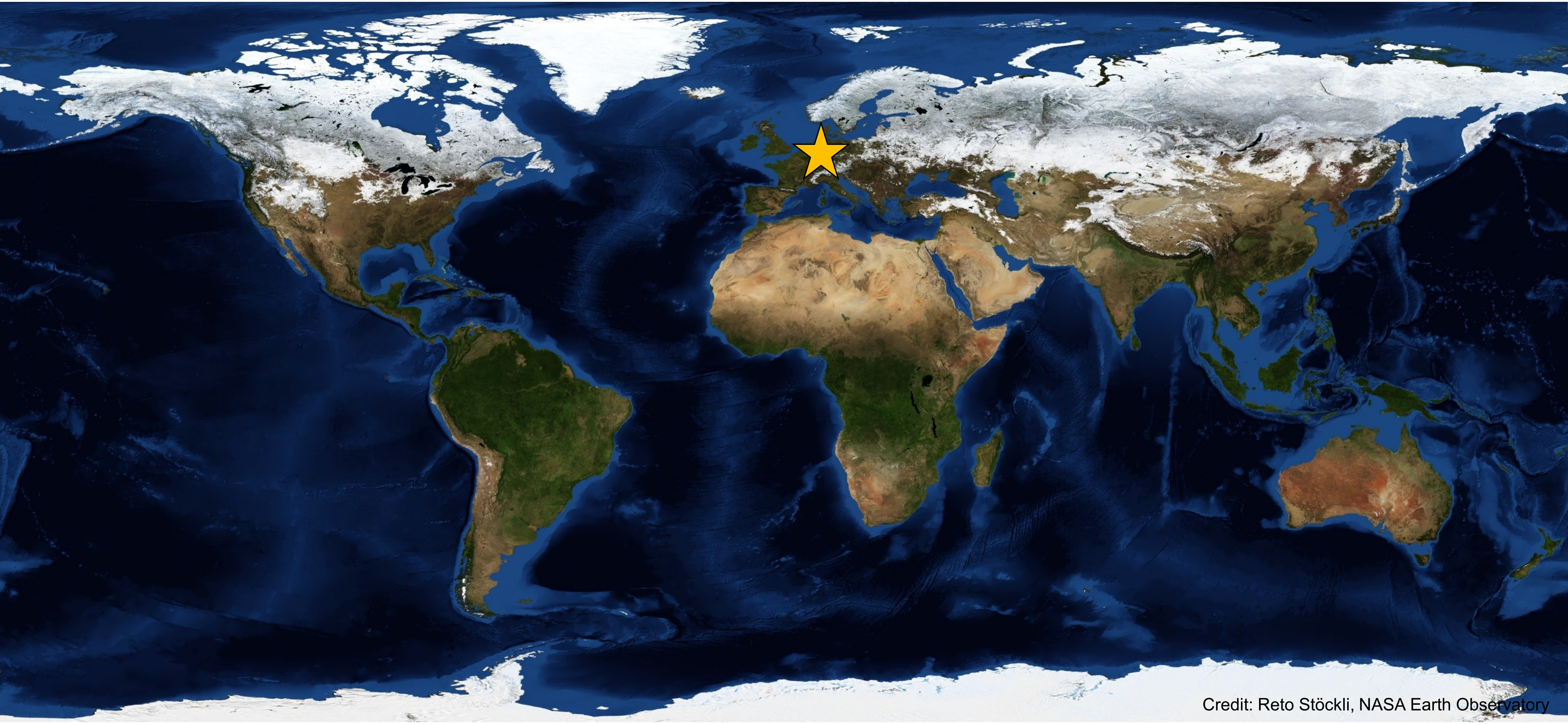
Latest Developments in X-Ray FELS* and Future Perspectives

Winni Decking, DESY, Hamburg, Germany

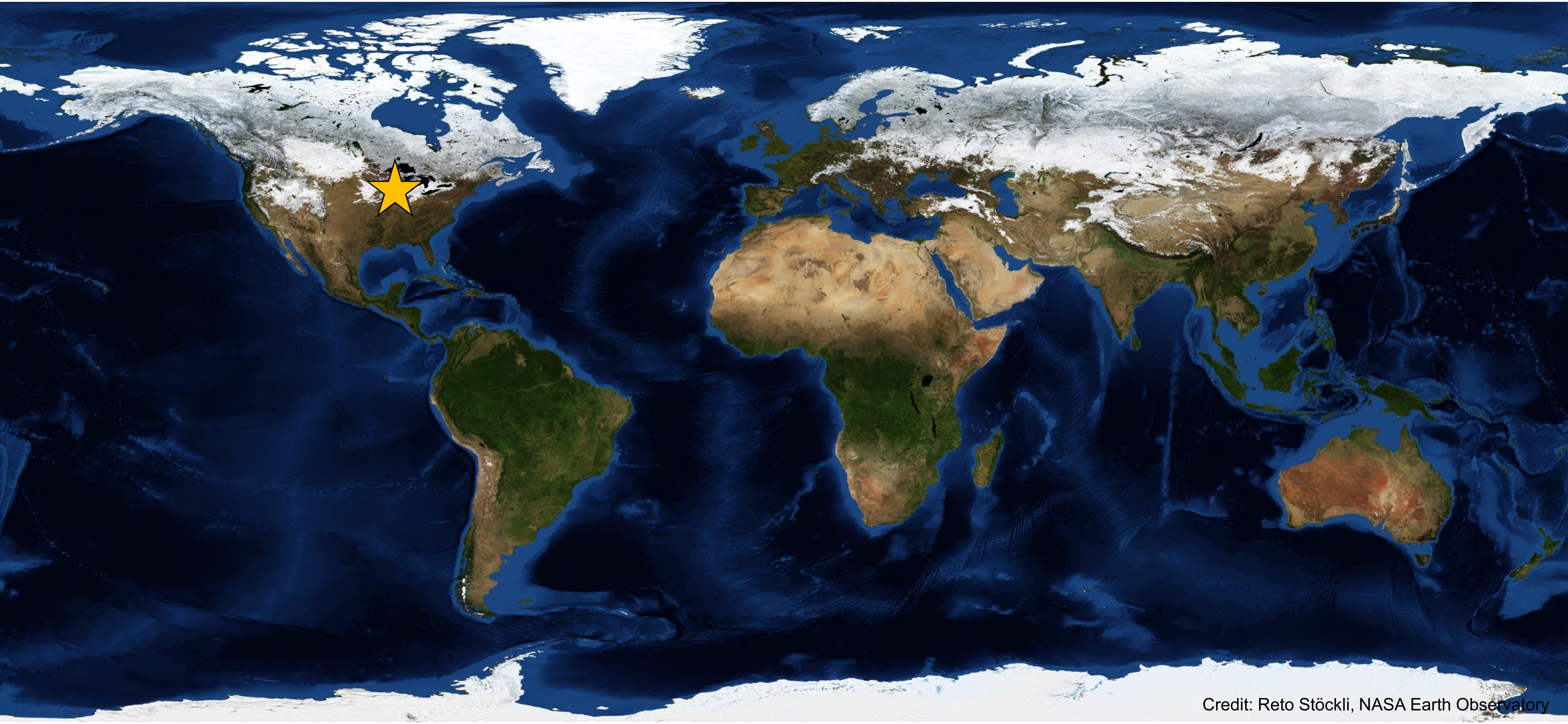
* X-Ray FEL: > 100 eV / < 10 nm

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

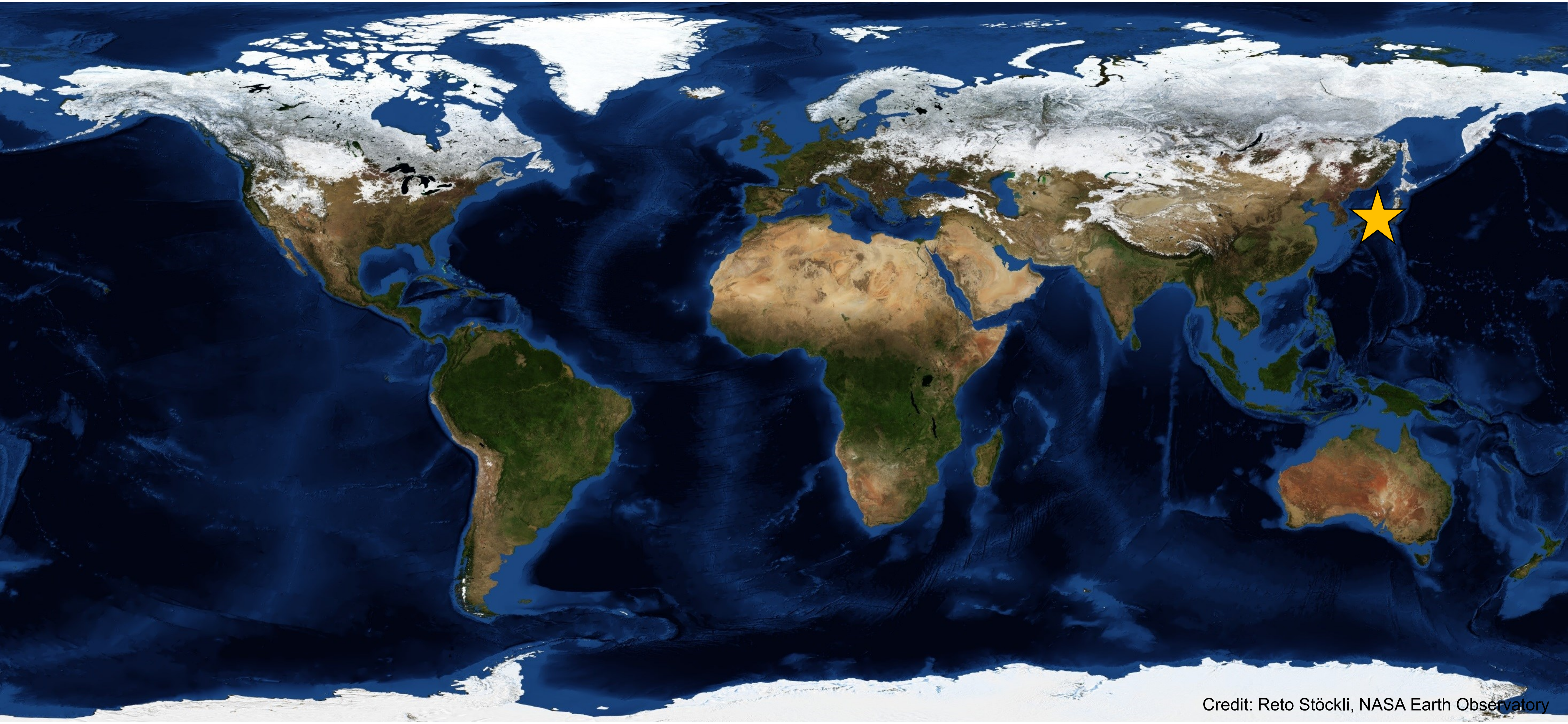
X-Ray FELs around the world – FLS1996



X-Ray FELs around the world – FLS1999



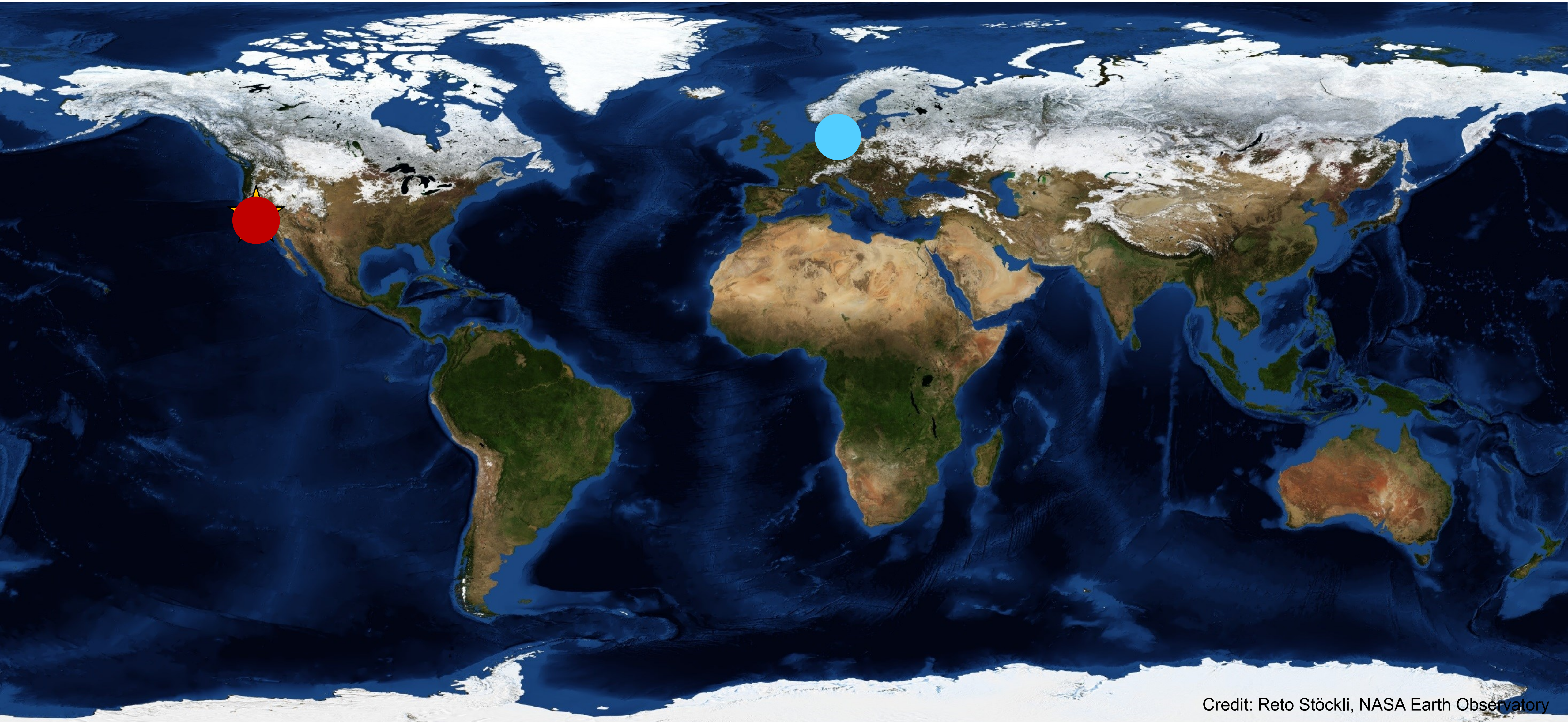
X-Ray FELs around the world – FLS2002



X-Ray FELs around the world – FLS2006

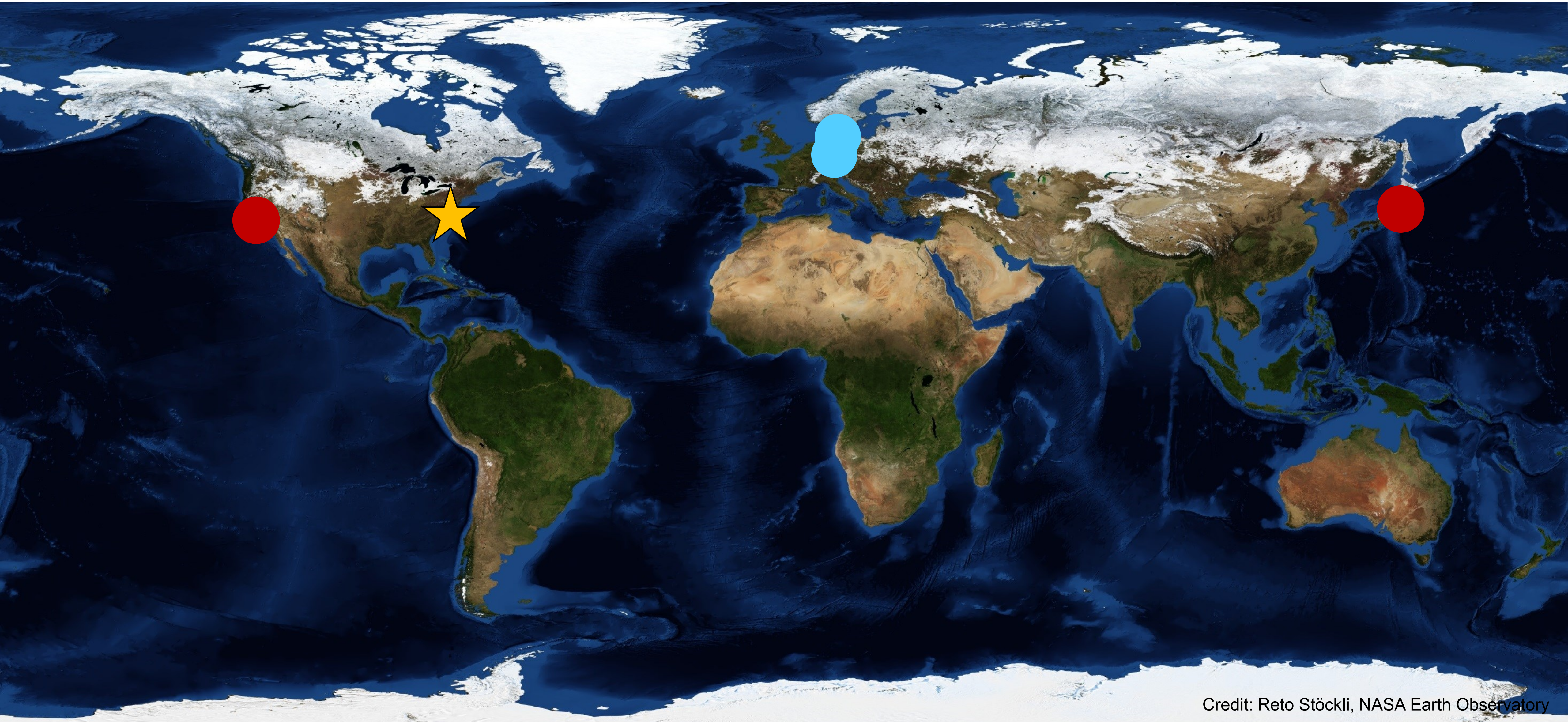
Credit: Reto Stöckli, NASA Earth Observatory

X-Ray FELs around the world – FLS2010

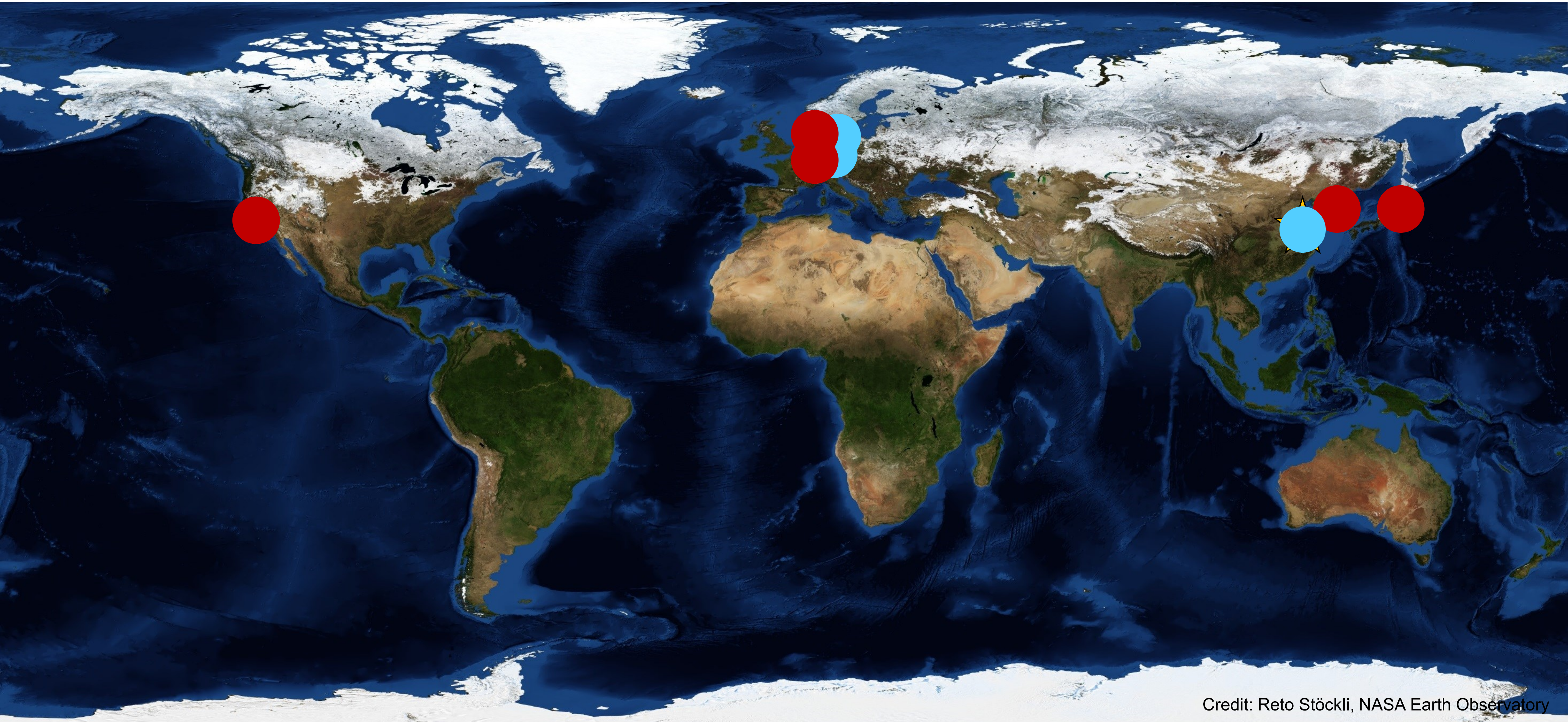


Credit: Reto Stöckli, NASA Earth Observatory

X-Ray FELs around the world – FLS2012

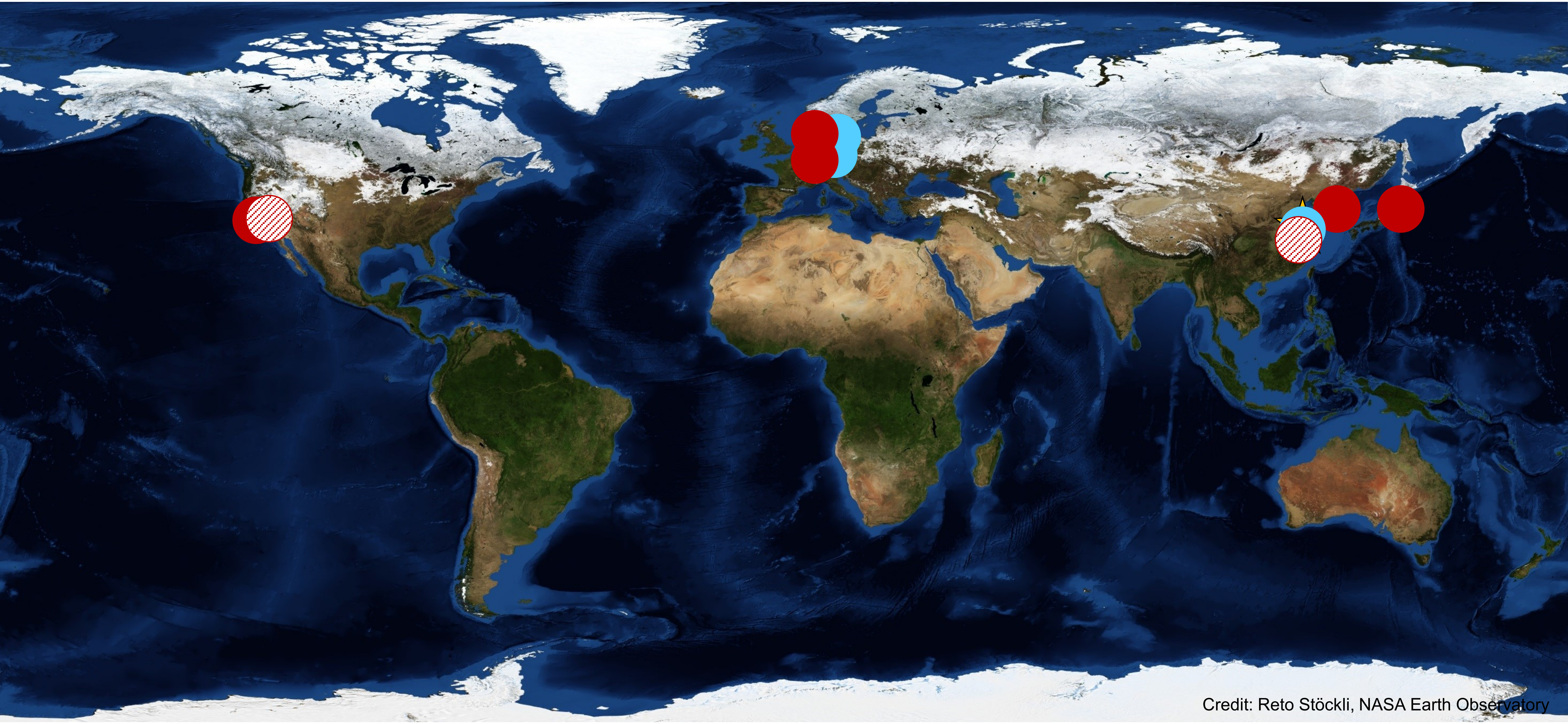


X-Ray FELs around the world – FLS2018



Credit: Reto Stöckli, NASA Earth Observatory

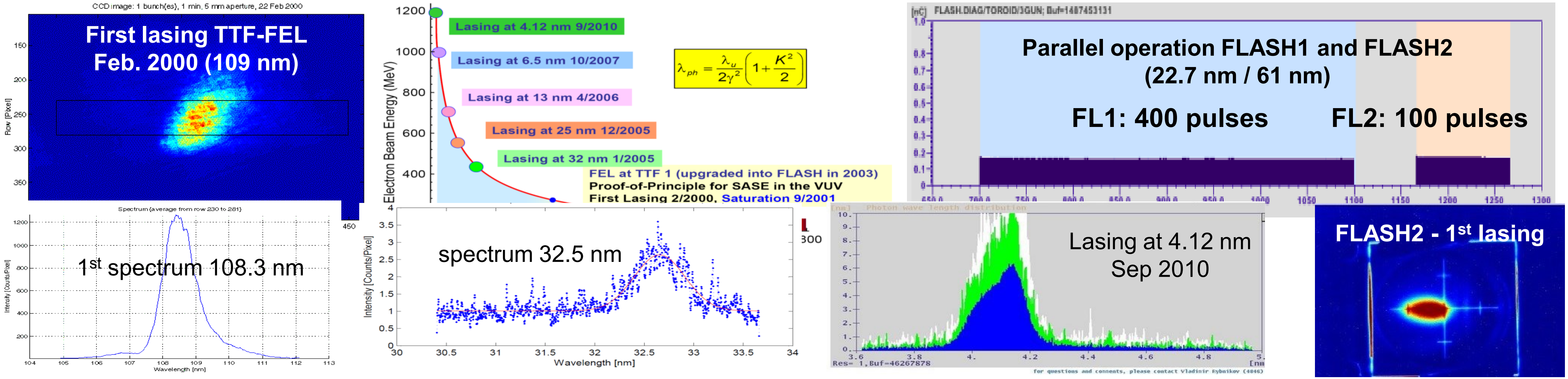
X-Ray FELs around the world – FLS202?



FLASH, DESY, Hamburg

- 1.2 GeV superconducting pulsed linac
- FLASH1: fixed gap undulator, 90 – 4 nm
- FLASH2: variable gap undulator, 90 – 4 nm
- 7 end-stations

FLASH: the pioneering soft x-ray SASE FEL



First lasing TTF-FEL
Feb. 2000 (109 nm)

First lasing FLASH
Jan 2005 (32 nm)

Lasing at 4.12 nm
Sep 2010

First lasing FLASH2
First parallel operation
Aug 2014

First parallel
User operation
Apr 2016

1995 | 2000 | 2005 | 2010 | 2015 | 2020

Construction and operation TESLA Test Facility Linac (TTF)

Undulator installation

Operation TTF-FEL

Construction and commissioning FLASH

Upgrade to 1 GeV

Upgrade to 1.25 GeV

User operation FLASH1

Construction and commissioning FLASH2

User operation FLASH2

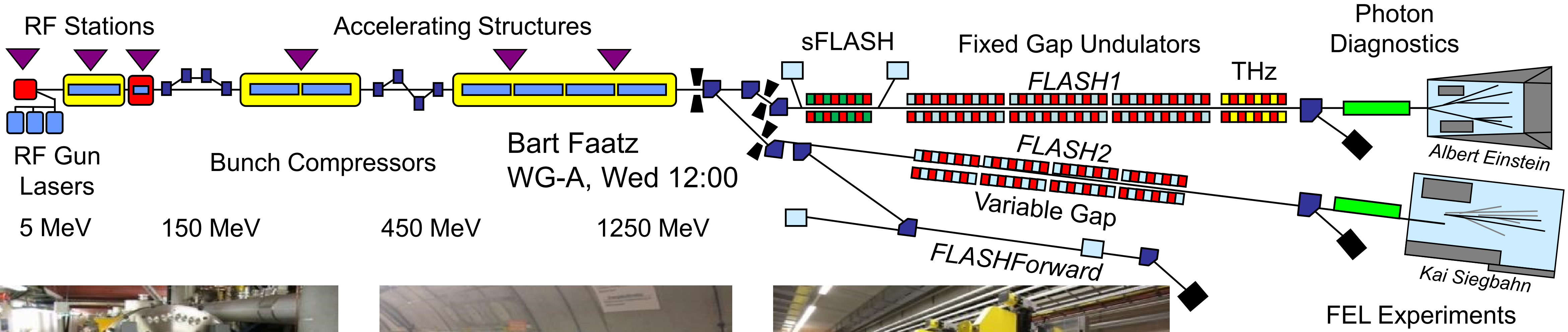
FLASH Layout 2017

3rd harmonic sc module 3.9 GHz

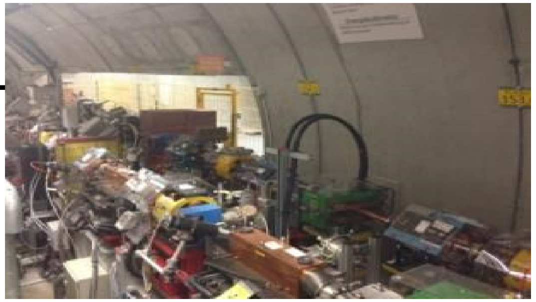
TESLA type superconducting accelerating modules 1.3 GHz

FLASH1 fixed gap undulators

FLASH1 Albert Einstein Hall



Normal conducting 1.3 GHz RF gun
Ce_2Te cathode / 3 injector lasers



Extraction to FLASH2

31

FLASH2 variable gap undulators

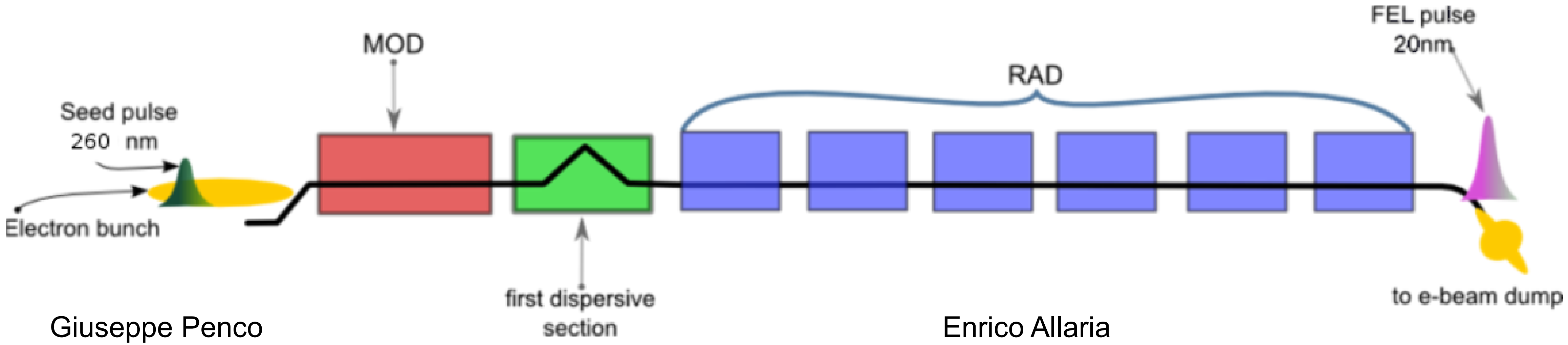
FLASH2 Kai Siegbahn Hall

Evgeny Schneidmiller
WG-A, Tue 17:00

FERMI, Elettra, Trieste

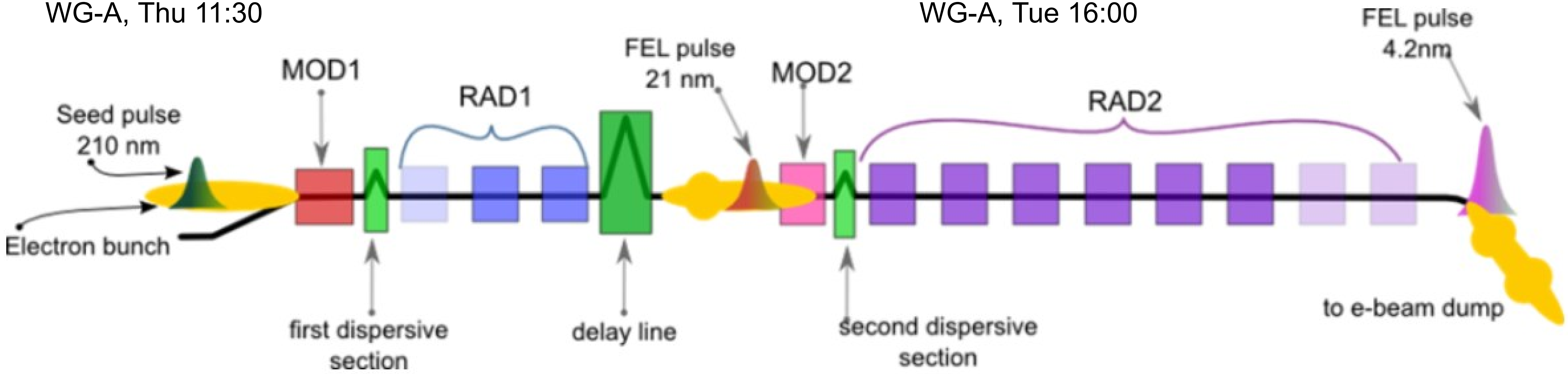
- 1.45 GeV S-band linac
- FEL1: single stage HGHG, APPLE undulators, 20 nm
- FEL2: 2-stage HGHG, APPLE undulators, 4 nm
- 5 (?) end-stations

FERMI: the pioneering seeding FEL



Giuseppe Penco
WG-A, Thu 11:30

Enrico Allaria
WG-A, Tue 16:00



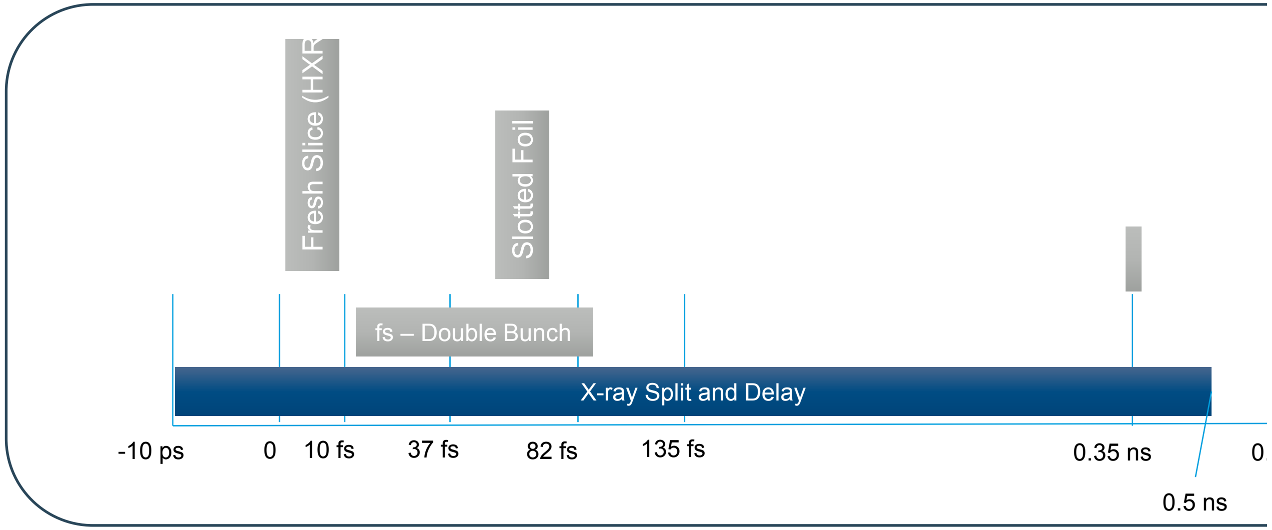
LCLS, SLAC, Palo Alto

- 14 GeV S-band linac
- XU: fixed gap undulator, 0.28 – 12.8 keV
- 7 end-stations

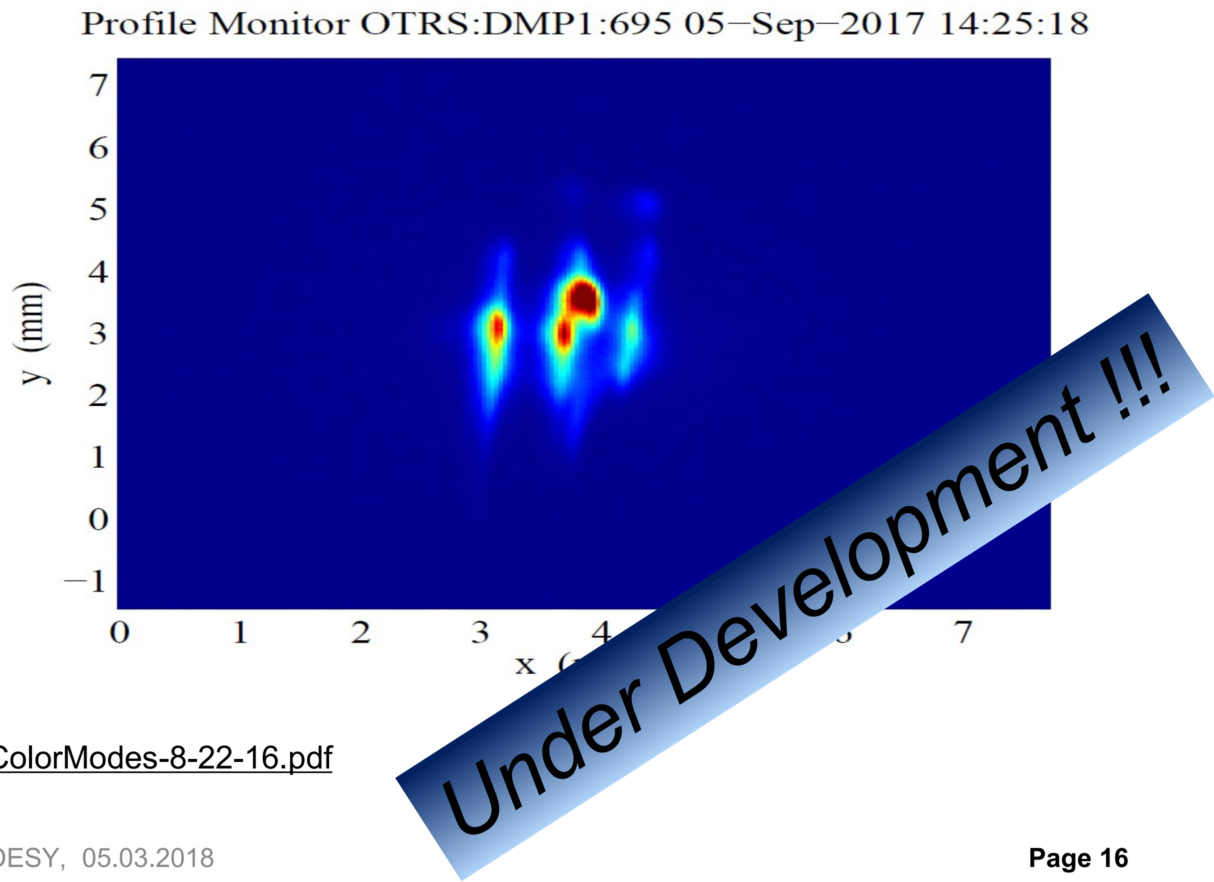
Accelerator based Dual-Pulse / Dual-Color Modes

- Double Slotted Foil
- Split Undulator
- Injector laser pulse splitting
- Multiple laser pulses at cathode (dual lasers)
- Fresh Slice Technique

Working on 2 .. 16 pulses now
→ Laser pulse splitting techniques



XTCAV image of 4 bunches lasing



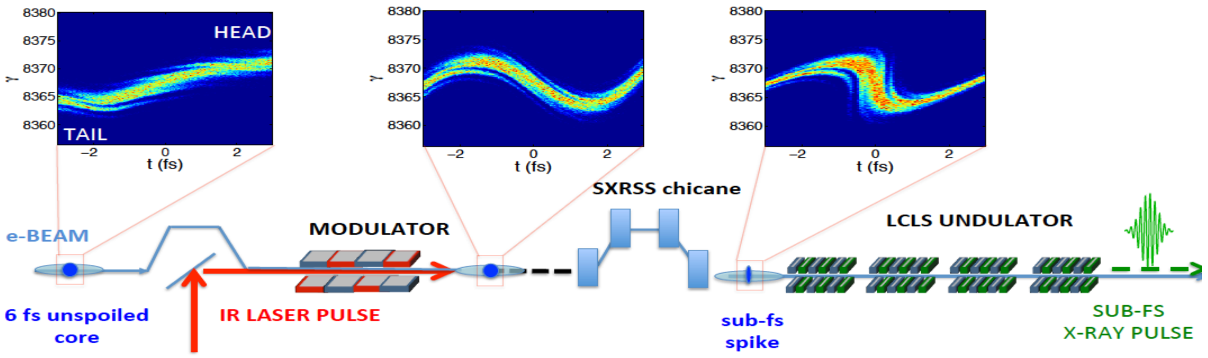
LCLS Machine FAQ: https://portal.slac.stanford.edu/sites/lcls_public/machinefaqpix/MultiColorModes-8-22-16.pdf

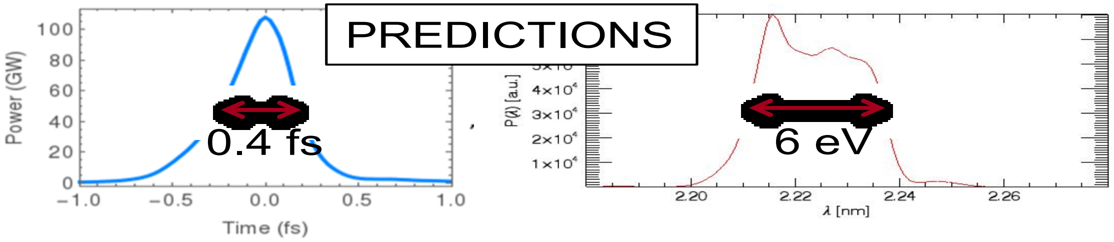
SLAC NATIONAL ACCELERATOR LABORATORY courtesy Axel Brachmann

Update

Progress (and published results!) in sub-femtosecond pulse generation

XLEAP - soft X-ray tests underway

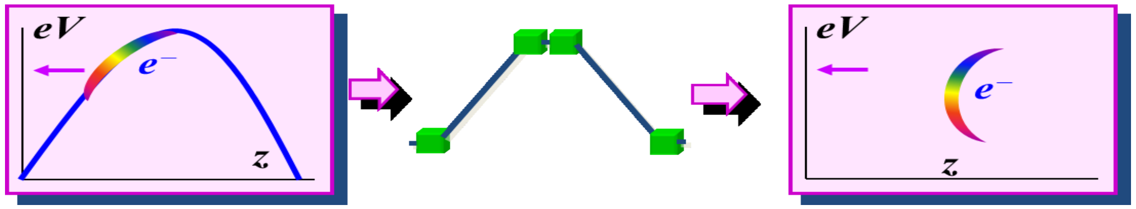




< 0.5 fs pulses with ~50 uJ per pulse

Use space-charge boost for bandwidth-broadening (4-5x larger than previously) for non-linear science applications

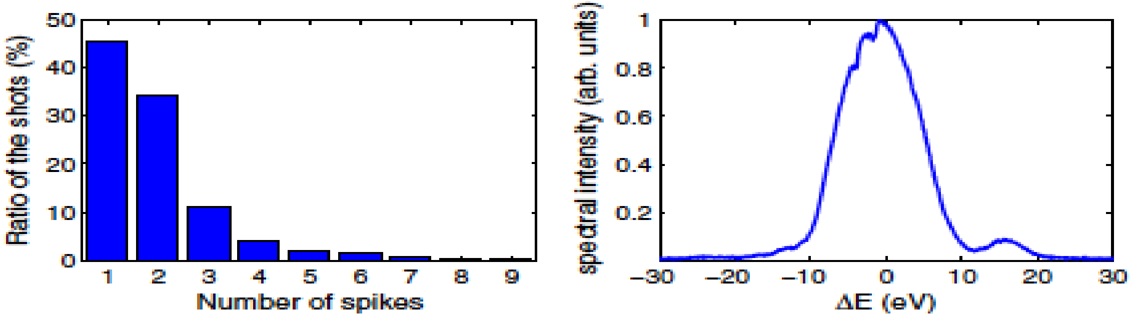
HXR: Isolated 200 as pulse produced



Nonlinear compression produces
High density head with low density tail

Measurements:

179 ± 58 as @ 9 keV (14.4 eV BW)
228 ± 85 as @ 5.6 keV (11.3 eV BW)
10 uJ x-ray pulse from 20 pC bunch



Huang et al,PRL 119, 154801 (2017)

James MacArthur
WG-A, Tue 14:00

Also:
Slotted foil results (400 as pulse): APL 111, 151101 (2017)
that also enable 2 pulse delivery

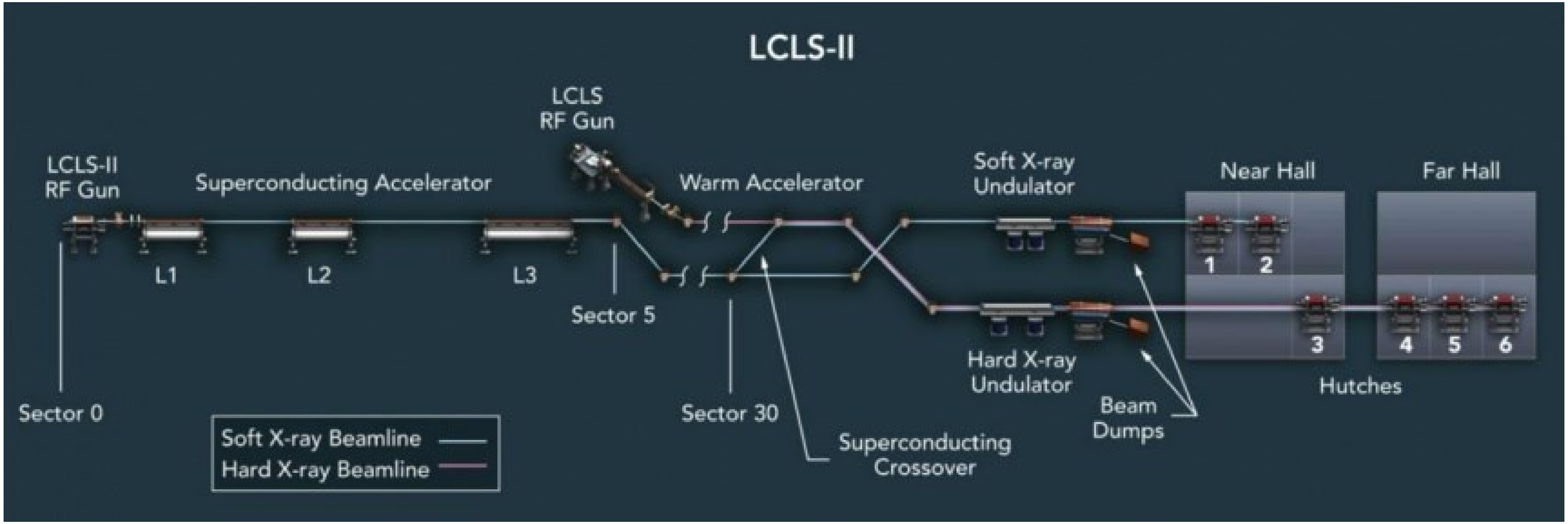
SLAC NATIONAL ACCELERATOR LABORATORY

courtesy
Axel Brachmann

LCLS II / LCLS II HE

Tor Raubenheimer
WG-A, Mo 14:30

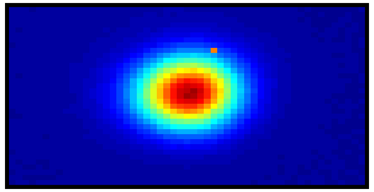
- 4 (8) GeV superconducting CW linac
- 2 new variable gap undulators (SXU, HXU)
- HXU can also be fed by S-band linac => 25 keV photons on 1st harmonic



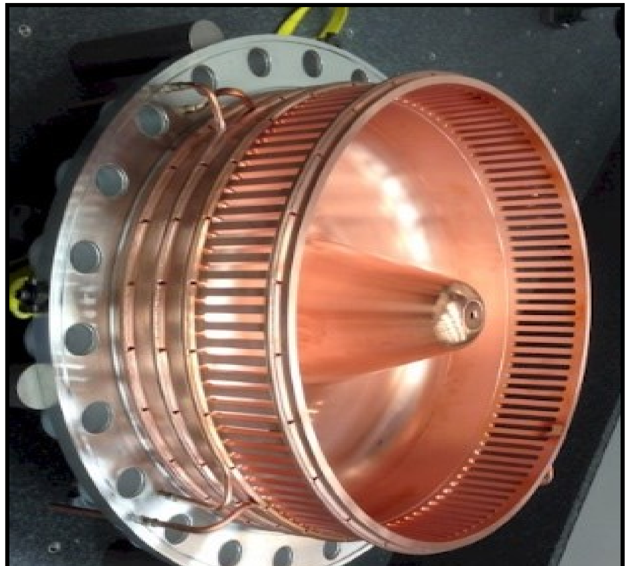
LCLS-II Gun and Injector Status

- *APEX* gun at *LBNL* has demonstrated *LCLS-II* beam brightness at 20 pC
- Gun in fab – Delivered to *SLAC* in Jan. 2018
- Early injector commissioning starts Mar.

Feng Zhou
WG-D, Thu 14:00-14:30

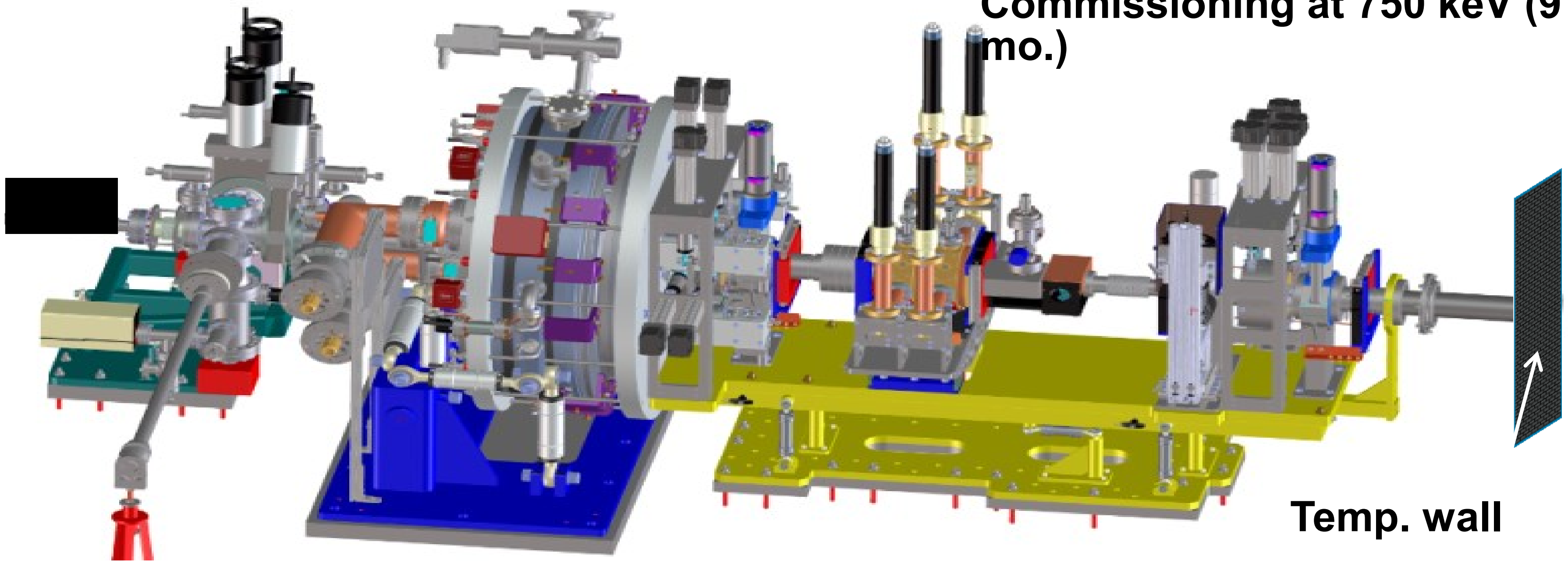


***APEX* beam**

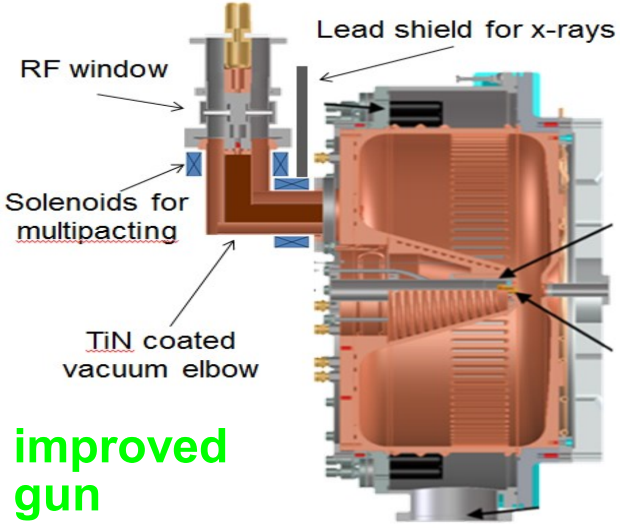


Gun in fab. at *LBNL*

Commissioning at 750 keV (9 mo.)



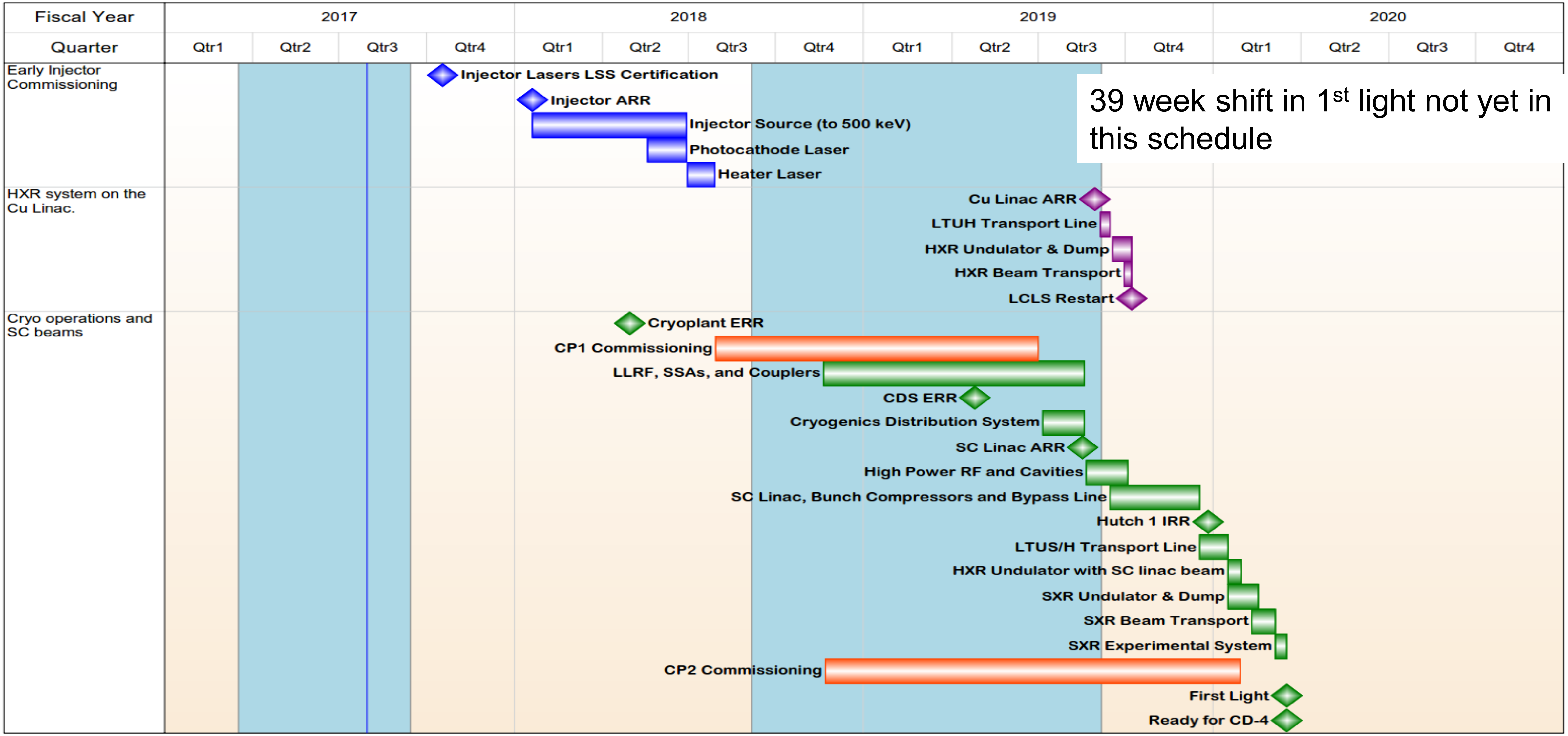
Temp. wall



improved gun

courtesy
Axel Brachmann

LCLS-II Commissioning Schedule



39 week shift in 1st light not yet in this schedule

courtesy
Axel Brachmann

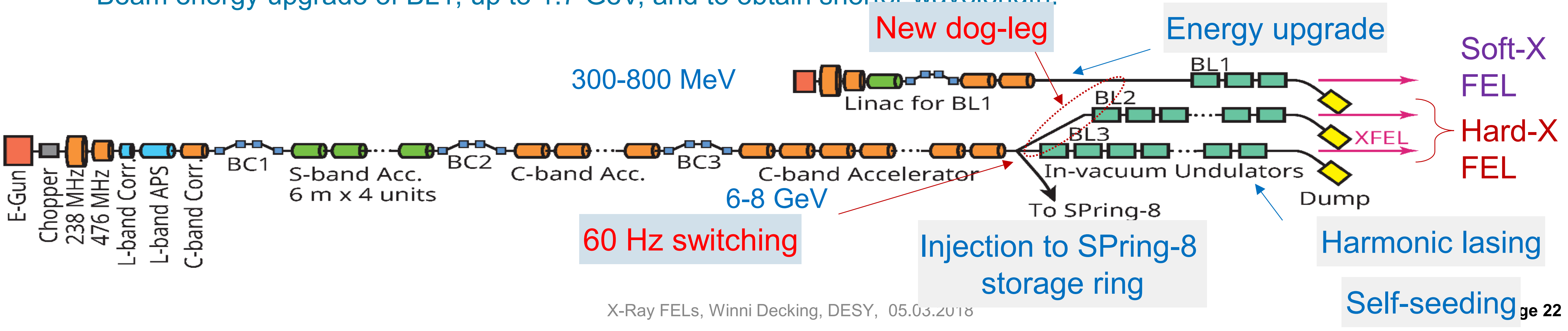
SACLA, RIKEN/Spring-8, Hyogo

- 8 GeV C-band linac
- 2 in vacuum variable gap undulators, 4-15 keV
- Thermionic gun
- Added 800 MeV accelerator for VUV/soft x-ray (20 – 150 eV)

Recent upgrades and future plans of SACLA

courtesy
Hitoshi Tanaka

- **Parallel user operation of 3 beamlines has been started.**
  - BL3 and BL2: Hard X-ray FEL (4-15 keV)
  - BL1: Soft X-ray FEL (20-150 eV)
- 60 Hz beam switching to BL3 and BL2, with arbitrary beam energy (6-8 GeV).
- New dog-leg optics cancels CSR effect and transport 10 kA beams to BL2.
- **Ongoing and future upgrade plans**
  - Beam injection to SPring-8 (and future SPring-8-II) storage ring in this year.
  - Harmonic lasing at hard-X FEL for shorter wavelength.
  - Reflection-type hard-X self-seeding for monochromatic FEL.
  - Beam energy upgrade of BL1, up to 1.7 GeV, and to obtain shorter wavelength.



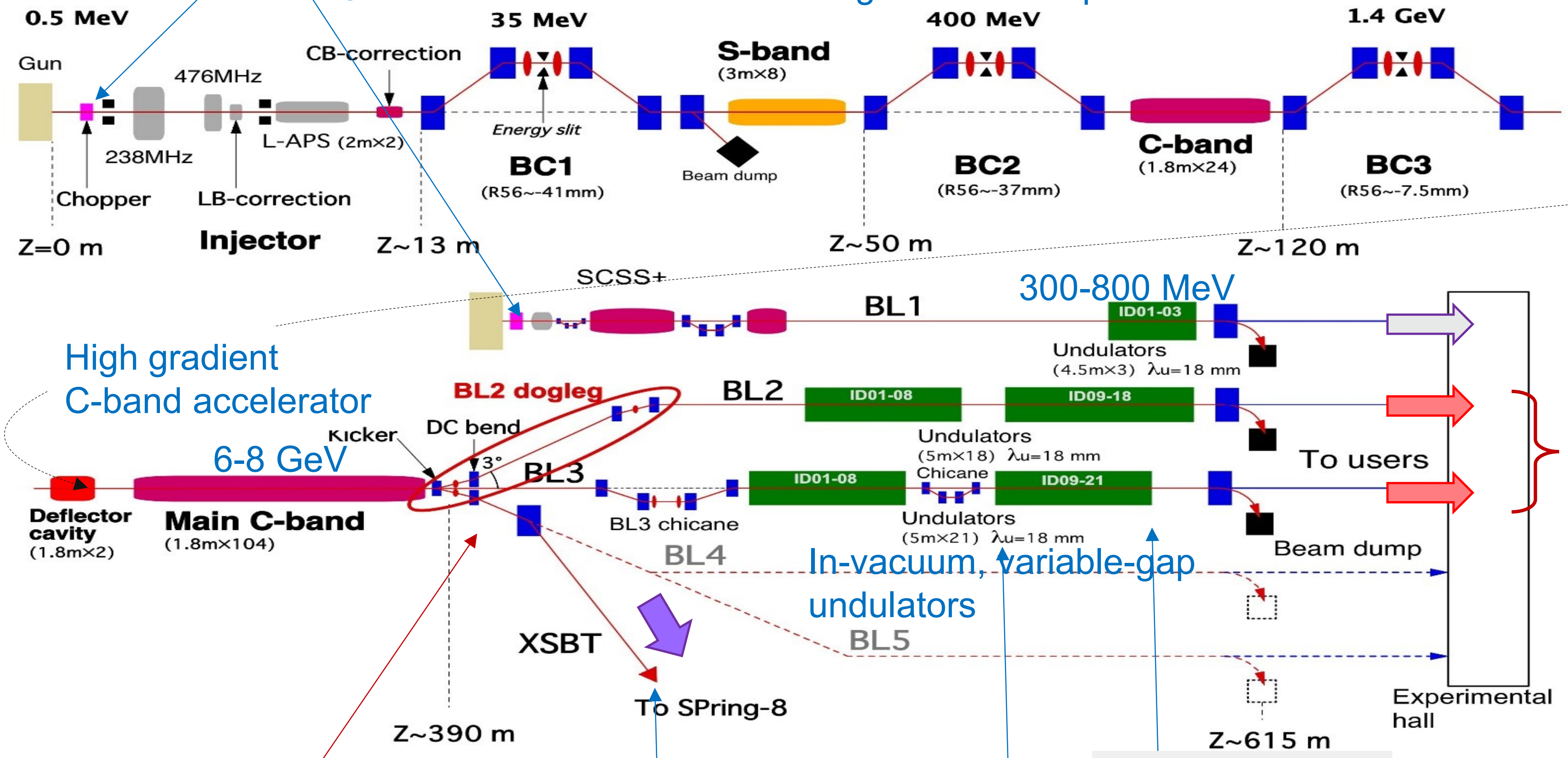
Recent upgrade and future plan of SACLA

courtesy
Hitoshi Tanaka

CeB6 thermionic gun

3 stage bunch compression

Upgrade of soft-X beamline



1 Soft-X Beamline
(20-150 eV)

2 Hard-X beamlines
(4-15 keV)

Harmonic lasing

CSR-free beam transport

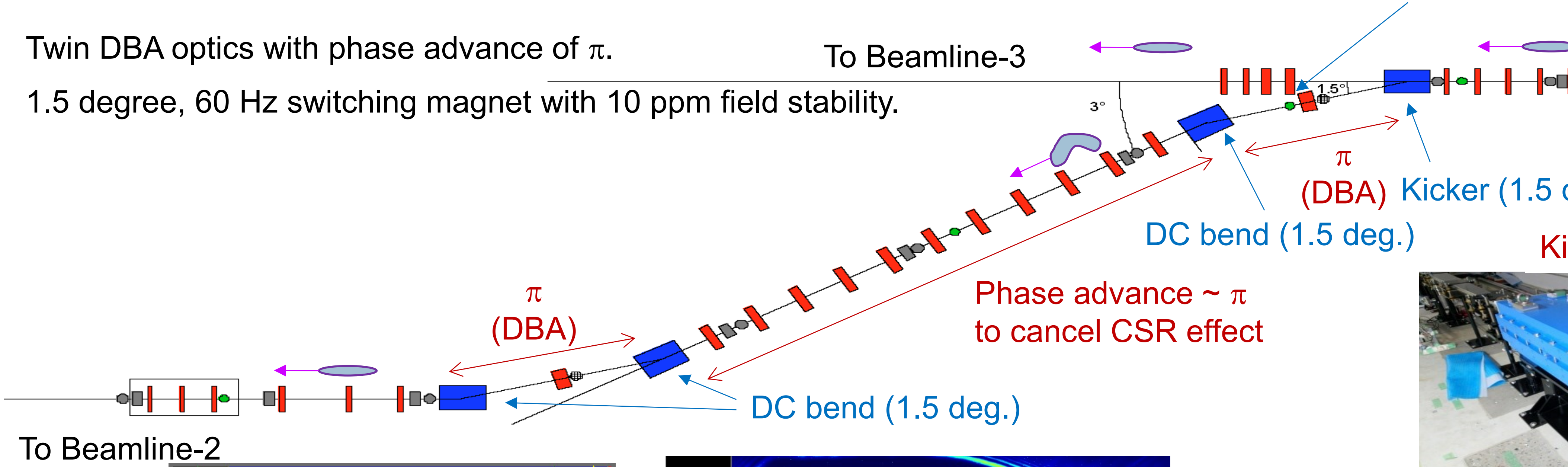
Injection to SPring-8 storage ring

Reflection-type self-seed
development

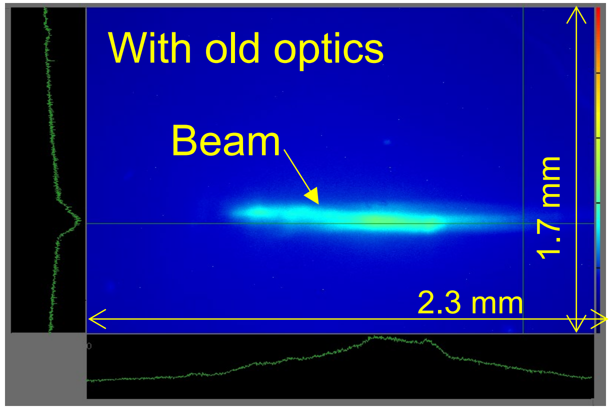
Parallel user operation
of 3 beamlines

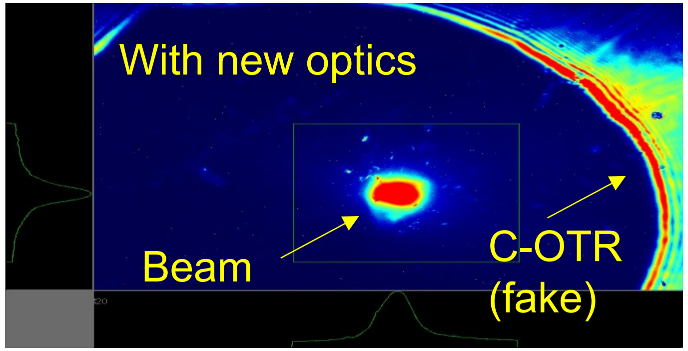
Relocation of the beam transport to BL2

- In the old dog-leg optics, CSR induced beam distortion limited the peak current.
- New optics was introduced for CSR cancellation,
  - Twin DBA optics with phase advance of π.
  - 1.5 degree, 60 Hz switching magnet with 10 ppm field stability.



Kicker magnet

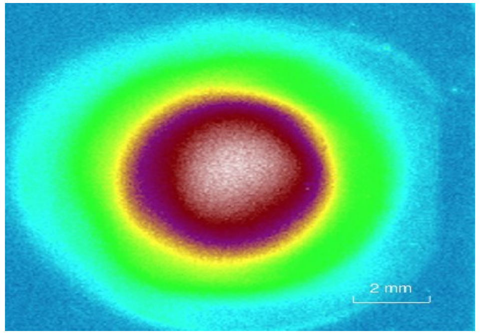




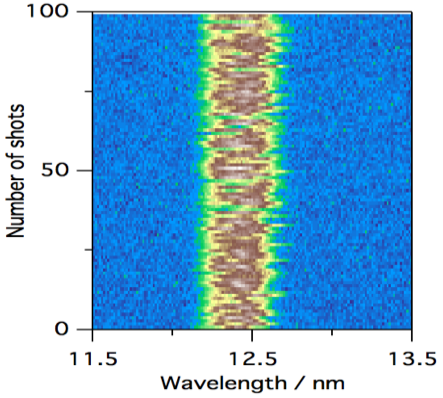
Upgrade of Soft X-ray beamline BL1

- Prototype FEL machine "SCSS" was relocated to BL1 for dedicated accelerator.
- Beam energy was increased to 800 MeV.
- Photon energy can be varied 20 - 150 eV.
- Future plan:
  - Higher peak current with nonlinear correction of the bunch compression.
  - Beam energy upgrade up to 1.7 GeV

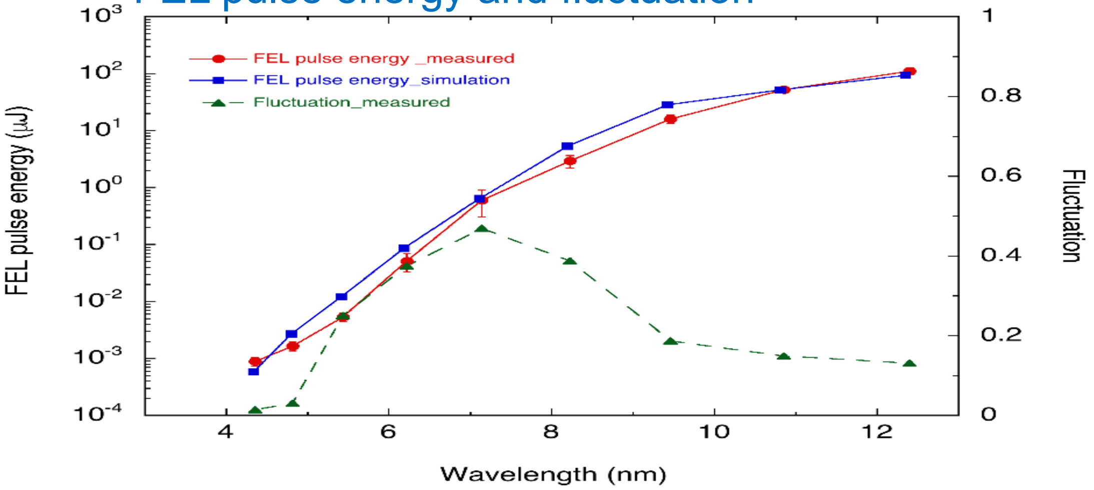
Spatial profile of the FEL

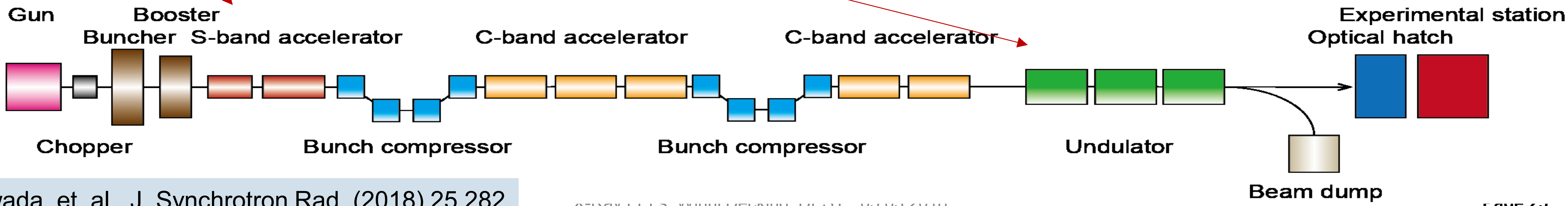


Shot-to-shot spectra



FEL pulse energy and fluctuation



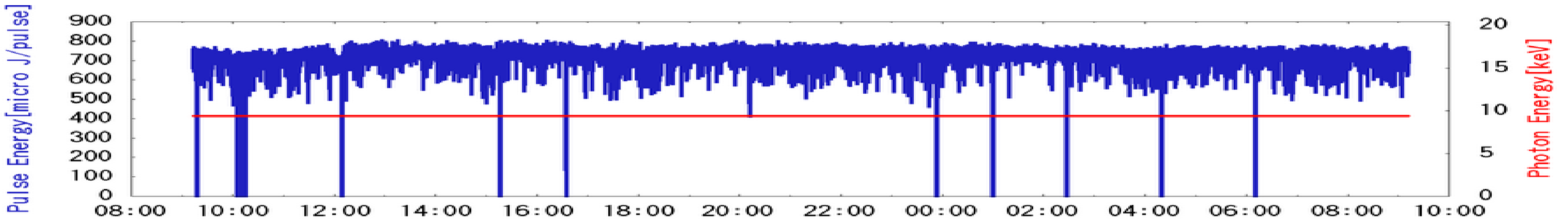


S. Owada, et. al., J. Synchrotron Rad. (2018) 25 282

Example of the Operation status

Pulse Energy	Photon Energy / Wavelength
736.4 micro J/pulse	9.4 keV / 0.131 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
30 Hz	7.6 %

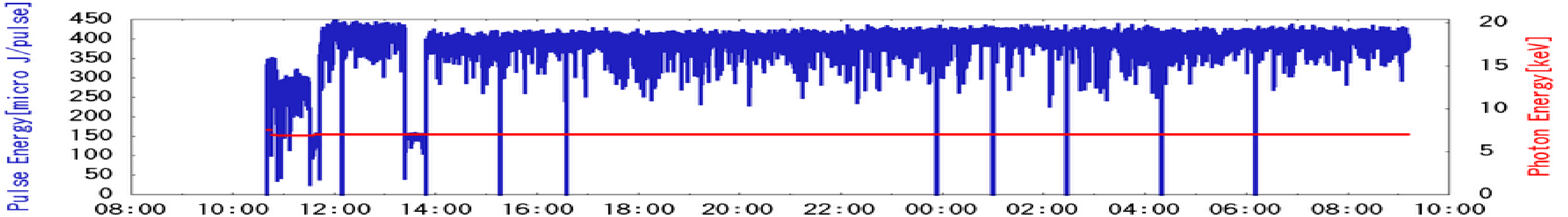
BL3 (Hard-X)
9.4 keV
700 μJ/pulse



60 Hz beam switching

Pulse Energy	Photon Energy / Wavelength
401.2 micro J/pulse	7.0 keV / 0.177 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
30 Hz	8.0 %

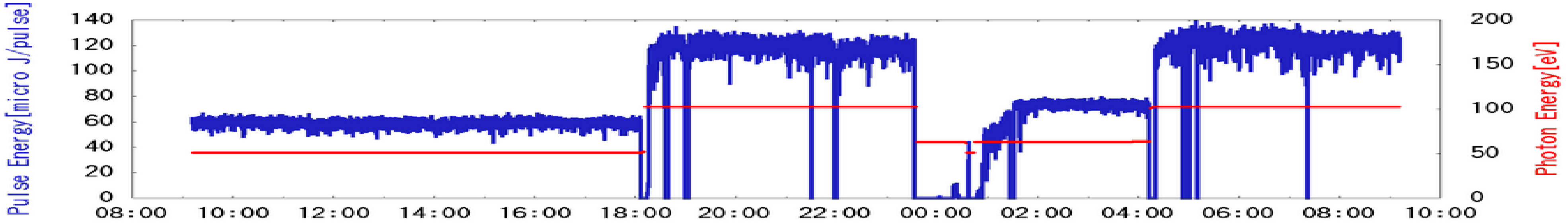
BL2 (Hard-X)
7.0 keV
400 μJ/pulse



Dedicated accelerator

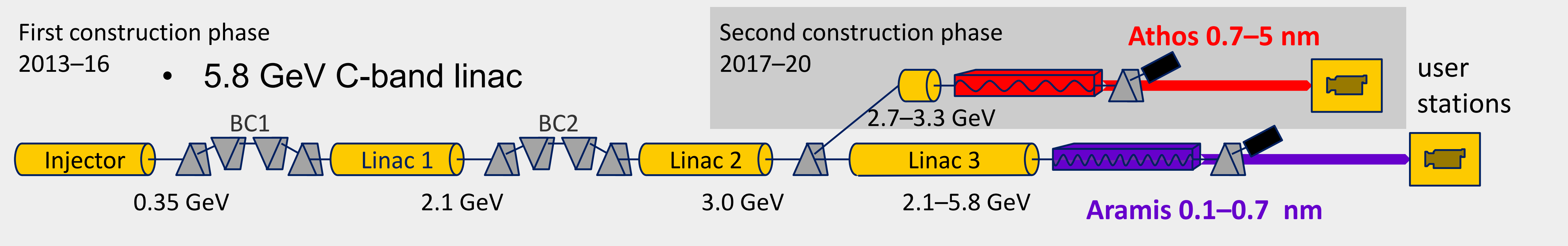
Pulse Energy	Photon Energy / Wavelength
108.9 micro J/pulse	102.6 eV / 12.1 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
60 Hz	19.3 %

BL1 (Soft-X)
103 eV
120 μJ/pulse



SwissFEL, PSI, Villigen

Soft X-ray FEL, λ=0.65–5.0 nm
Variable polarization, Apple-X undulators
First users 2021



Hard X-ray FEL, λ=0.1–0.7 nm
Linear polarization, variable gap,
in-vacuum undulators
First users 2018

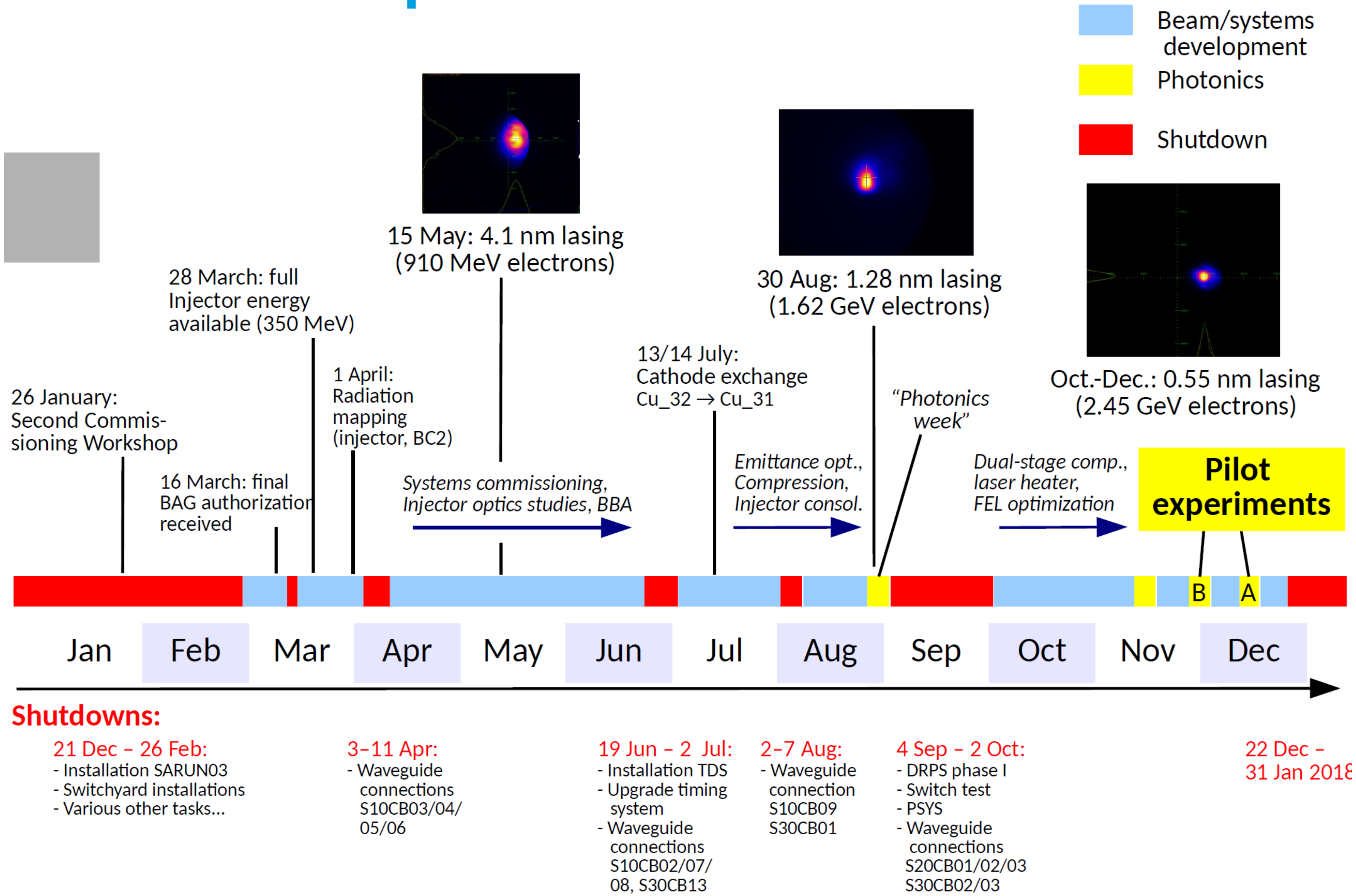
Main parameters:

Photon wavelength	0.1–5 nm
Photon energy	0.2–12 keV
Pulse duration	1–20 fs
Electron energy	5.8 GeV
Electron bunch charge	10–200 pC
Repetition rate	100 Hz

PAUL SCHERRER INSTITUT PSI

courtesy
Thomas Schietinger

SwissFEL Operations 2017



SwissFEL has reached its 2017 milestone of first pilot experiment.

Electron energy currently limited to 3 GeV, to be raised to the nominal 5.8 GeV by June 2018.

Stable running at 200 µJ demonstrated for 2.2 keV photon energy.

Many important commissioning steps have been skipped and will have to be done in 2018!

Regular user operation to start in January 2019.

courtesy Thomas Schietinger

Outlook Athos (soft-X-ray line)

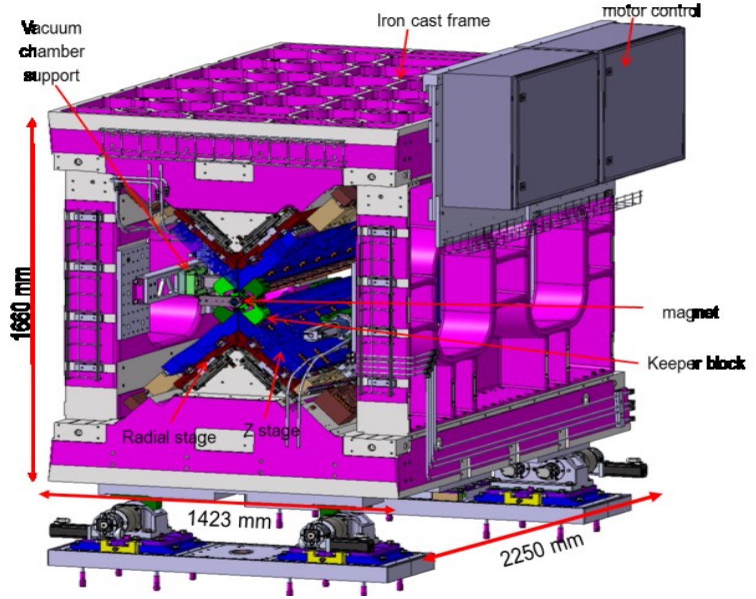
Redesigned soft-X-ray undulator line featuring
16 Apple-X U38 undulators:

- full polarization control
- independent K and polarization control
- transverse gradient undulator (TGU)
- symmetric force distribution (gap = slit)

Small interundulator magnetic chicanes to enable

- Optical klystron mode
- High-brightness mode
- Terawatt-attosecond mode

One large magnetic chicane for two-color operation
(delay between –10 fs and +500 fs)



Athos U38 undulator concept

Schedule:

- Athos dogleg ready for commissioning Feb. 2018
- Undulator installation Jan. 2019 – March 2020
- First pilot experiment end 2020
- User operation 2021.

Eduard Prat
Plenary, Mo 10:00

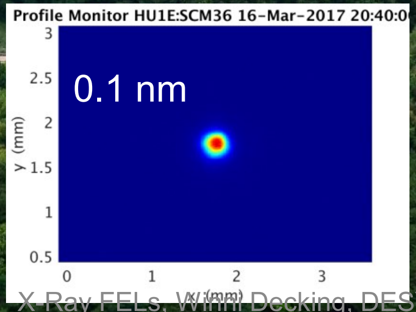
SwissFEL switchyard, Nov. 2017

courtesy
Thomas Schietinger

PAL-XFEL

0.1 nm hard X-ray FEL using a 10 GeV S-band linac

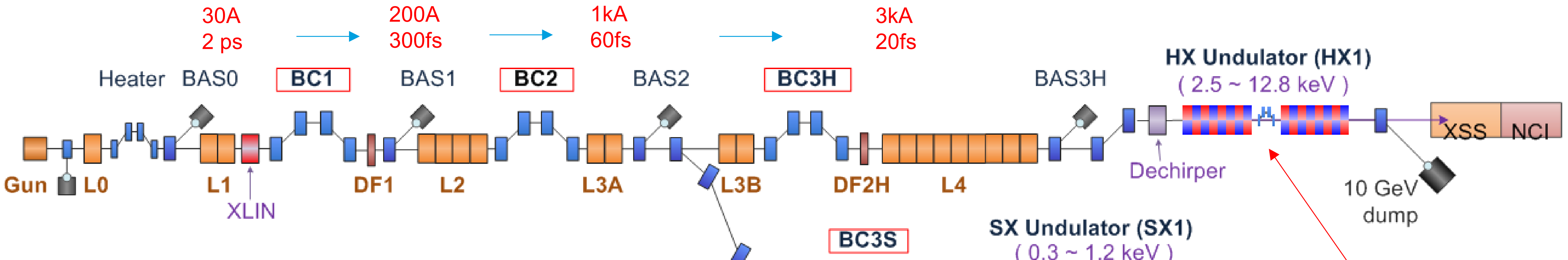
Apr. 2011: PAL-XFEL project started
Jun. 2012: Ground-breaking
Dec. 2014: Building completed
Jan. 2016: Installation completed
Apr. 2016: Commissioning started
Jun. 2017: User-service started



- **14 Jun. 2016 First SASE lasing at 0.5 nm**
- **28 Oct. 2016 Lasing at 0.15 nm**
- **27 Nov. 2016 Saturation of 0.15 nm**
- **16 Mar. 2017 Saturation of 0.1 nm**

Chang-Ki Min
WG-A, Mo 15:00

PAL-XFEL Parameters



Main parameters

e^- Energy	10 GeV
e^- Bunch charge	20-200 pC
Slice emittance	< 0.5 mm mrad
Repetition rate	30 Hz (60 Hz)
Pulse duration	10 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

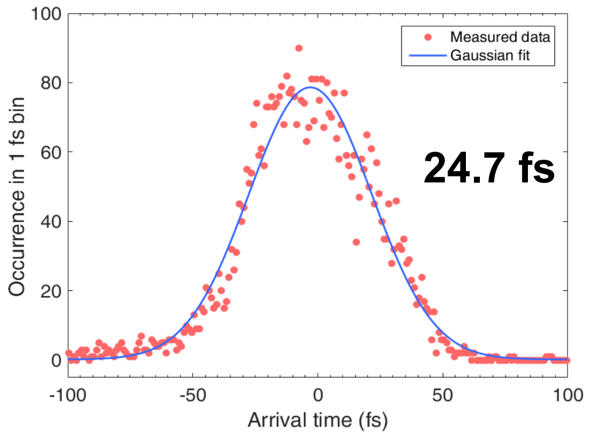
Undulator Line	HX1	SX1
Photon energy [keV]	2.5 ~ 12.8	0.3 ~ 1.2
Beam Energy [GeV]	4 ~ 10	3.15
Wavelength Tuning	energy	gap
Undulator Type	Planar, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

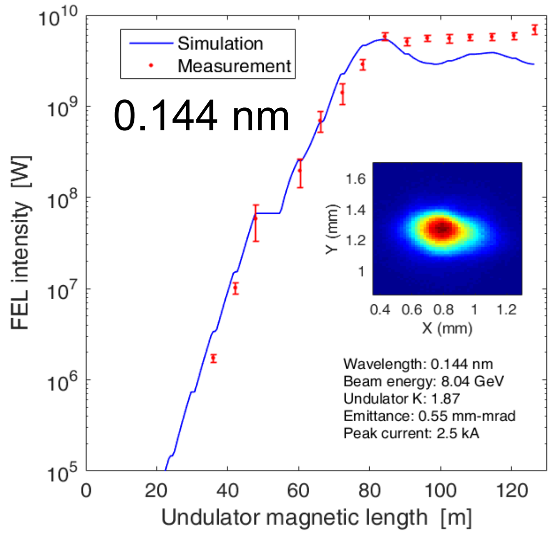
courtesy
Heung-Sik Kang

Machine Performances

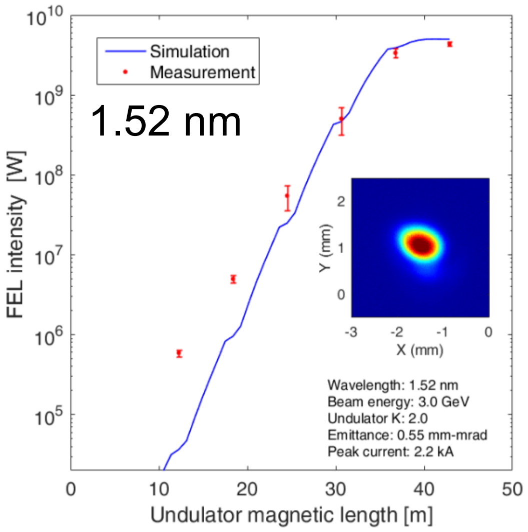
- FEL position stability: 8~9% of beam size
- FEL power stability: ~ 4.0% RMS
- E-beam energy jitter: < 0.02 %
- E-beam arrival time jitter: < 20 fs
- FEL pulse energy: ~1 mJ at 9.7 KeV
- Saturated FEL up to 15.0 KeV
- FEL beam availability: > 98%

OXC : Optical laser & XFEL Cross-correlator





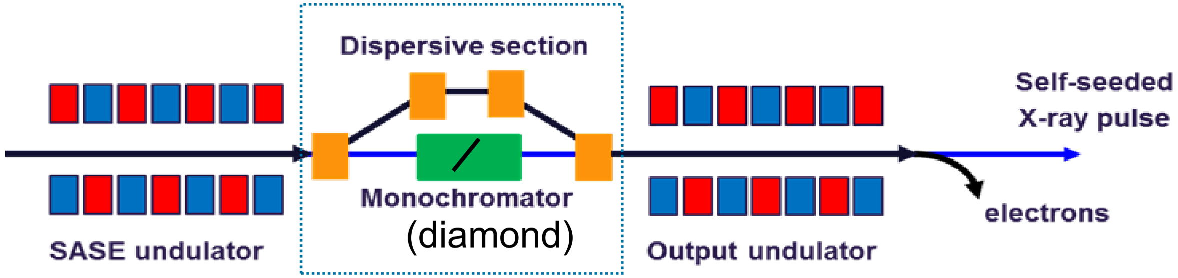
Simulation:
emittance: 0.55 mm-mrad
peak current: 2.5 kA



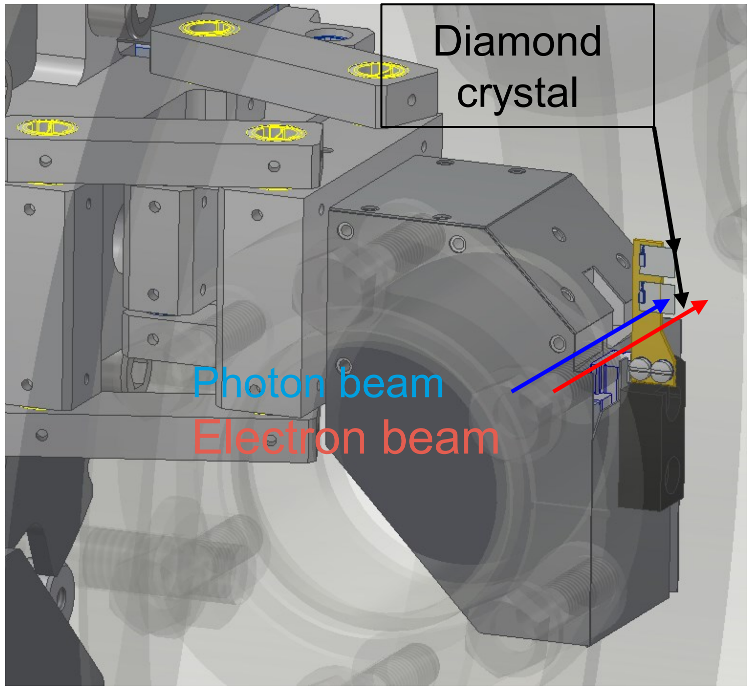
Simulation:
emittance: 0.55 mm-mrad
peak current: 2.2 kA

courtesy
Heung-Sik Kang

Plan of Year 2018



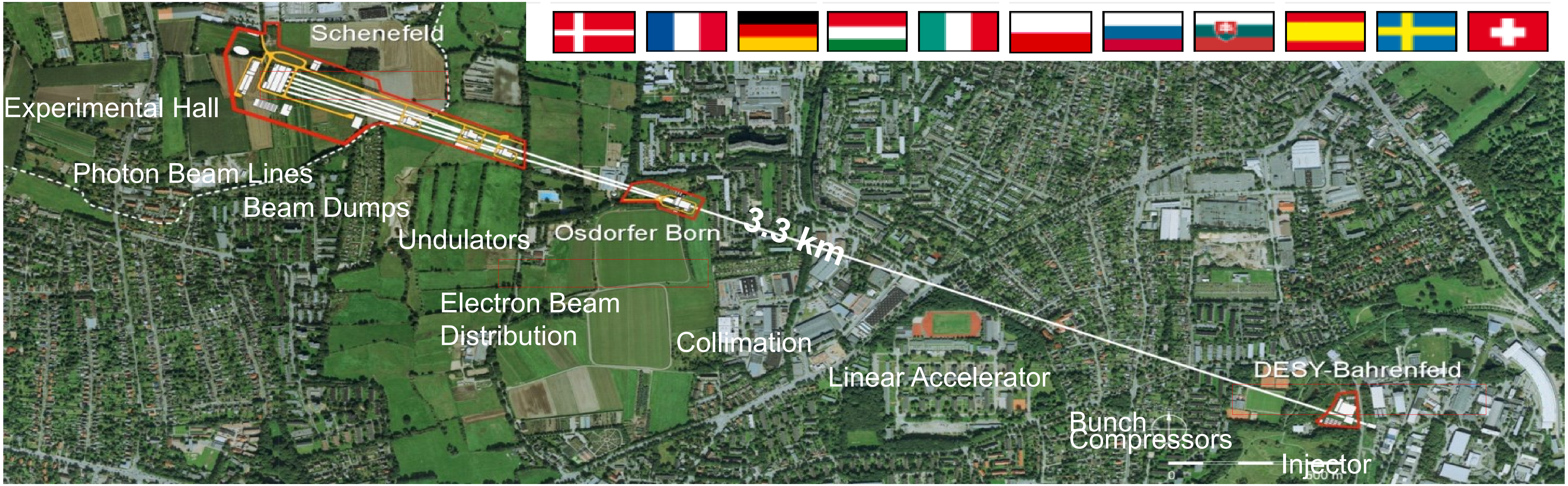
- **Self-seeding mode operation for HX-FEL**
  – Commissioning will begin in March 2018
- **60 Hz operation**
  – A three days' test of 60 Hz operation was successfully done.
  – Its full operation is scheduled in March 2018 after the SLED cavity tuning controller is ready to operate.
- **Pulse-by-pulse switching operation for SX-FEL**
  – A kicker and a septum will be ready by February 2019
  – Commissioning will begin in March 2019
  – Monochromator will be installed in February 2018



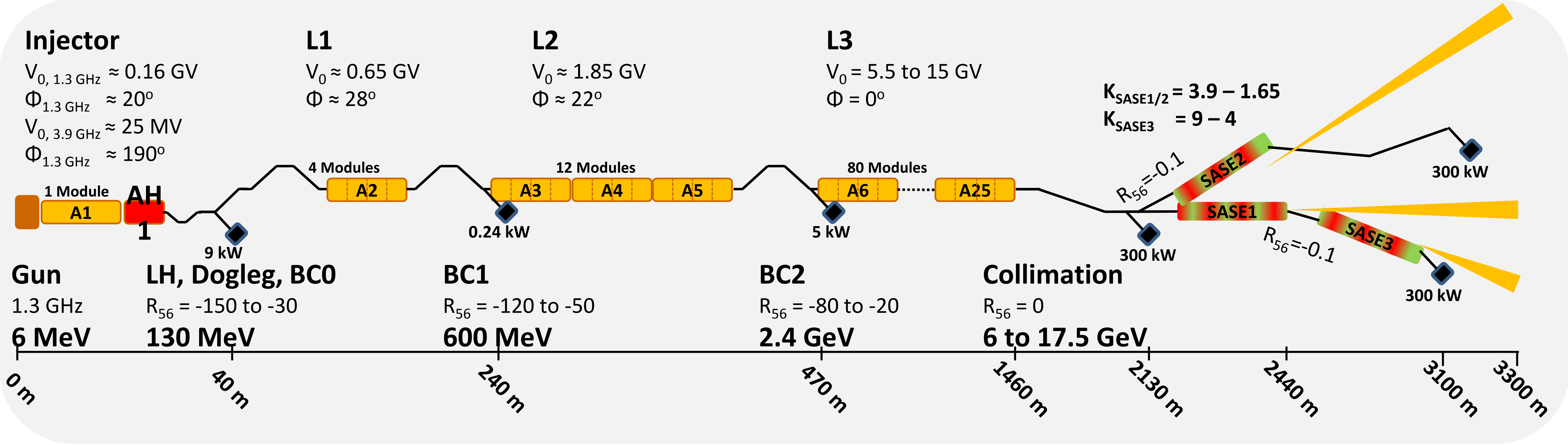
courtesy
Heung-Sik Kang

European XFEL, Hamburg

- International project realised in Hamburg area, Germany
- 17.5 GeV pulsed superconducting linac
- 27000 pulses per second in 10 Hz burst mode
- Three variable gap undulators for hard and soft X-rays
- Initially 6 equipped experiments
- All accelerator and beamlines in tunnels 6 -25 m below surface



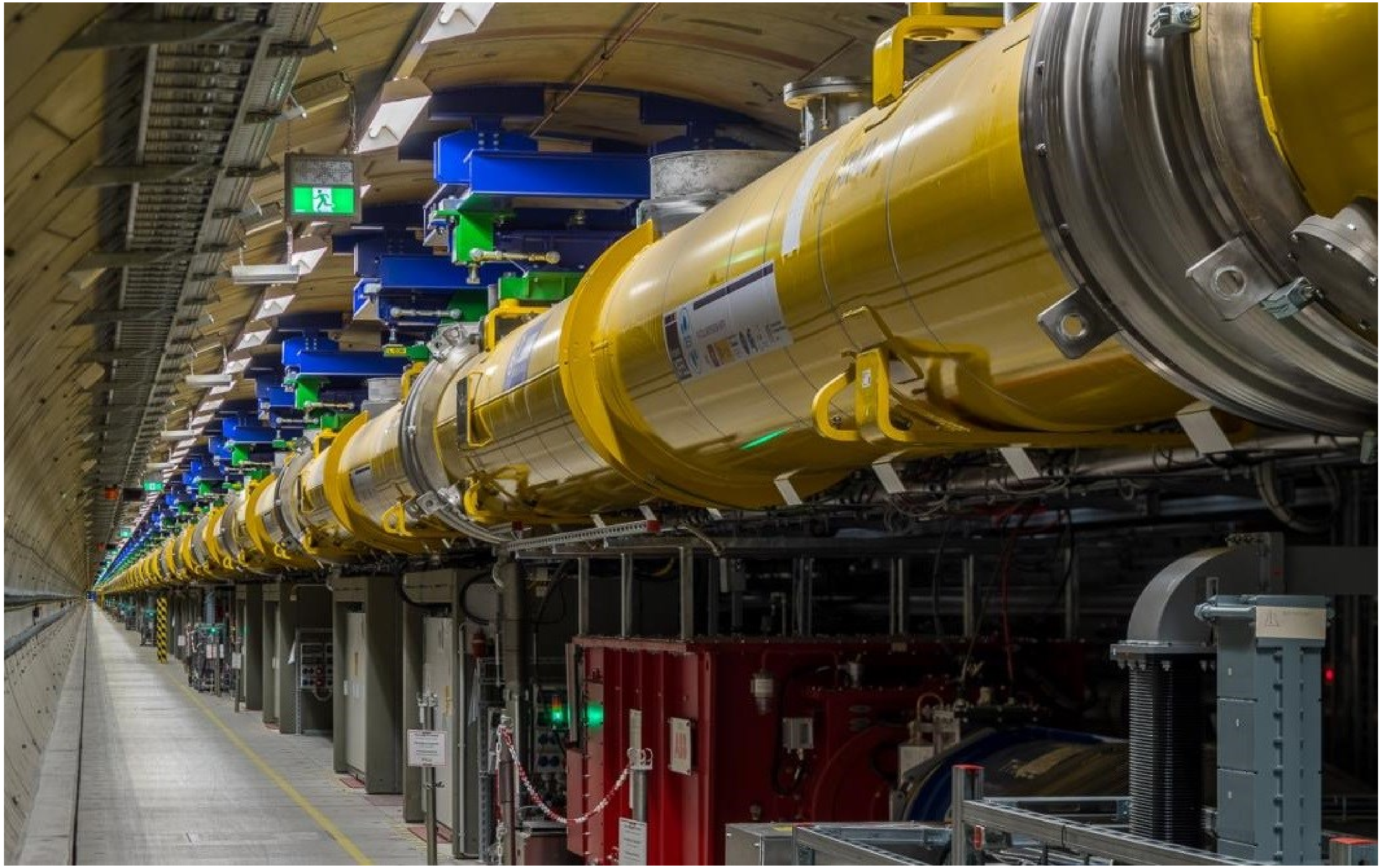
Accelerator Overview



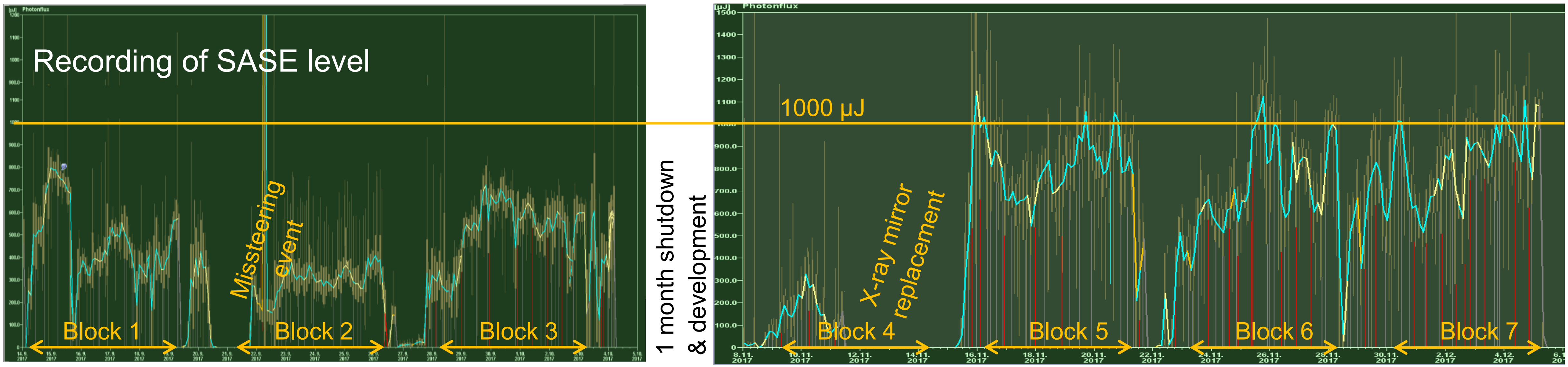
Superconducting linac with 97 1.3 GHz superconducting modules
10 Hz pulsed mode with 600 µs flat-top, 2700 bunches/pulse
Variation of bunch charges between 20-1000 pC foreseen to vary final pulse length
Fast distribution of bunches into beam distribution lines

Accelerator complete & in operation

- Accelerator commissioned according to schedule and towards expected parameter
- **23 out of 25 RF** stations commissioned (last two will be ready in Q2/218)
- Maximum beam energy **14.9 GeV**, user operation with **14.0 GeV**
- Routine operation with **300 bunches/second** in user mode
- Test operation in linac mode with **3000 bunches/second** (≈ 18 kW beam power)



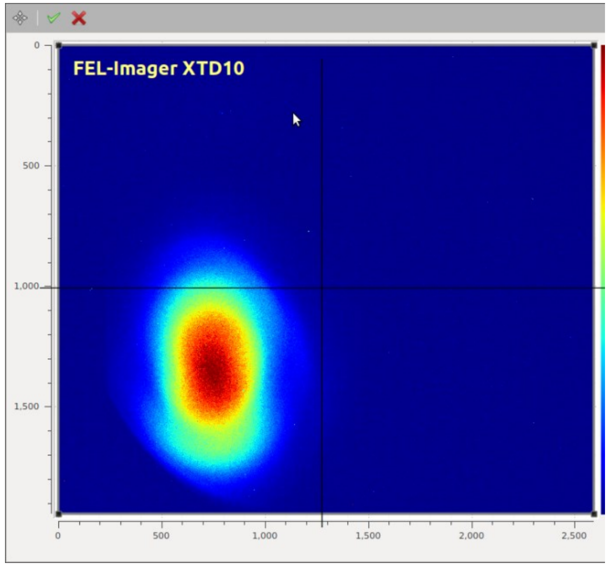
Facility performance in user run

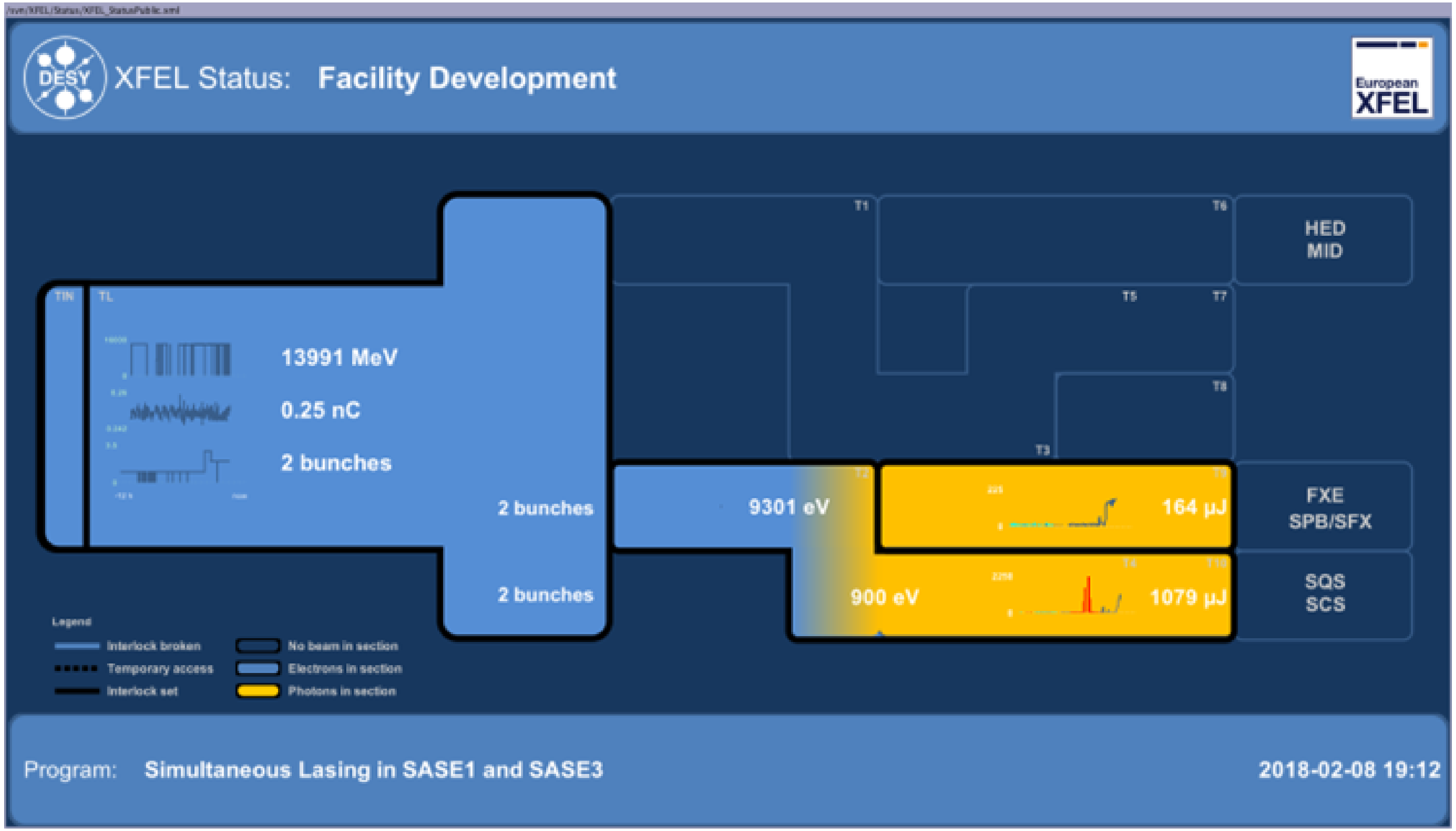


- Seven 5 day user blocks from 9/2017 – 11/2017 (just 4 month after 1st lasing)
- 9 keV, 10-300 bunches/second
- Little tuning needed (because of limited flexibility offered), but frequent small wavelength changes and variation of bunch number (1-30)

Lasing SASE3

- Lasing on 08.02.2018 at fist attempt (after BBA) at 900 eV
- Meanwhile up to 4 mJ





http://tesla.desy.de/status_PNGs/

2018 E-beam Parameters

Quantity		Project Goal	Achieved	Routine	2018 Goal
electron energy	GeV	8,12.5,14,17.5	6-14.9	14	8/12.5/14/17.5 GeV
bunch repetition frequency within pulse	MHz	Up to 4.5	1.1, 4.5	1.1	1.1
bunch charge	pC	20 – 1000	100, 500	250, 500	200, 500
electron bunch length after compression	fs (FWHM)	2 – 180	20, 90	40, 90	40, 90
beam power	kW	500 kW	18 kW	1.8 kW	50 kW
undulators in operation (lasing)		SASE1-3	SASE1,3	SASE1,3	SASE1-3
photon energy (SASE1)	keV	0.25 - 25	1,6,9-14	9-9.5	6-15
photon pulses / s / undulator		27000	3000	300	3000
saturation power (@ 14 GeV, 250 pC, 9 keV)	mJ	1	1.5	0.4	1

Plans for 2018

- SASE1: About 1200h experiment commissioning & 1600 h user operation, improve performance and flexibility

- SASE2: First e-beam in March, first lasing in May
  - Commission laser and photon systems parallel to user runs
  - First user experiments in 2019
  - In the meantime: parasitic studies (harmonic lasing, kicker schemes, photon diagnostics)
  - Installation of Self-Seeding Chicanes (December)

Evgeny Schneidmiller
WG-A, Tue 17:00

- SASE3:
  - First user experiments end of 2018
  - In the meantime: parasitic studies (harmonic lasing, kicker schemes, photon diagnostics)

Shan Liu
WG-A, Tue 17:30

- Accelerator:
  - Full energy by summer
  - Full # of bunches after linac by end of 2018

Existing High-Gain FELs in China

Laboratory Tour
Fri 14:00

SDUV-FEL:
65m, 180MeV, 250-350nm

DCLS:
150m, 300MeV, 50-150nm

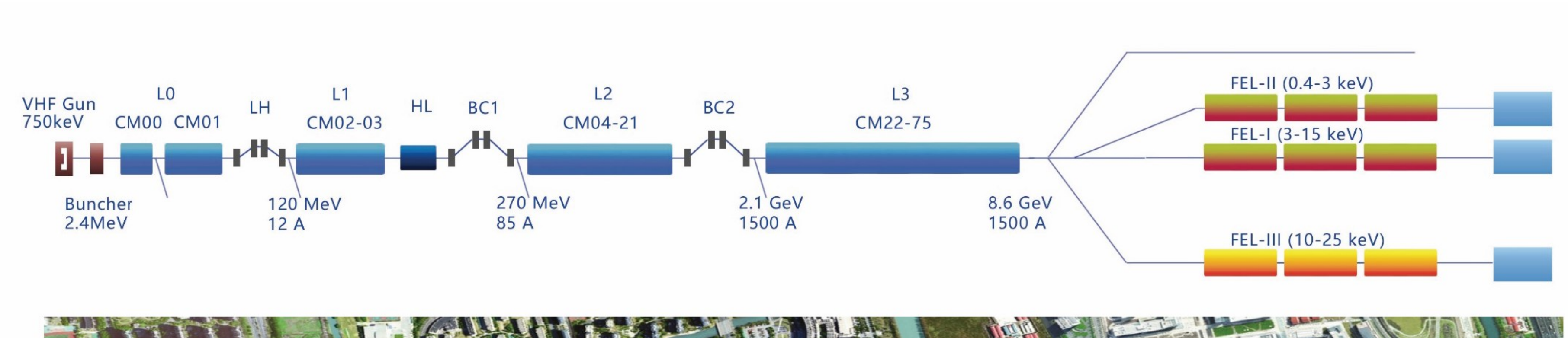
Operating

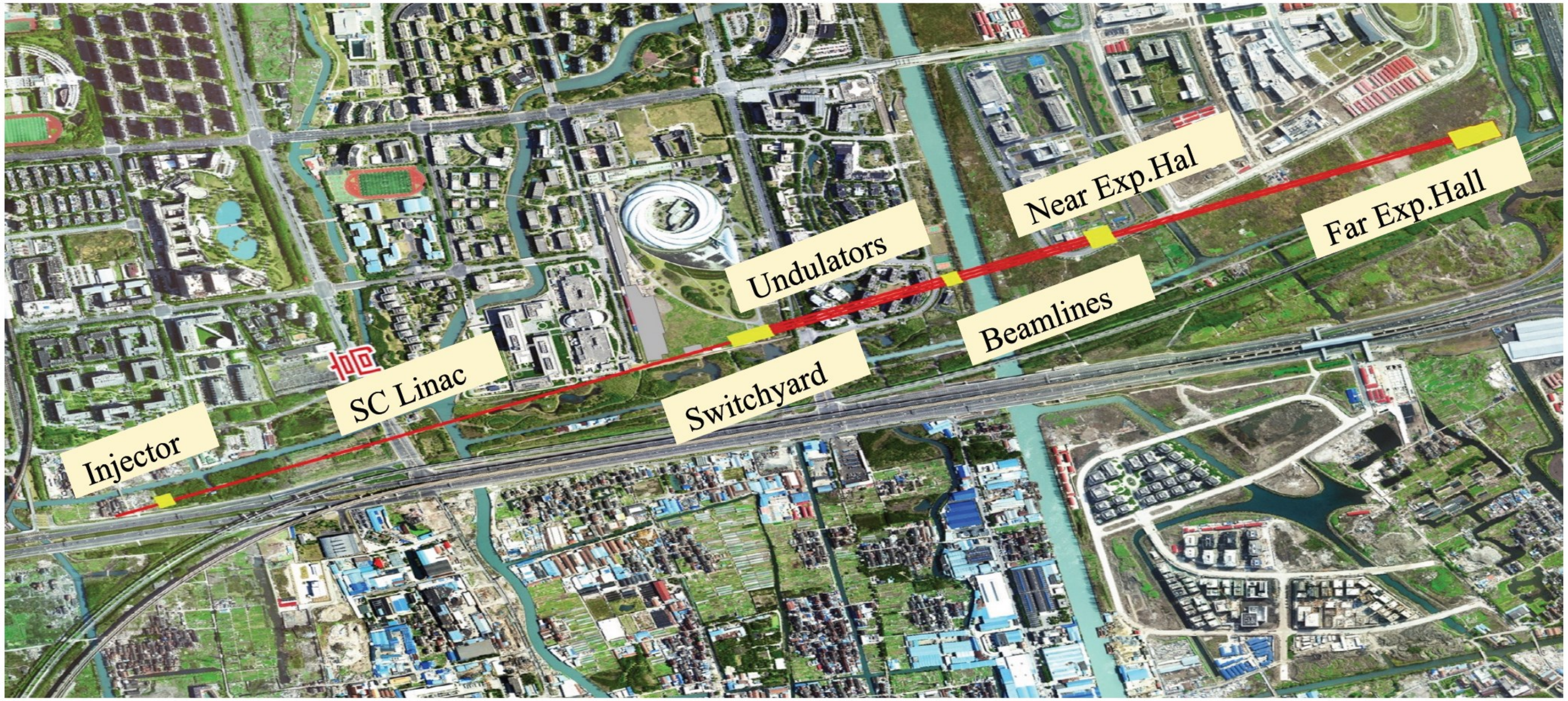
Under commissioning

SXFEL Facility:
300m, 840MeV, 9-40nm
530m, 1.6GeV, 2-10nm

Courtesy
Zhijuan Zhu

HXFEL, SINAP/ShanghaiTech University, Shanghai

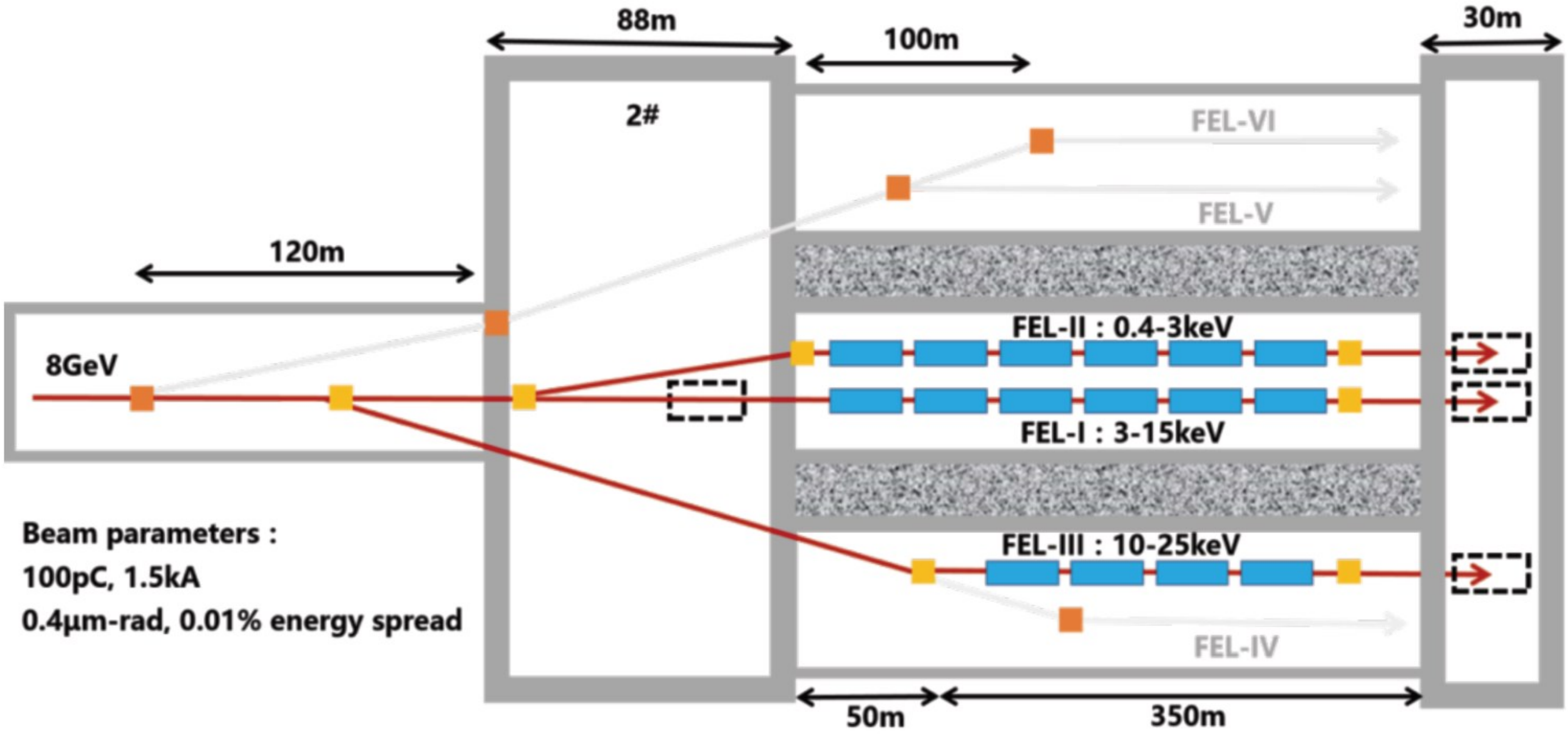




Dong Wang
WG-A, Mo 14:00

Courtesy
Zhijuan Zhu

Beam Distribution and FEL Systems for Shanghai HXFEL



Courtesy
Zhijuan Zhu

Main Parameters of Shanghai HXFEL

	Nominal	Range	Unit
Beam energy	8	4-8.6	GeV
Bunch charge	100	10-300	pC
Max Repetition rate	< 1	up to 1	MHz
Electron beam power	0.8	0 - 2.4	MW
Photon energy	0.4-25	0.4-25	keV
Pulse length	20-50	5-200	fs
Peak brightness	5×10^{32}	1×10^{31}-1×10^{33}	Photons/μm^2/rad^2/s/0.1%BW
Average brightness	5×10^{25}	1×10^{23}-1×10^{26}	Photons/μm^2/rad^2/s/0.1%BW
Total facility length	3.1	3.1	km
Total tunnel length	5.7	5.7	km
Tunnel diameter	5.9	5.9	m
2K Cryogenic power	12	12	kW
RF Power	2.28	3.6	MW

Courtesy
Zhijuan Zhu

Summary

- 7 X-ray user facilities in operation in 2018 (from 0 in 2008)
- 2 new facilities are under construction/planned based on superconducting CW linac
- Trends:
  - Parallel beam operation (FLASH, European XFEL, SACLA, PAL, PSI, LCLS)
  - Two pulse operation (LCLS, FERMI, FLASH)
  - Bandwidth control (HGHG, EEHG, self-seeding, harmonic lasing)
  - Shorter pulses
- Challenges
  - Attosecond pulses & timing
  - Control and operability of muli-user/multi-mode machines
  - Source for CW accelerators
  - SC undulators for low energy / high rep-rate machines
  - Increase the user base

Session WG-A
Thu 11:00-12:30

Session WG-A
Wed 14:00-18:00

Franz Kaertner
Plenary, Wed 10:00

Session WG-A
Mo 16:00-18:00, Thu 09:00-10:30

Feng Zhou
WG-D, Thu 14:00-14:30

Joel Fuerst
Plenary, Mo 12:00-12:30

All this is only possible thanks to the excellent team spirit within the light source community

Team work and collaboration is key (& fun)

Thanks to Thomas Schietinger (PSI), Axel Brachmann (SLAC), Heunk-Sik Kang (PAL) & Hitoshi Tanaka (SACLA) for providing me with slides


の仲間たちと記念撮影!
SACLAとSPring-8がつながれば、
もっとたくさんの人が、もっと大きな世界を見ることができます。