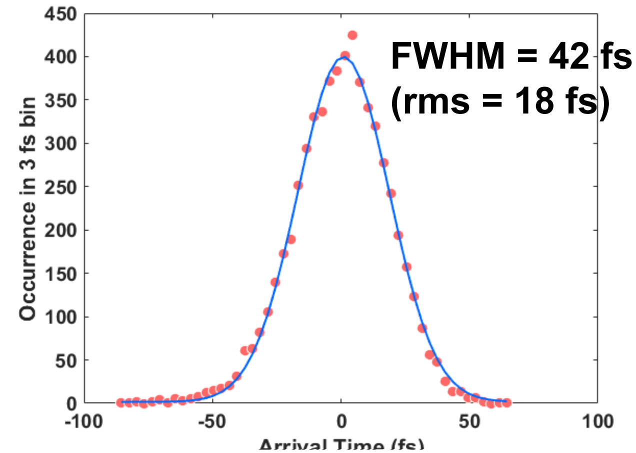
PAL-XFEL Machine Performance

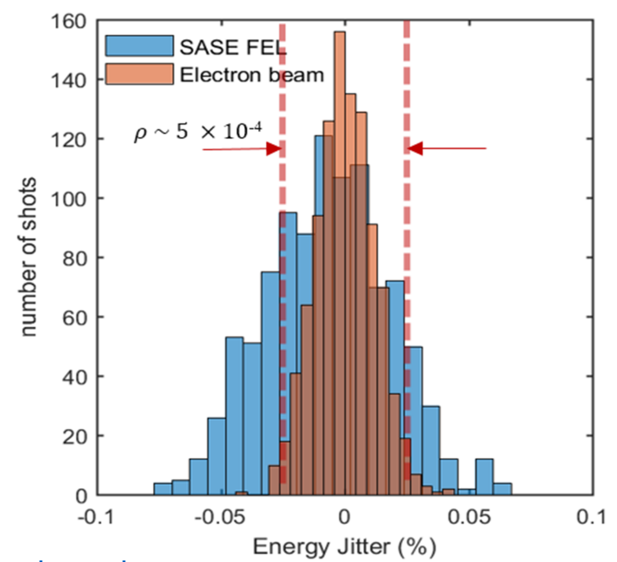
PAL XFEL provided by H. S. Kang

A highly stable FEL performance is achieved through both a FEL optimization and a high performance of the linac

- **A mJ-level XFEL intensity** is available for photon energies from 2.5 to 14.5 keV
- **Temporal stability: ~18 fs (rms)** between X-ray pulses and optical pulses from a synchronized laser system
  - **Electron beam arrival time jitter**: ~ **12 fs**
- **Relative electron beam energy jitter: < 1.5 x 10-4**
  - RF stability (rms)
    - L1 (w/o SLED) : **0.01 degrees / 0.01%**
    - L2, L3, & L4 (w/ SLED) : **0.015 degrees / 0.02%**
- FEL power stability < 5% RMS
- FEL position stability < 10% of beam size
- FEL central wavelength jitter 0.024 % (1/2 of SASE BW)
- FEL beam availability ~ 95%

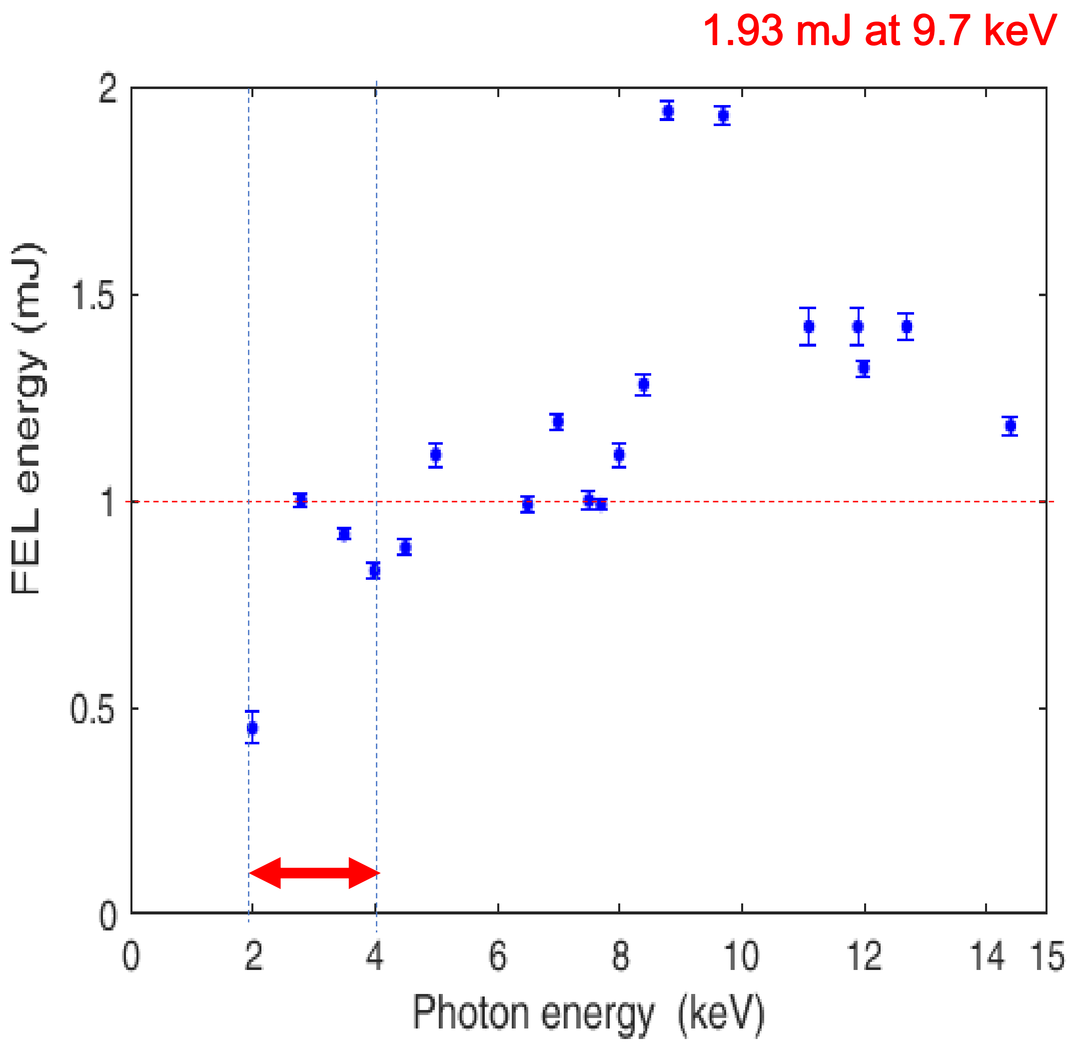
Arrival time Jitter Histogram (between Laser and XFEL at sample)



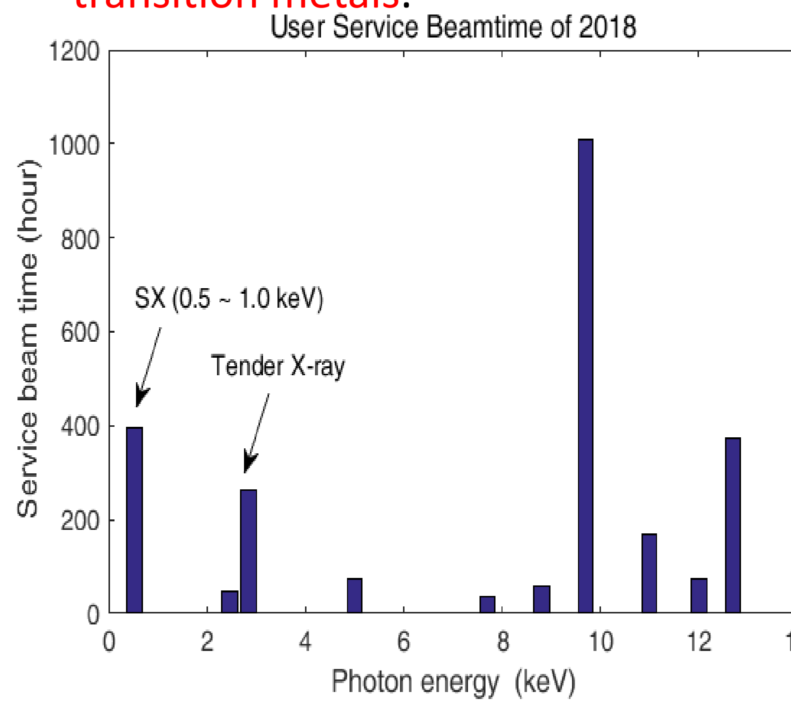


H.-S. Kang et al., FEL performance achieved at PAL-XFEL using a three-chicane bunch compression scheme, *J. Synchrotron Rad.* (2019). 26

X-ray FEL Intensity



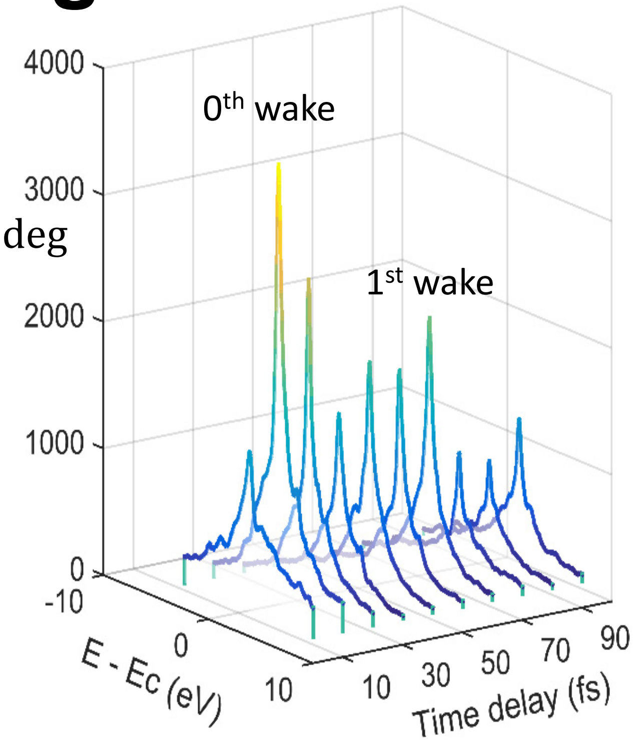
- Access to the tender X-ray range (2.0 ~ 4 keV) presently is only available at PAL-XFEL
- This regime allows access to the Ru L edge and the M edges of the 4d transition metals.

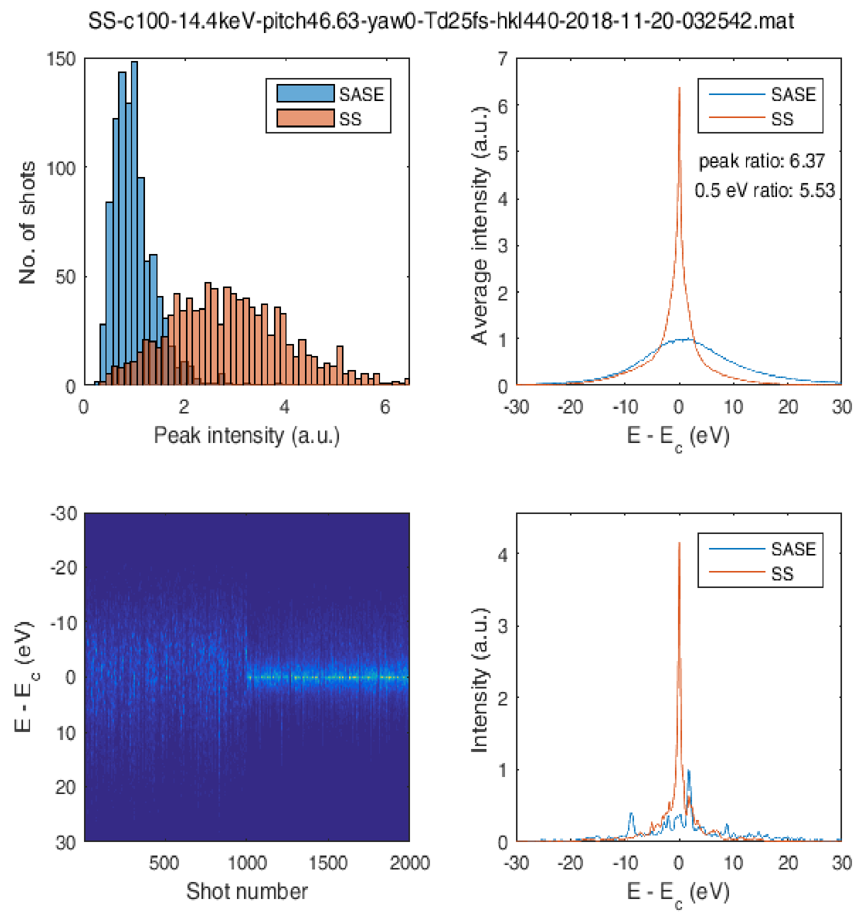


PAL XFEL provided by H. S. Kang

Self-seeding at 14.4 keV using 100 μm crystal

- Seeding conditions
  - $[hkl] = [440]$
  - Pitch angle = 46.63 deg
  - $\Lambda_H = 6.41$
  - $T_0 = 1.8716$ fs
  - $t_s \sim 50$ fs
  - $t_d \sim 30$ fs





- Time-delay: 25 fs (0th wake of FBD)
- Peak intensity ratio of SS and SASE: **6.37**
- A fraction of 1-eV BW over entire spectrum
  - SASE: 0.047, SS : 0.226
- FEL energy: ~400 μJ (seeded), ~1 mJ (SASE)
- BW reduction: ~ 35 times
  - SASE: 16.9 eV, SS: 0.49 eV

Future plan:
2-nd Hard X-ray FEL Line (HX2)

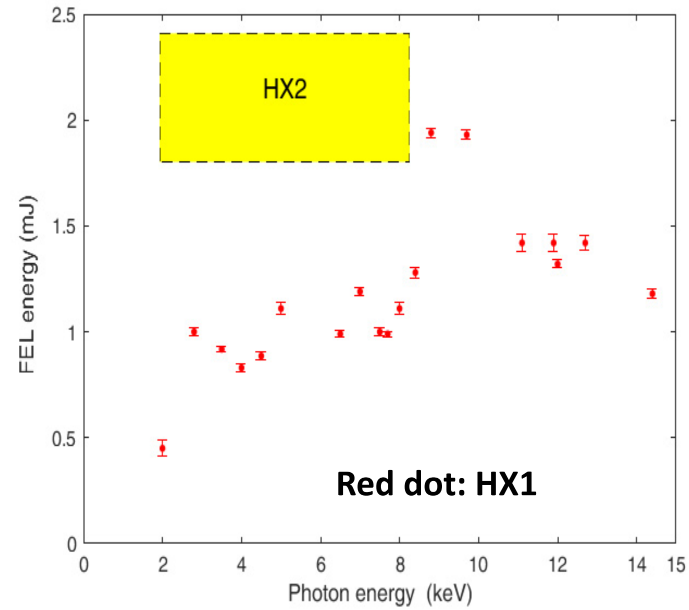
PAL XFEL provided by H. S. Kang

❖ To provide more beamtime to HX users

- Competition for HX beamtime is becoming very tough. (4: 1)
- A half of beamtime goes to foreigners
- Many complains come from Korean users.

❖ Design of the 2-nd HX FEL line (HX2) was started in 2018.

- Lattice design was finished
- A construction proposal was submitted to the committee
- A 3-year construction and a half-year commissioning: **No interruption of use service operation during the construction period**



❖ Baseline of 2-nd HX FEL line (HX2)

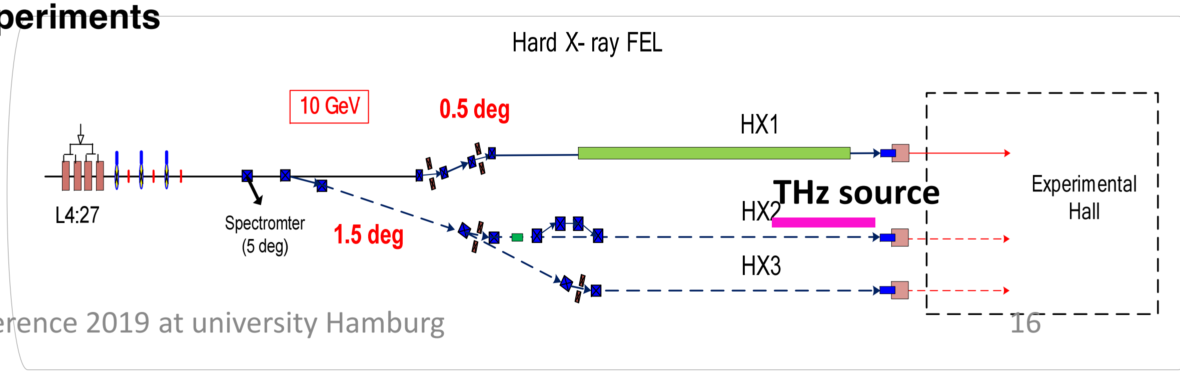
- Hard X-ray FEL line with 20 undulators (very similar to HX1)

  : Pulse-by-pulse simultaneous operation of HX1 & HX2

- **THz source for THz pump – XFEL probe experiments**
  - up to 20 THz, > 100 μJ
  - 30-MeV linac-based THz source:

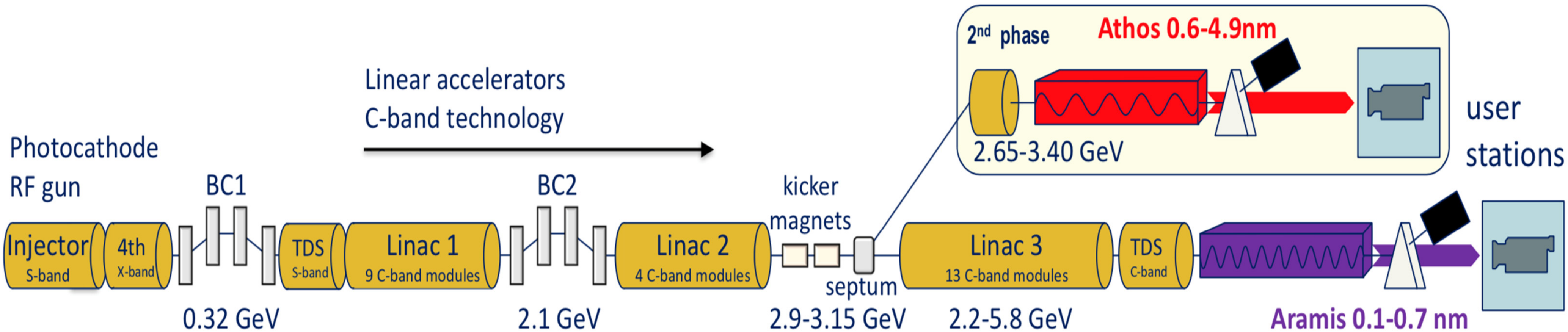
    a photo-cathode RF-gun,

    one S-band A/S, and one undulator



SwissFEL

SwissFEL provided by Löhl Florian



ARAMIS

- Hard X-ray FEL, λ = 0.1 nm – 0.7 nm
- Linear polarization, variable gap, in-vacuum UNDs
- First users fall 2017
- Operation modes: SASE

ATHOS

- Soft X-ray FEL, λ = 0.6 nm – 4.9 nm
- Variable polarization, Apple-X UNDs (2 m length)
- First users planned for 2020
- Operation modes: SASE & seeded & many more

SwissFEL main parameters

Wavelength range (nm)	0.1 – 4.9
Photon energy (keV)	0.25 – 12.4
Pulse duration (rms)	sub 1 fs – 40 fs
Nax. Electron energy (GeV)	5.8 GeV (6.2 GeV)
Electron bunch charge (pC)	10 – 200
Repetition rate	up to 100 Hz

SwissFEL provided by Löhl Florian

Key features of the SwissFEL accelerator

- **All design specifications met or exceeded**
- **Smallest emittance of all x-ray FELs** (see THB03)
- **Reliable use of solid-state klystron modulators in the entire accelerator**
- **Facility designed for low operating costs**
  Lowest power consumption of all hard x-ray facilities
  (1.7 MW total power @ 100 Hz for accelerator)
- **Simultaneous 100 Hz operation in two FEL lines**
  Acceleration of two bunches per RF pulse, 28 ns separated
  Use of fast kicker magnet for separation (see WEP038)
- **Successful use of 15 mm period, variable gap, in-vacuum undulators**

FEL parameters in Aramis hard x-ray beam line

SwissFEL provided by
Löhl Florian

- **Nominal photon energy of 12.4 keV reached in January 2019**
- **Maximum pulse energies:**

900 μJ @ 3.7 keV	780 μJ @ 7.2 keV
680 μJ @ 9 keV	550 μJ @ 12 keV

- **Pulse duration: typically 30-50 fs rms**
- **Sub-fs (rms) pulses demonstrated**
  - Large fraction of single spike shots
- **Large bandwidth mode demonstrated and used in first experiment**
  - Bandwidth of 3 % with up to 400 μJ of pulse energy
- **Several new operation modes under studies (e.g. two color, etc.)**
- **100 Hz operation demonstrated, user operation presently mainly 25 to 50 Hz due to bottlenecks in experiment DAQ system**

SwissFEL provided by
Löhl Florian

Outlook: Athos soft x-ray beam line

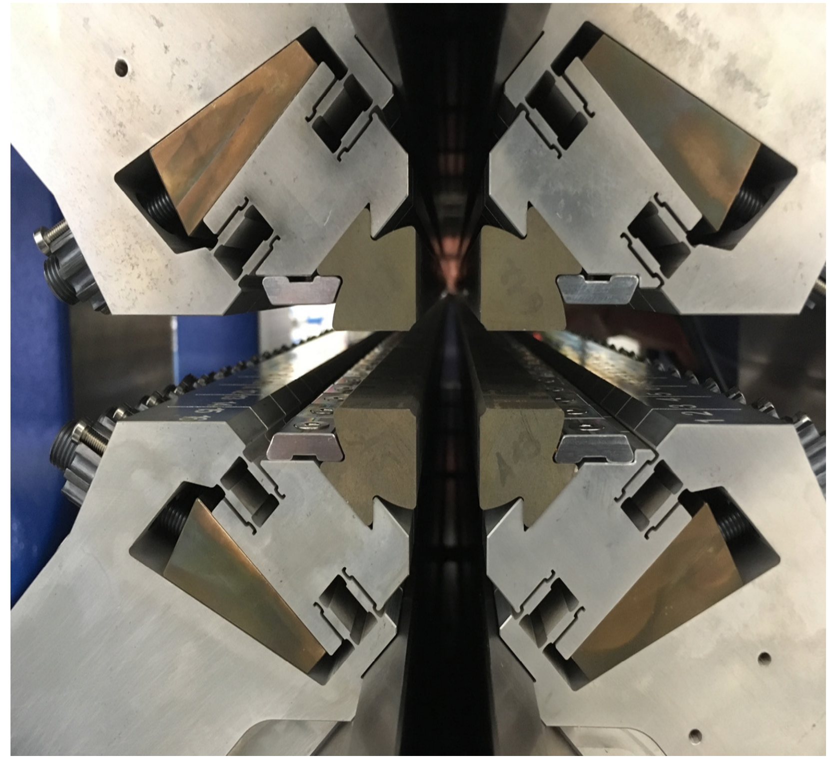
Main goal: parallel, independent operation of two FEL beam lines

- **Two pulse operation Aramis / Athos successfully demonstrated**
- **Currently finishing the installation of the Athos soft x-ray beam line**
- **First beam transport scheduled for December 2019**
  FEL commissioning for 2020
- **Collaboration with CERN and DESY on post-undulator x-band deflector for longitudinal phase space diagnostics with sub-fs resolution**
- **First FEL using Apple-X undulators and distributed delay chicanes**
  Full control of polarization, K, and K-gradient
  Enabling many new FEL schemes

SwissFEL provided by Löhl Florian

Aramis and Athos accelerator lines

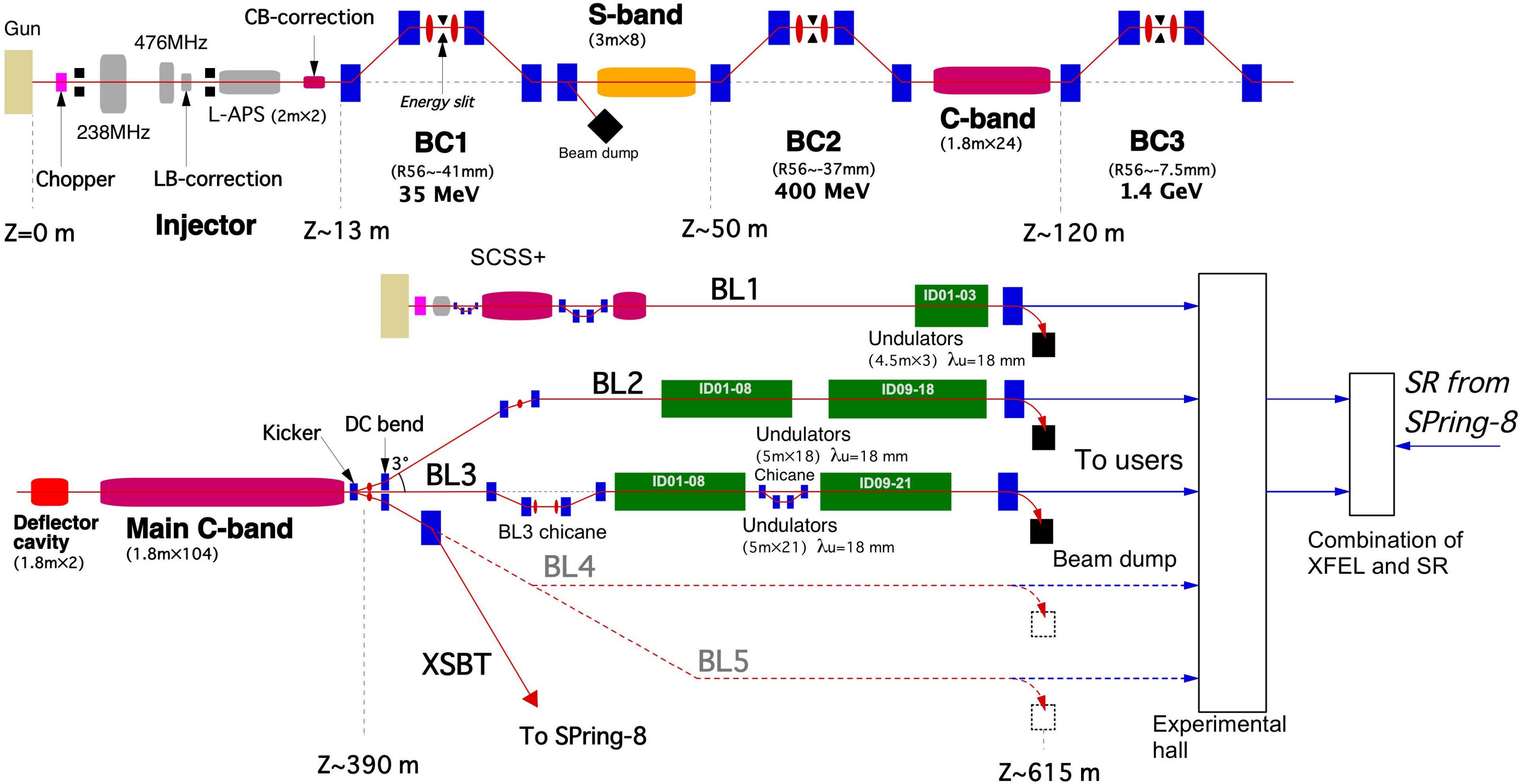
New Apple-X undulator



SACLA

SACLA provided by Toru Hara

(SPring-8 Angstrom Compact free-electron LAser)



BL1: EUV and soft x-ray (20-150 eV)
BL2 and BL3: hard x-ray (4-20 keV)

SACLA provided by Toru Hara

2017/11/29	SACLA Operation Status

Operation Mode	
BL1 Study	
Hutch in Use	
BL1 EH4a	
Pulse Energy	Photon Energy / Wavelength
72.2 micro J/pulse	122.3 eV / 10.1 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
60 Hz	19.2 %

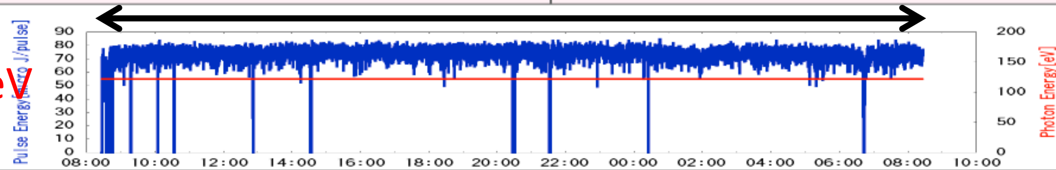
BL1

40-150 eV

~100 uJ/pls@100 eV

60 Hz

24 hours



2017/11/29	SACLA Operation Status	08:25:40

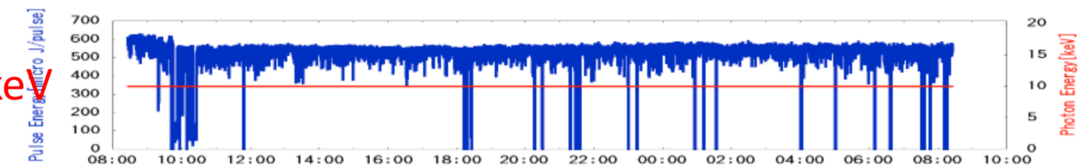
Operation Mode	
BL2 User Operation	
Hutch in Use	
BL2 EH3,4b	
Pulse Energy	Photon Energy / Wavelength
568.3 micro J/pulse	10.0 keV / 0.124 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
30 Hz	7.6 %

BL2

4-15 keV

~ 0.5 mJ/pls@10 keV

30 Hz (60 Hz max)

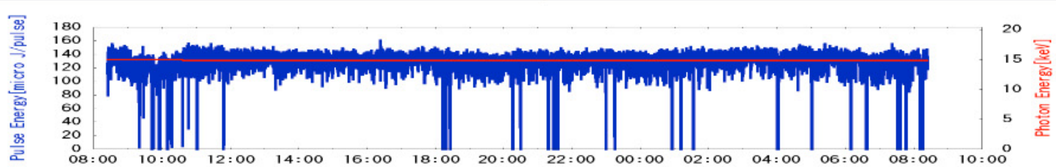


[BL1] [BL2] [BL3]

2017/11/29	SACLA Operation Status	08:24:30

Operation Mode	
BL3 User Operation	
Hutch in Use	
BL3 EH4	
Pulse Energy	Photon Energy / Wavelength
133.5 micro J/pulse	14.9 keV / 0.083 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
30 Hz	17.0 %

BL3



SACLA provided by
Toru Hara

Multi-beamline (standard) operation

BL1 soft x-ray FEL	
Beam energy	800 MeV max.
Bunch charge	0.2-0.3 nC
Peak current	0.3 kA
Bunch length	< 1 ps (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.1
Number of undulators	4.5 m x 3
Photon energy	20-150 eV
FEL pulse energy	0.1 mJ at 100 eV

BL1 is driven by SCSS+ accelerator.

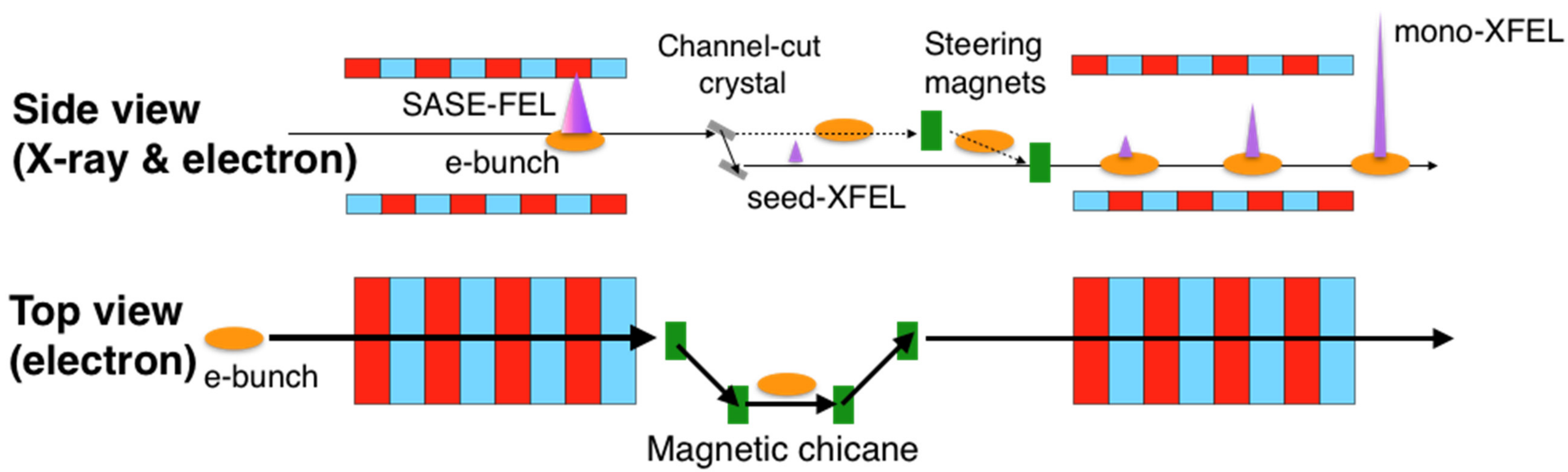
BL2 and BL3 XFEL	
Beam energy	8.5 GeV max.
Bunch charge	0.2-0.3 nC
Peak current	> 10 kA
Bunch length	< 20 fs (FWHM)
Repetition	60 Hz
Undulator period	18 mm
Undulator K value	< 2.6
Number of undulators	5 m x 18 (BL2) 5 m x 21 (BL3)
Photon energy	4-20 keV
FEL pulse energy	0.6 mJ at 10 keV

BL2 and BL3 share the electron beam of SACLA main accelerator.
For XSBT, 8 GeV-1 ps beam is used.

SACLA provided by Toru Hara

Variety of operations released to experiments

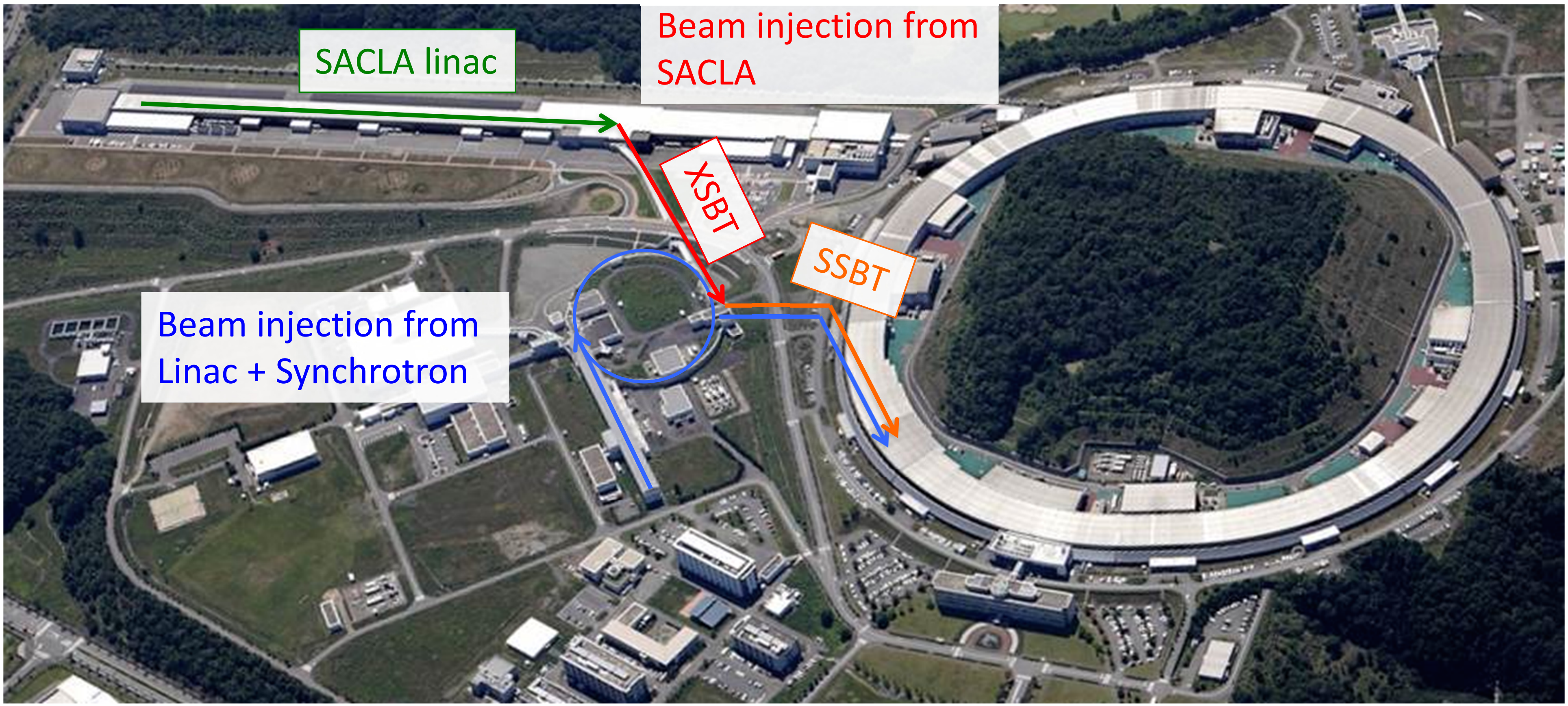
- SASE with a short duration of less than 10 fs in FWHM
- Seeded XFEL with a narrow spectral bandwidth of a few eV
- Double XFEL pulses with SDO (split-delay optics)
- Two color SASE
- Two color with a seeded XFEL and SASE
- Micro SASE beams of 0.1 um, 1 um and 10 um
- Pump & probe with a fs time resolution



Beam injection to SPring-8 storage ring

SACLA provided by Toru Hara

- SACLA will replace the current injector of SPring-8.
- Long electron bunches are used to avoid CSR effects.
- Beam injection while keeping XFEL operation is the next step.



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A strong point of cold XFELs is its high repetition rate reaching a MHz regime.

Here, we introduce the feasibility to achieve a high repetition rate of a few kHz using warm technologies.

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Here, we introduce the feasibility to achieve a high repetition rate of a few kHz using warm technologies.

We have two approaches, “cryogenic” and “DAA (dielectric assist accelerating) structure”.

Nuclear Inst. and Methods in Physics Research, A 866 (2017) 40–47

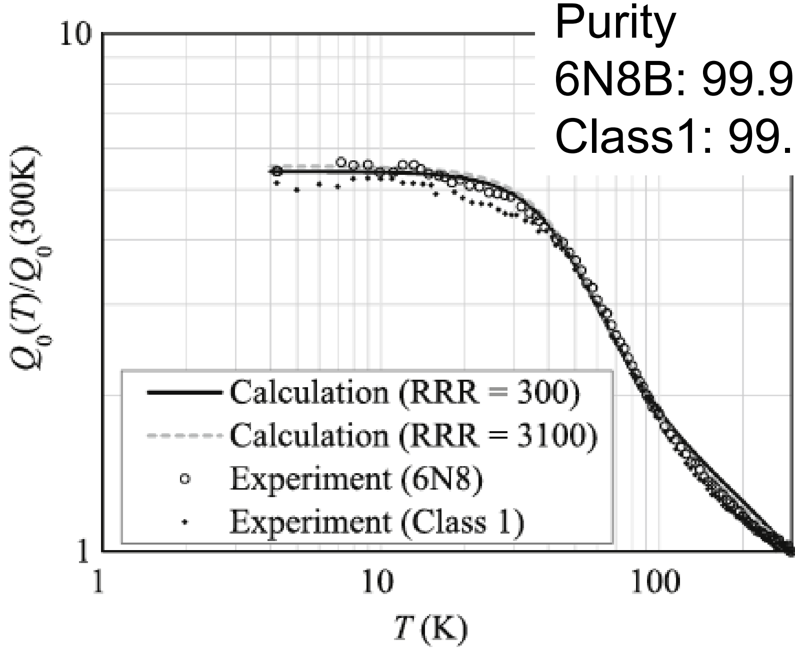
Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Development of low-loss cryo-accelerating structure with high-purity copper

Akihiro Iino [a,*], Seiya Yamaguchi [a,b], Takakazu Shintomi [b], Toshiyasu Higo [a,b], Yoshisato Funahashi [b], Shuji Matsumoto [a,b], Shinichiro Michizono [a,b], Kenji Ueno [b], Katsumi Endo [c]



Purity
6N8B: 99.99998%
Class1: 99.99%

RRR (Residual Resistivity Ratio) defined by

$$\frac{\rho(300K)}{\rho(4K)}$$

Q_0(20 K)/Q_0(300 K) ~ 5.3 for C-band structure having an RRR of 500 or above under low power conditions

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 011302 (2016)

(DAA)

Dielectric assist accelerating structure

D. Satoh,[1,*] M. Yoshida,[2] and N. Hayashizaki[3]

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[2]*High Energy Accelerator Research Organization KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

[3]*Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Meguro, Tokyo 152-8550, Japan*

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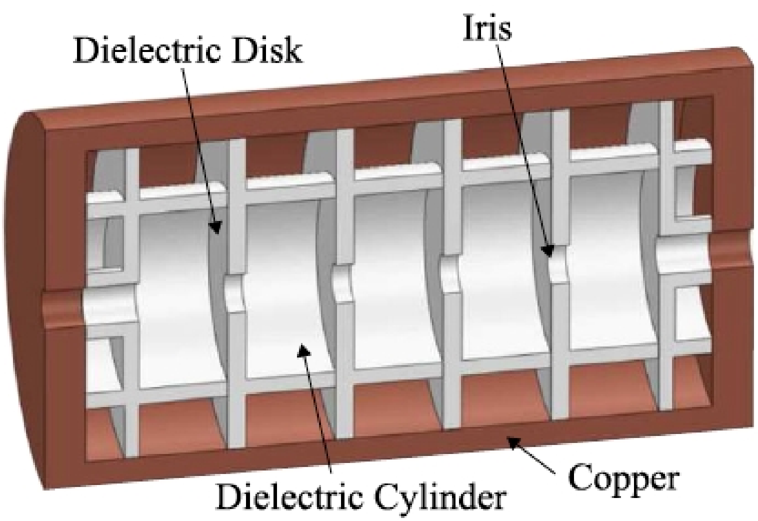
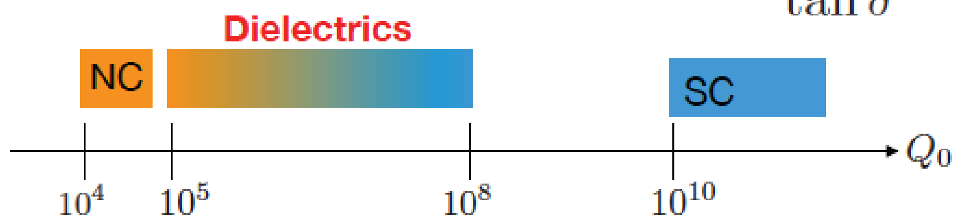


Ex) sapphire has low-loss tangent:

$$\tan\delta < 10^{-8} (@T < 50K) \quad Q_0 \sim \frac{1}{\tan\delta} \sim 10^8$$



DAA has a potential of high Q enabling a high repetition rate of ~ kHz.

5. Summary

Warm XFELs have been operated very well as user facilities and met the users demands by providing high performance XFELs.

By using warm XFELs, various operation modes such as “two color SASE”, “seeded XFEL with a narrow spectral bandwidth”, “Short pulsed XFEL”, etc. have been well developed and may give a good basis for the upgrade of cold XFEL operations.

Warm XFEL’s week point is a lower repetition rate compared with that of a cold XFEL. However, new approaches are expected to open the door to a higher repetition rate with a warm XFEL.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Thank you for your attention!