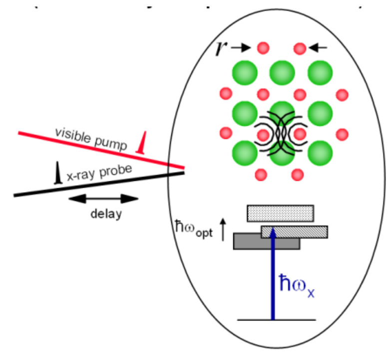
Free Electron Lasers in the Soft X-ray Regime

John Corlett
LBNL

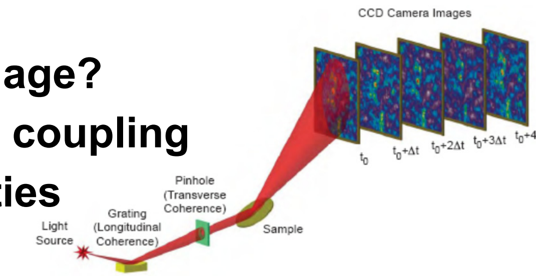
Soft X-ray science: understand *function* of materials

Need to understand chemical bonding & interacting electrons
- Where are the electrons? What are they doing? Why? How?
- Can they be controlled and manipulated?

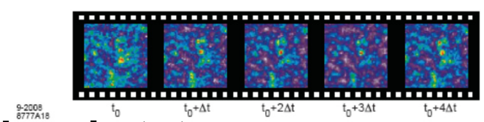


- Understanding Chemical Reactivity
  - charge transfer, catalysis, photosynthesis (natural and artificial)

- Understanding Correlated Materials – what will follow the silicon age?
  - charge correlation, nanoscale organization, charge/spin/lattice coupling
  - superconductivity, colossal magnetoresistance, exotic properties



- Imaging structure ⇒ imaging “function” in biological systems
  - structure ♦ dynamics ♦ function
  - identify conformational states -pathways connecting conformational states



- Soft X-ray probes and pumps for Imaging, structure determination, and spectroscopy
  - Accessing K- and L-edges of the earth-abundant elements
  - Diffraction/scattering in the few to several keV photon energy range

Key soft X-ray FEL performance parameters

- Spatial (transverse) coherence
  - Requirements set by real-space imaging, diffractive imaging, and photon-correlation spectroscopy
- Temporal (longitudinal) coherence
  - Fourier-transform-limited pulses – trade-off time and energy resolution
    - ~100 fs pulses with ~10 meV bandwidths to sub-femtosecond pulses with ~10 eV bandwidths
- Synchronization and integration with conventional pulsed laser sources
- Modest to high peak flux and brightness
- High repetition rate with regularly spaced pulses
- High average flux and brightness
  - High repetition rates (100 kHz or greater)
- Tunability throughout the transition-metal L-edges and polarization control
- Two-color capability for non-linear spectroscopies and X-ray pump/X-ray probe
- High degree of amplitude, wavelength, and position stability
- Multiple simultaneous users

The X-ray laser revolution!

Upgrades and expansion
FLASH-II
SACLA
FERMI FEL2
LCLS-II

Worldwide soft X-ray FEL activities

- Existing soft X-ray FEL user facilities and their upgrade/expansion projects
  - FLASH + FLASH-II
  - LCLS + LCLS-II
  - FERMI@elettra + FEL2
  - SACLA + upgrade projects
- Under construction and planned user facility projects
  - European XFEL
  - SwissFEL
  - PAL-XFEL
- Other facility proposals
  - NGLS, SXFEL, IRIDE, WiFEL ...
- Many FEL R&D projects and facilities
  - APEX, ATF, CLARA, JLAB, LUNEX-5, MAX-IV, NLCTA, SCSS, SDL, SDUV FEL, SPARC, WiFEL, ...

Overview of this talk

- Existing soft X-ray FEL user facilities and their upgrade/expansion projects
  - FLASH + FLASH-II
  - LCLS + LCLS-II
  - FERMI@elettra + FEL2
  - SACLA + upgrade projects
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  - European XFEL
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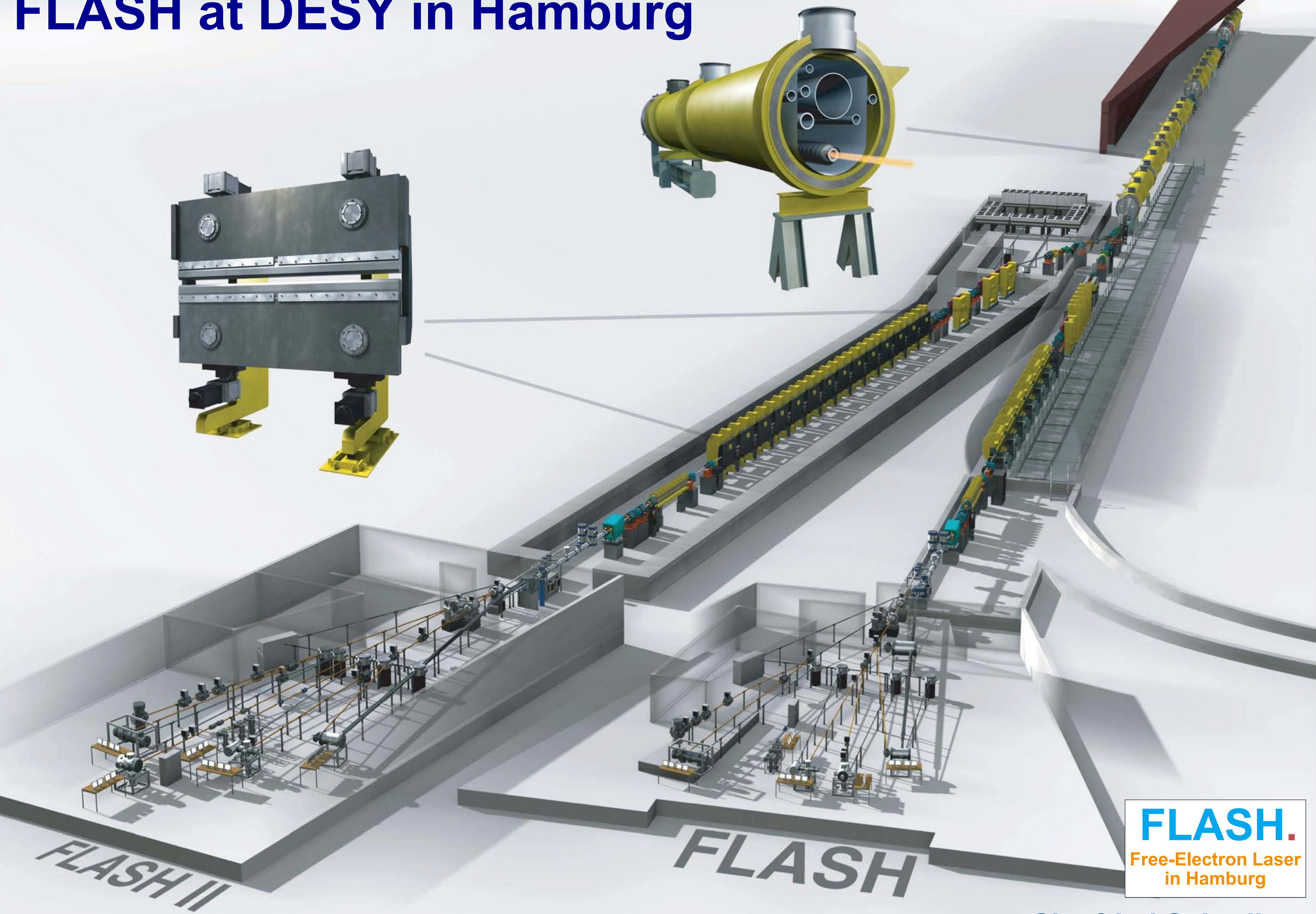
FLASH at DESY in Hamburg



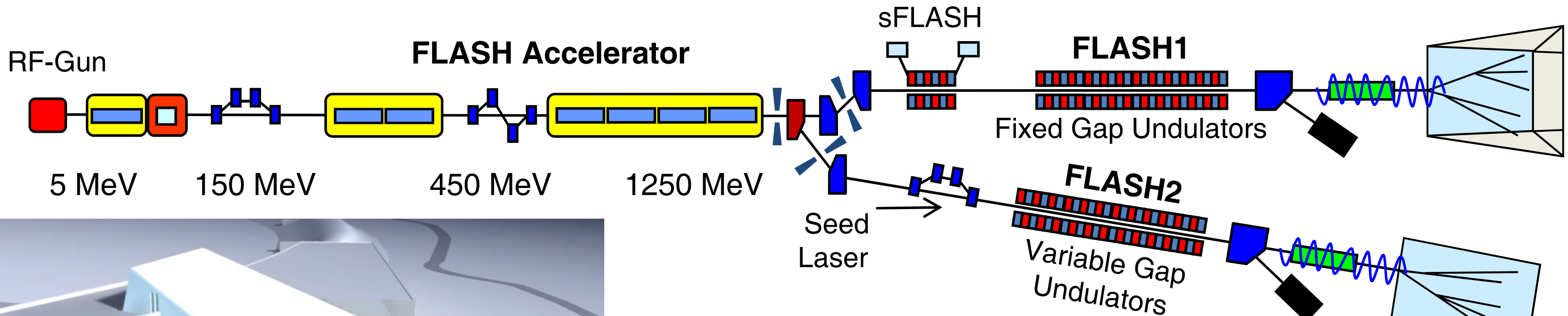
FLASH.
Free-Electron Laser in Hamburg

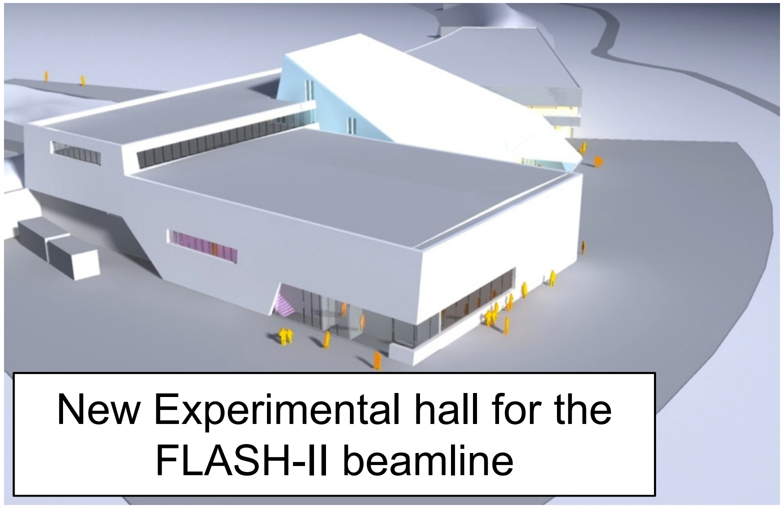
Siegfried Schreiber

FLASH II Project

Siegfried Schreiber

- Second FEL undulator line with variable gap undulators in a separate tunnel
- Second photocathode laser
- Fast kicker to distribute beam within an RF pulse
- Second experimental hall for photon beamlines and experiments
- Implementation of seeding schemes for improved radiation properties
- Under construction; first beam expected early 2014

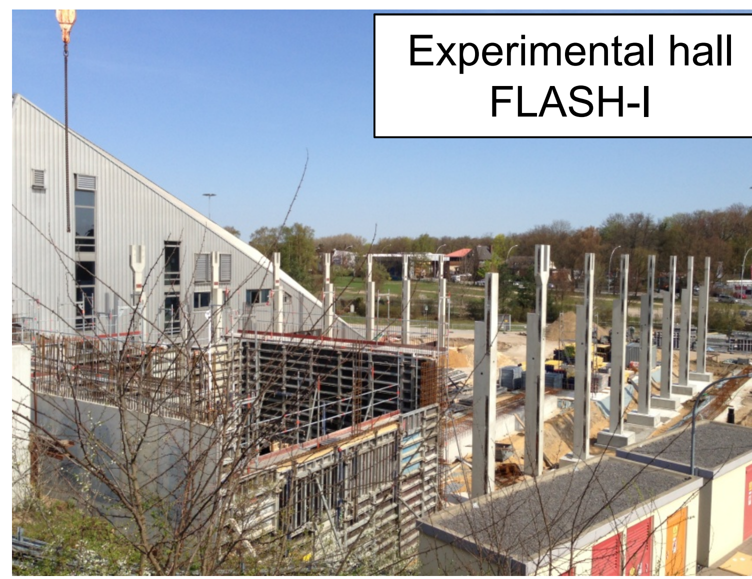




New Experimental hall for the FLASH-II beamline

FLASH-II construction, May 2013

Siegfried Schreiber



Parameters FLASH-II beamline

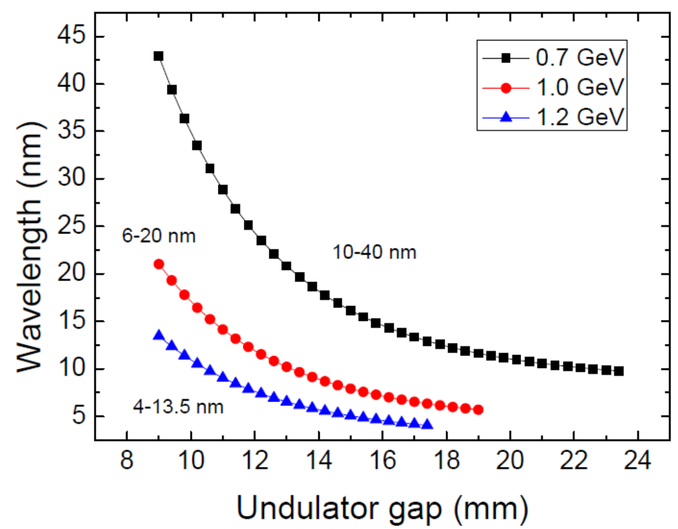
FLASH.
Free-Electron Laser in Hamburg

Siegfried Schreiber

Electron beam	
Beam Energy	0.5 – 1.25 GeV
Emittance (norm.)	1 – 3 mm mrad
Energy Spread	0.5 MeV
Peak Current	2.5 kA
Bunch charge	0.02 – 1 nC
Bunch spacing	1 – 25 µs
Repetition rate	10 Hz

Undulator	
Period	31.4 mm
Segment Length	2.5 m
Segments	12
Gap	Variable
Focusing	FODO

Energy	Wavelength
0.7 GeV	10 – 40 nm
1.0 GeV	6 – 20 nm
1.25 GeV	4 – 13.5 nm

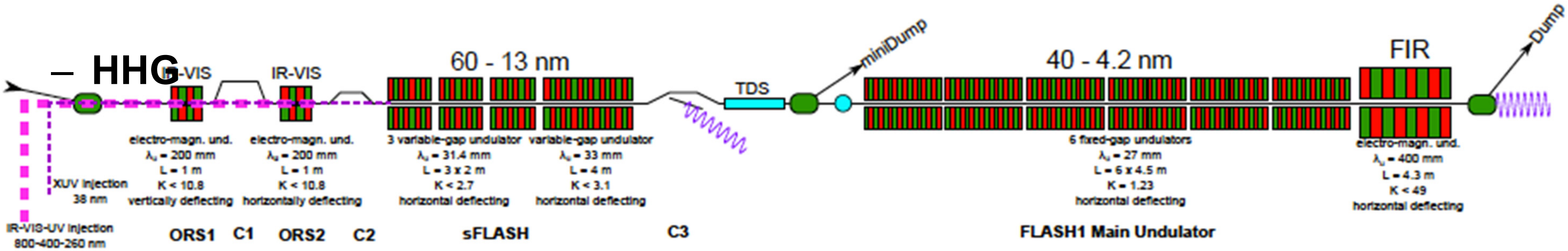


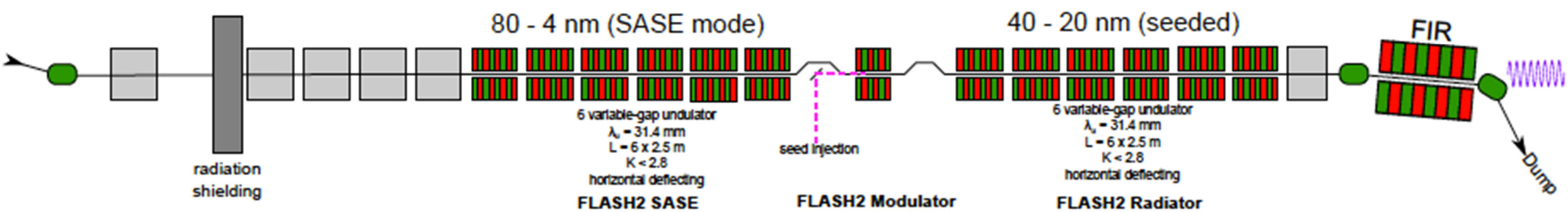
Seeding plans

FLASH.
Free-Electron Laser in Hamburg

Jorn Bodewadt and Christoph Lechner

- **FLASH-I**
  - **HGHG (single stage and cascaded seeding)**
  - **EEHG**
  - **HHG**



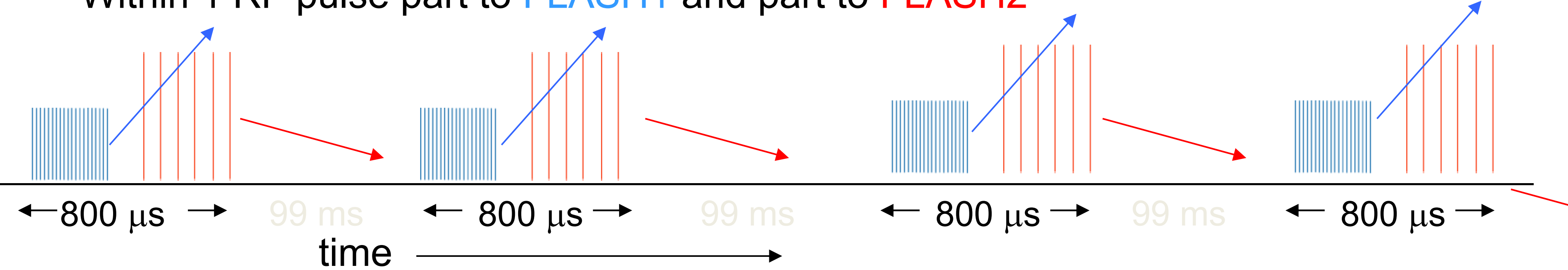


- **FLASH-II**
  - **UV seed**
  - **Initial 10Hz burst mode with an intra-burst repetition rate of 100 kHz**
  - **Upgrade to 1MHz**
  - **Hardware for FLASH2 seeding installed by the end of 2014**

Beamline switching (FLASH-I and FLASH-II)

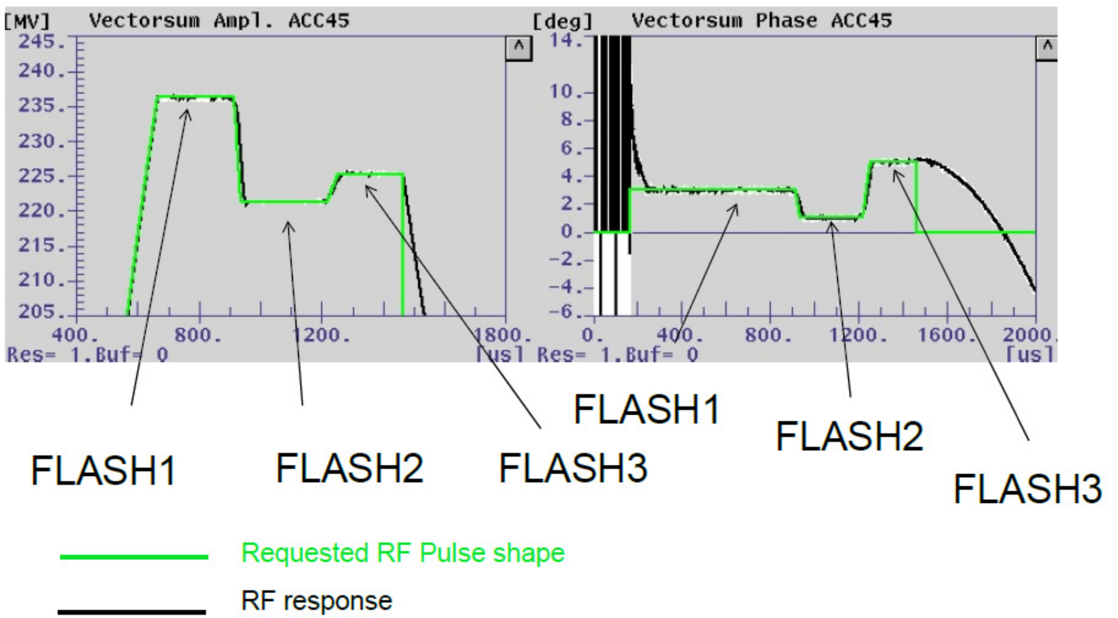
Siegfried Schreiber

Within 1 RF pulse part to FLASH1 and part to FLASH2



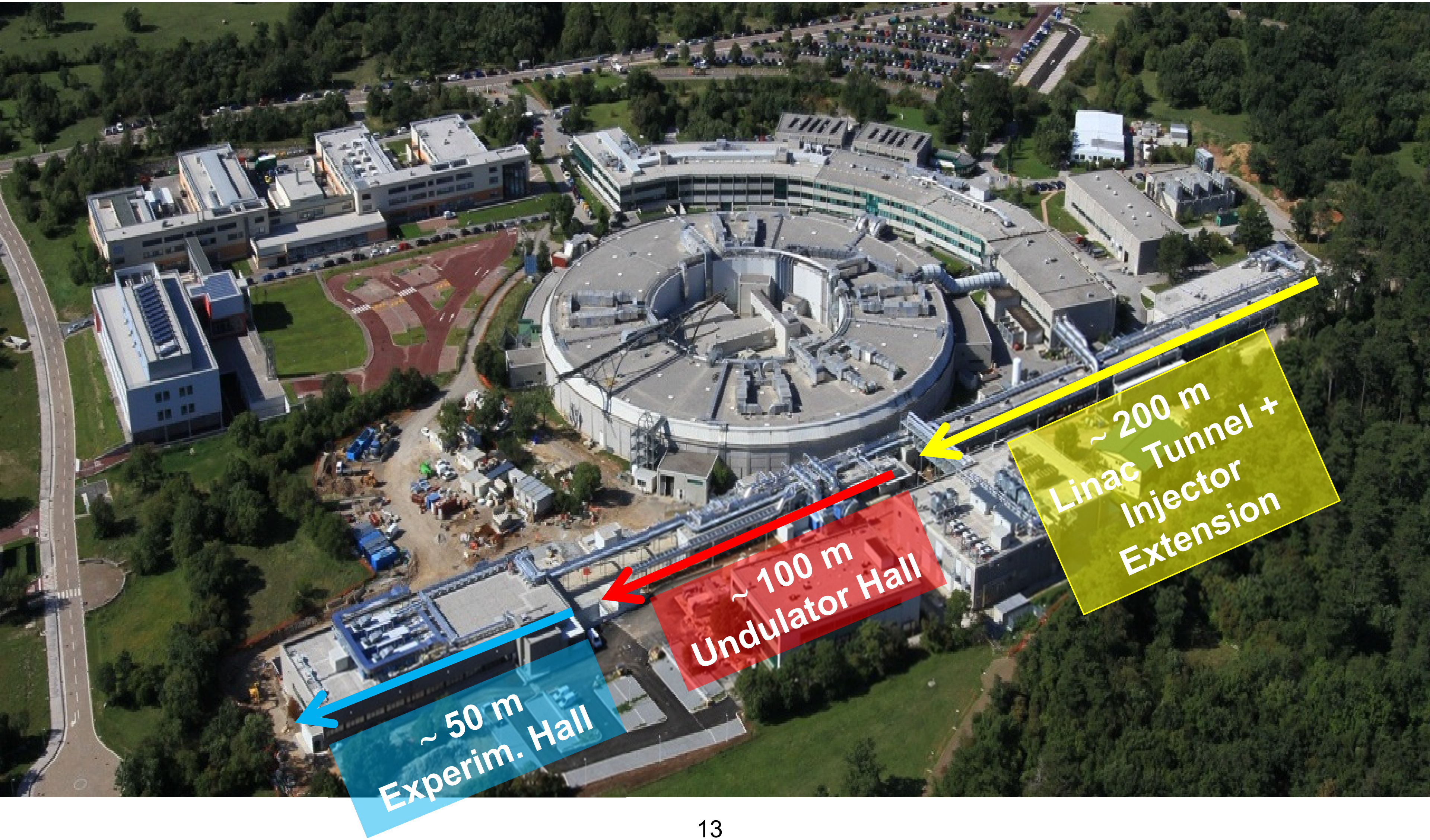
- **Flexibility in**
  - **Intra-train repetition rate**
  - **Number of pulses per train**
  - **Longitudinal pulse shape**
  - **Single pulse energy**
- **For both(!) user experiments**
- **Basics tested successfully**

Amplitude and Phase of Acceleration



FERMI at Sincrotrone Trieste

FERMI Commissioning Team



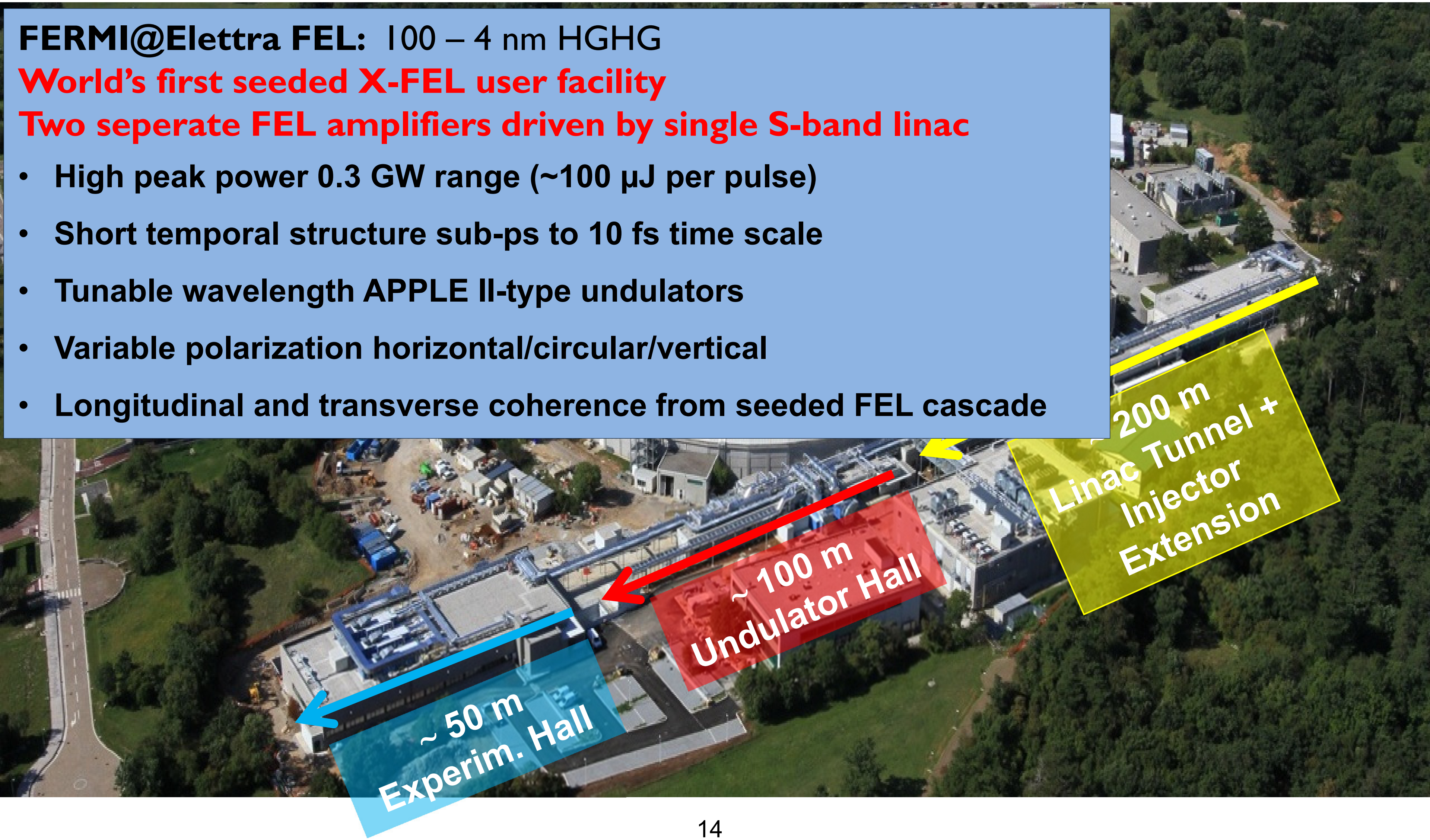
FERMI at Sincrotrone Trieste

FERMI@Elettra FEL: 100 – 4 nm HGHG

World's first seeded X-FEL user facility

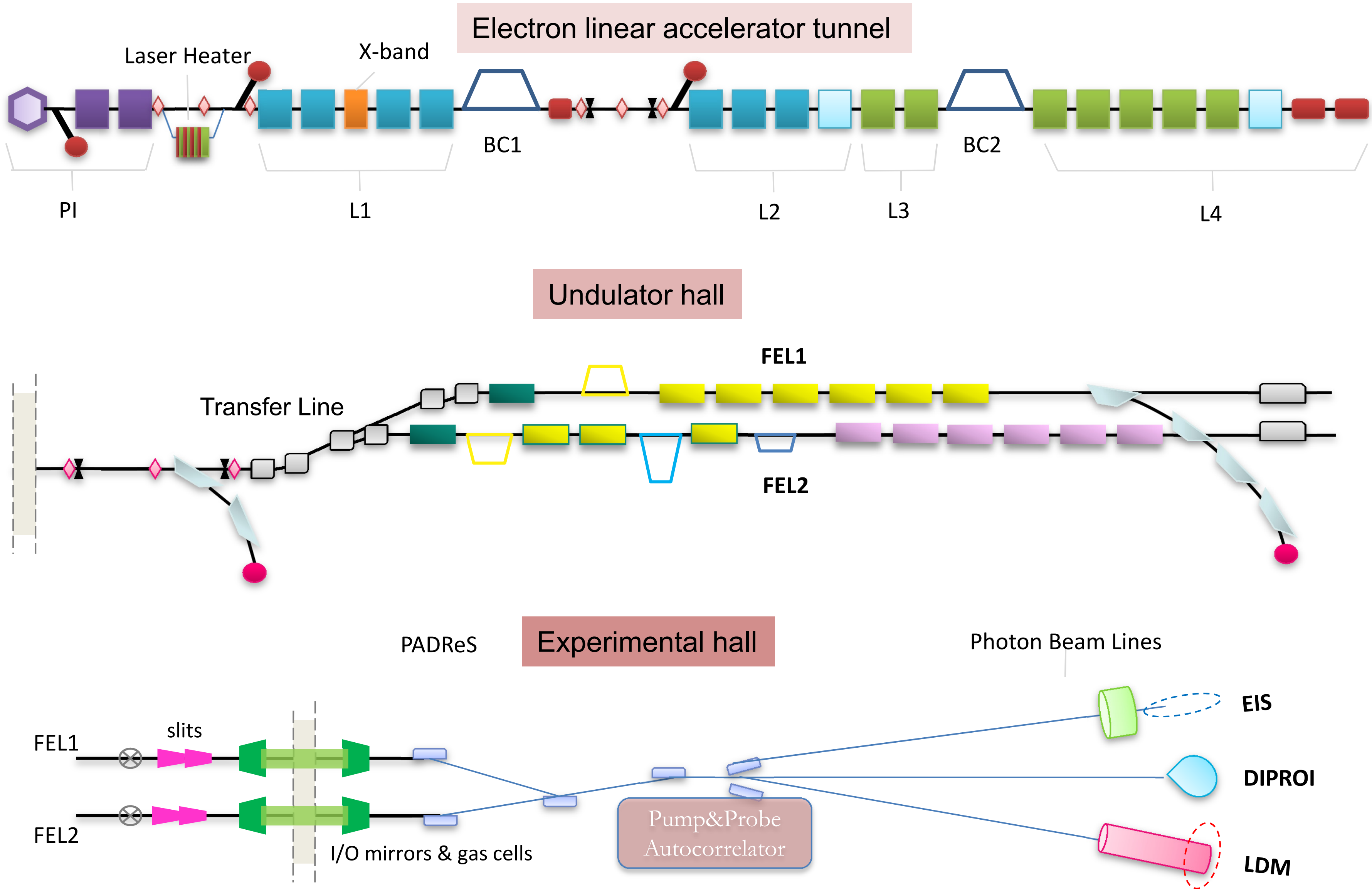
Two seperate FEL amplifiers driven by single S-band linac

- **High peak power 0.3 GW range (~100 μJ per pulse)**
- **Short temporal structure sub-ps to 10 fs time scale**
- **Tunable wavelength APPLE II-type undulators**
- **Variable polarization horizontal/circular/vertical**
- **Longitudinal and transverse coherence from seeded FEL cascade**



FERMI layout

FERMI Commissioning Team



FERMI FEL status

FERMI Commissioning Team

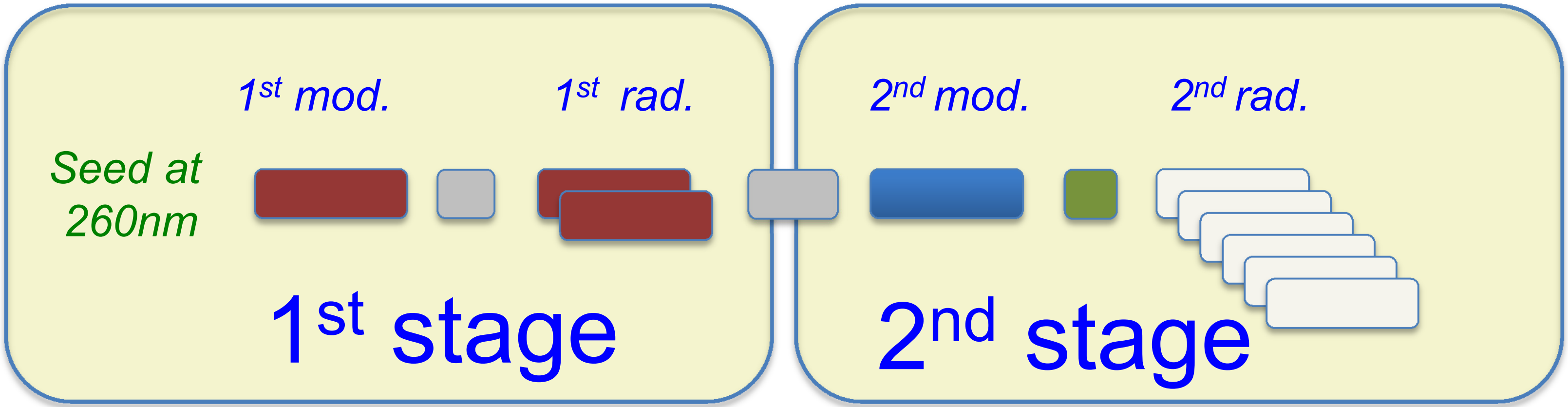
- FEL-1: Single stage cascaded FEL, full specifications achieved in 2012, now dedicated to user experiments
  - Continuously tuneable wavelength 20-65 nm (up to 100nm possible with specific machine setup)
  - Bandwidth (best) 5×10^{-4} @ 32 nm
  - Energy per pulse 30-100 uJ (depending on wavelength setting – up to a factor 2-3 more relaxing the spectral purity requirements)

- FEL-2: 2–stage, fresh bunch, cascade FEL, in commissioning
  - October 2012 commissioning @ 1.0 GeV, ~50 uJ @10.8 nm
  - Extended wavelength range down to 8 nm in March 2013 (@1.23 GeV) commissioning
  - Down to 5 nm in June 2013 (@1.4 GeV)
  - Coherent emission at 3 nm September 2013

FERMI FEL-2: commissioning

FERMI Commissioning Team

The Fresh Bunch Injection Technique

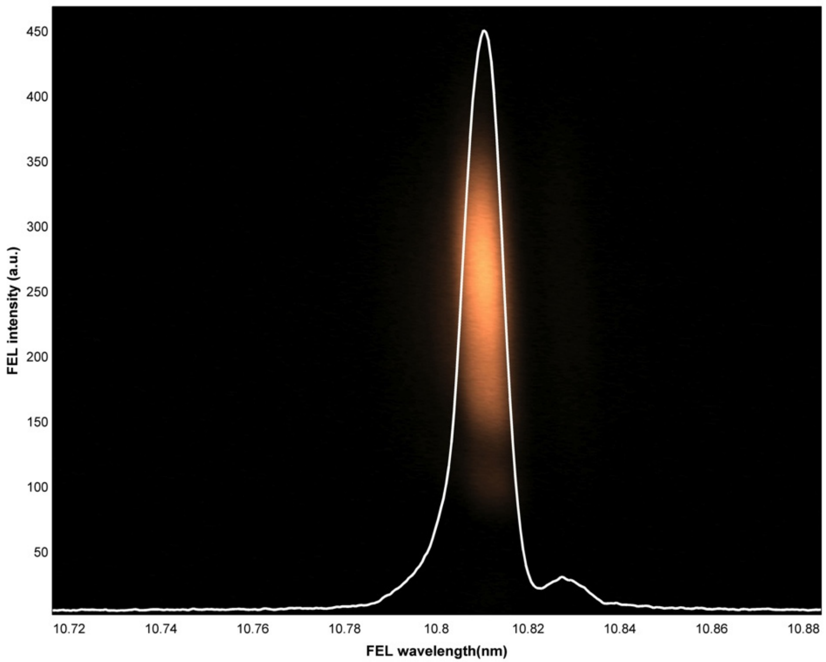


Two HGHG FEL stages (each equivalent to FEL-1)

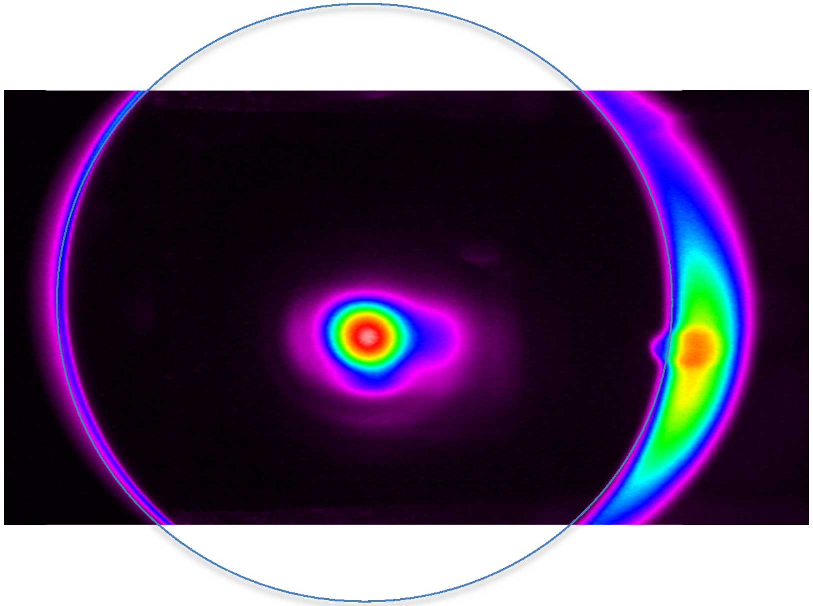
- **The first stage is seeded in the UV by aTi:Sa laser, 3rd harmonic**
  - **Radiates at ~4–6 harmonic**
- **The second stage is seeded by the first stage FEL**
  - **Radiates at a further harmonic**
- **The two FELs operate with the same electron beam**

FEL-2 First commissioning at 10.8 nm*

FERMI Commissioning Team



Narrow linewidth, single mode spectrum

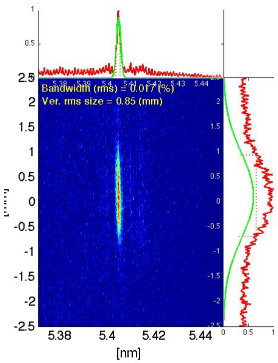


Gaussian like transverse mode

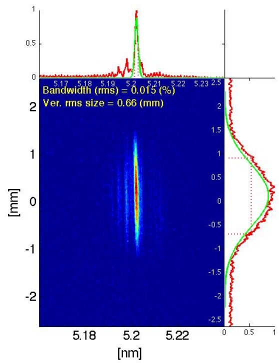
** E. Allaria et al. "Two Stage, Seeded Soft X-Ray Free-Electron Laser", submitted to Nature Photonics*

Coherent emission at shorter wavelengths

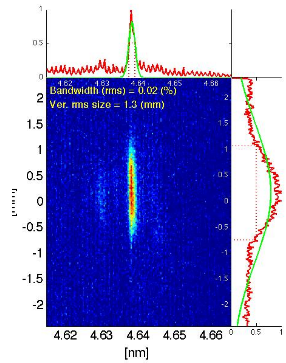
FERMI Commissioning Team



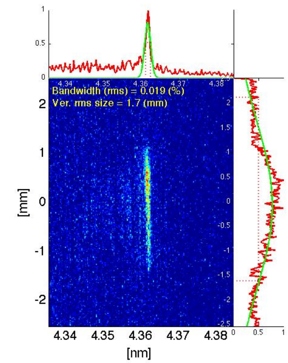
5.41 nm



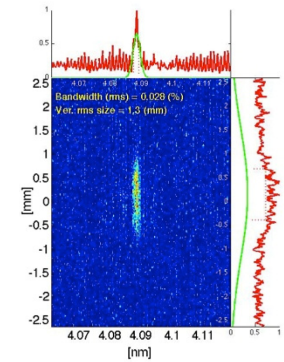
5.2 nm



4.64 nm

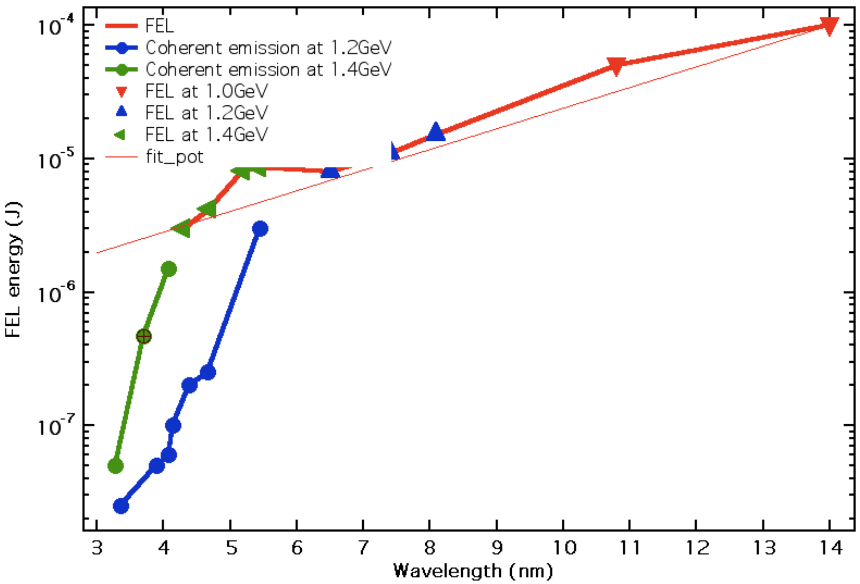


4.36 nm



4.09 nm

rms bandwidth ~$2x10^{-4}$

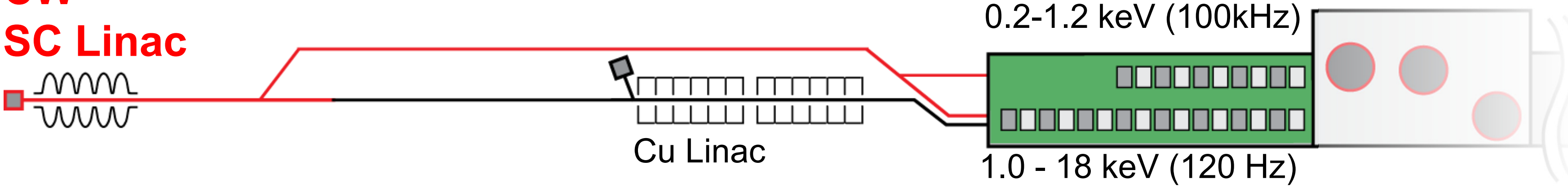


- **Coherent emission with FEL-2 has been obtained down to about 3nm**
- **Although very weak, single shot spectra have beam measured up to 4 nm and the good ones show narrow line (10^{-4})**
- **Real FEL gain is at the moment limited to about 4 nm due to the electron beam energy limit**
- **Larger energy per pulse would be accessible with brighter electron beam (higher peak current)**

LCLS-II outline

Tor Raubenheimer

4 GeV
CW
SC Linac



- **Uses much existing SLAC infrastructure to house the FEL**
- **NEW high brightness high rep-rate injector**
- **Two sources: NEW high rate SCRF linac and 120 Hz NC LCLS-I linac**
- **NEW undulators *always* operate simultaneously in any mode**

Undulator	SC Linac (up to 100kHz)	Cu Linac (up to 120Hz)
North	0.25-1.2 keV	
South	1.0-5.0 keV	Up to 18 keV Higher peak power pulses

Preliminary schedule completes project in 2020

LCLS-II preliminary operating parameters

Tor Raubenheimer

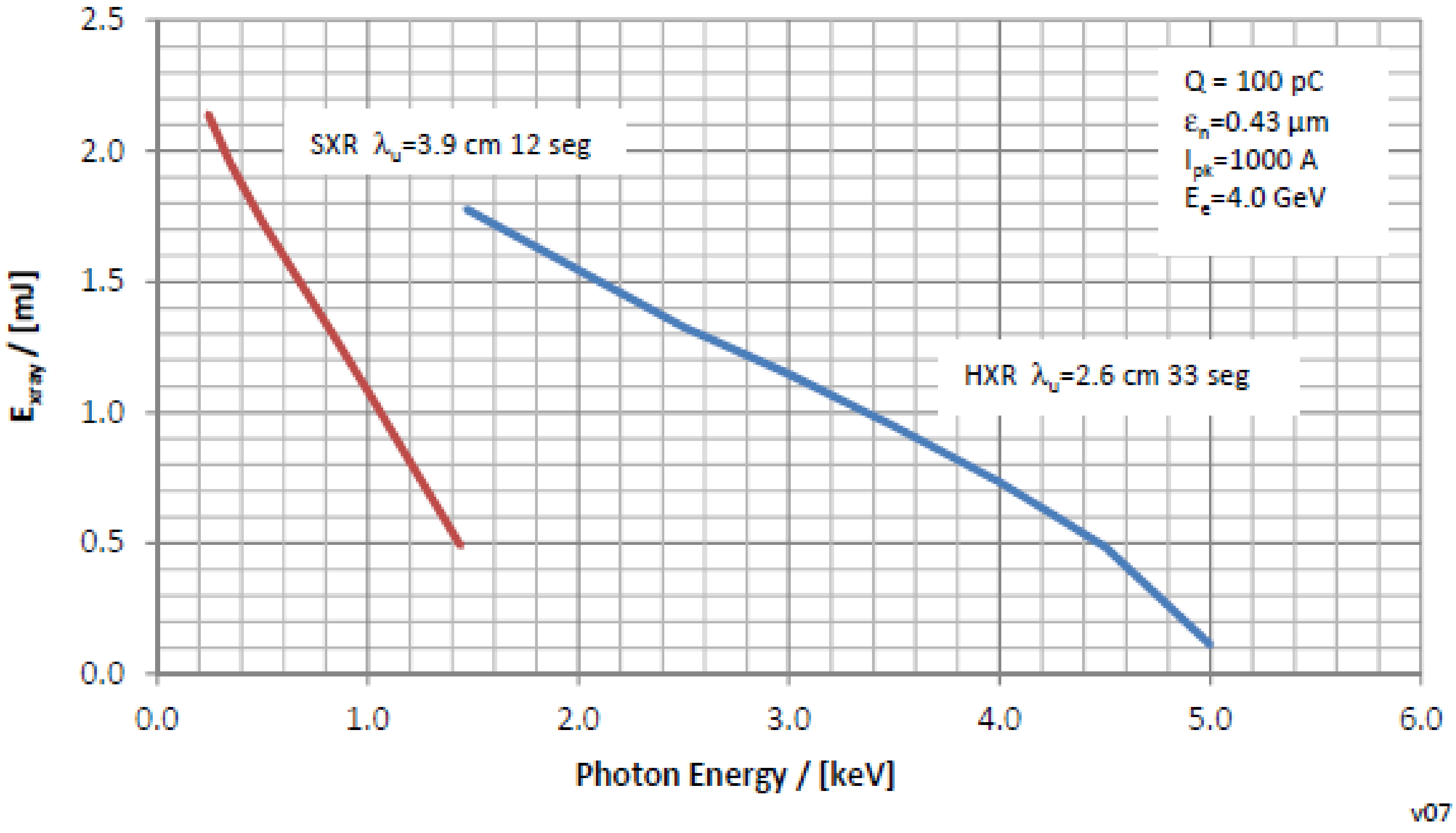
Preliminary LCLS-II Summary Parameters		v0.7	8/30/13
	North Side Source	South Side Source	
Running mode	**SC Linac**	**SC Linac**	Cu Linac
FEL mode	**Self-seeded**	**Self-seeded**	Self-seeded
Repetition rate	**up to 1 MHz***	**up to 1 MHz***	120 Hz
Electron Energy	**4 GeV**	**4 GeV**	14 GeV
Undulator period	**~40 mm**	**~26 mm**	~26 mm
Photon energy	**0.25-1.2 keV**	**1-5 keV**	1-20 keV
Max Photon pulse energy (mJ) (full charge, long pulse)	**up to 2 mJ***	**up to 2 mJ***	up to10 mJ
Peak Spectral Brightness (10 fs pulse) (low charge, 10pC)	**3.9×10^{30} ****	**12×10^{30} ****	247×10^{30} **
Peak Spectral Brightness (100fs pulse) (full charge, 100pC)	**3.0×10^{30} ****	**6.9×10^{30} ****	121×10^{30} **

* Limited by beam power on optics

**N_photons/(s*mm^2*mrad^2*0.1% bandwidth)

LCLS-II X-ray pulse energy at High Rate

Tor Raubenheimer



LCLS-II initial assumed beam parameters

Tor Raubenheimer

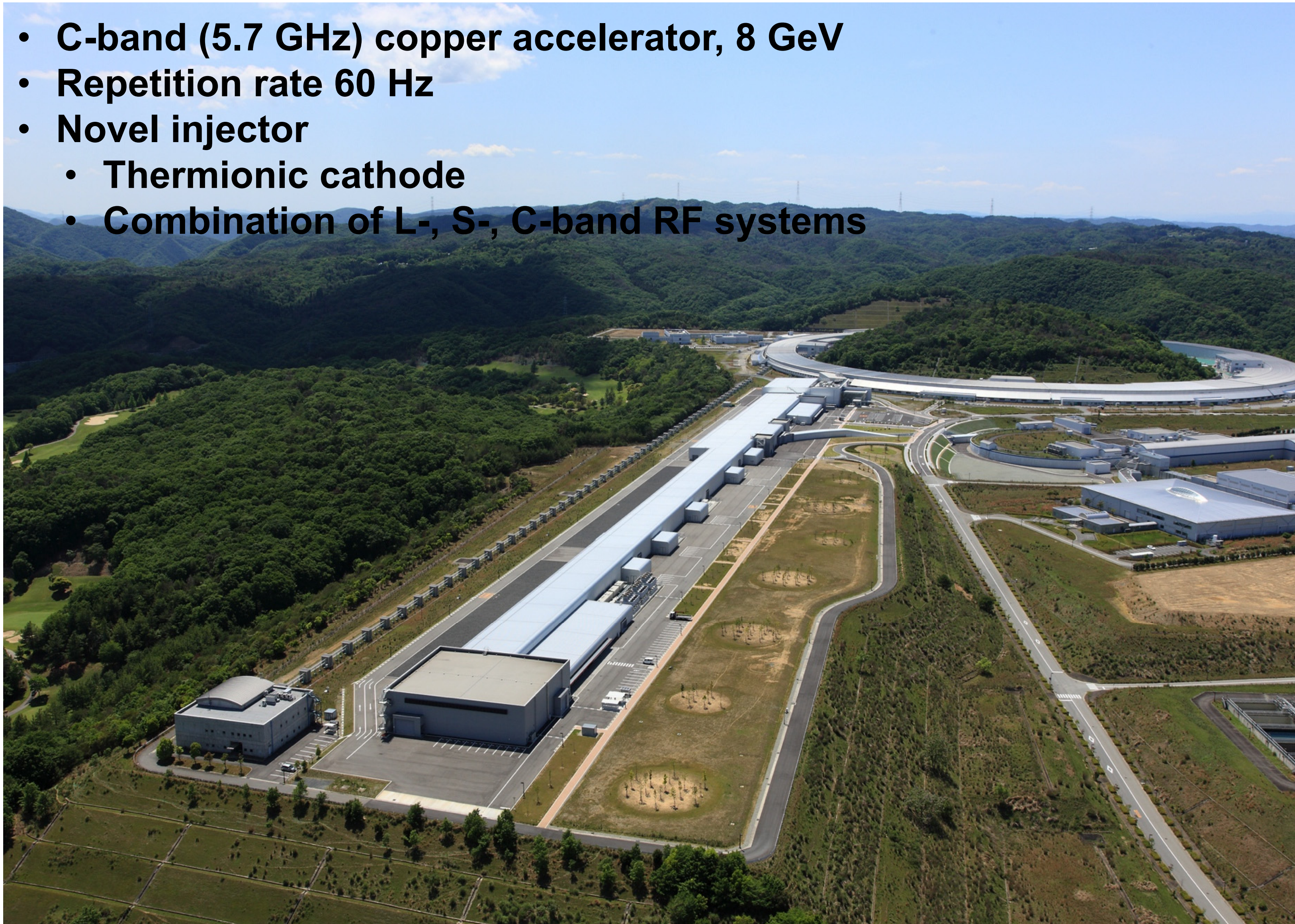
	NLS	NGLS	LCLS-II
Beam energy [GeV]	2.25	2.4	4
Bunch charge [pC]	200	300	100
Emittance [mm-mrad]	0.3	0.6	0.43
Energy spread [keV]	150	150 keV	300 keV
Peak current [kA]	0.97	0.5	1
Useful bunch fraction [%]	40	50	50

- **APEX high rep-rate high-brightness injector**
- **ILC-like 1.3 GHz linac, modifications to allow CW operation**
- **Initial 2 FELs**
- **Upgradeable (switchyard) to drive additional FELs**

SACLA upgrade plans

Hitoshi Tanaka

- C-band (5.7 GHz) copper accelerator, 8 GeV
- Repetition rate 60 Hz
- Novel injector
  - Thermionic cathode
  - Combination of L-, S-, C-band RF systems



Major upgrade projects

Hitoshi Tanaka

Goals of higher laser availability and performance

Converting the present SACLA system step-by-step into the system with:

- multi-electron beam drivers,
- various seeding schemes,
- pulse-by-pulse beam switcher,
- 5 UND BLs including one SX BL

P1: Construction of new undulator beamline BL2
~Mar. 2015

P2: Pulse-by-pulse e-beam switching
~June 2015

P3: Construction of self-seeding system
~Dec. 2013

P4: Relocation and upgrade of SCSS test accelerator
~Dec. 2014

P5: Increase of e-beam energy up to 9- GeV
~Sep. 2014

P represents "Project"

P4: Relocation of SCSS test accelerator

Hitoshi Tanaka

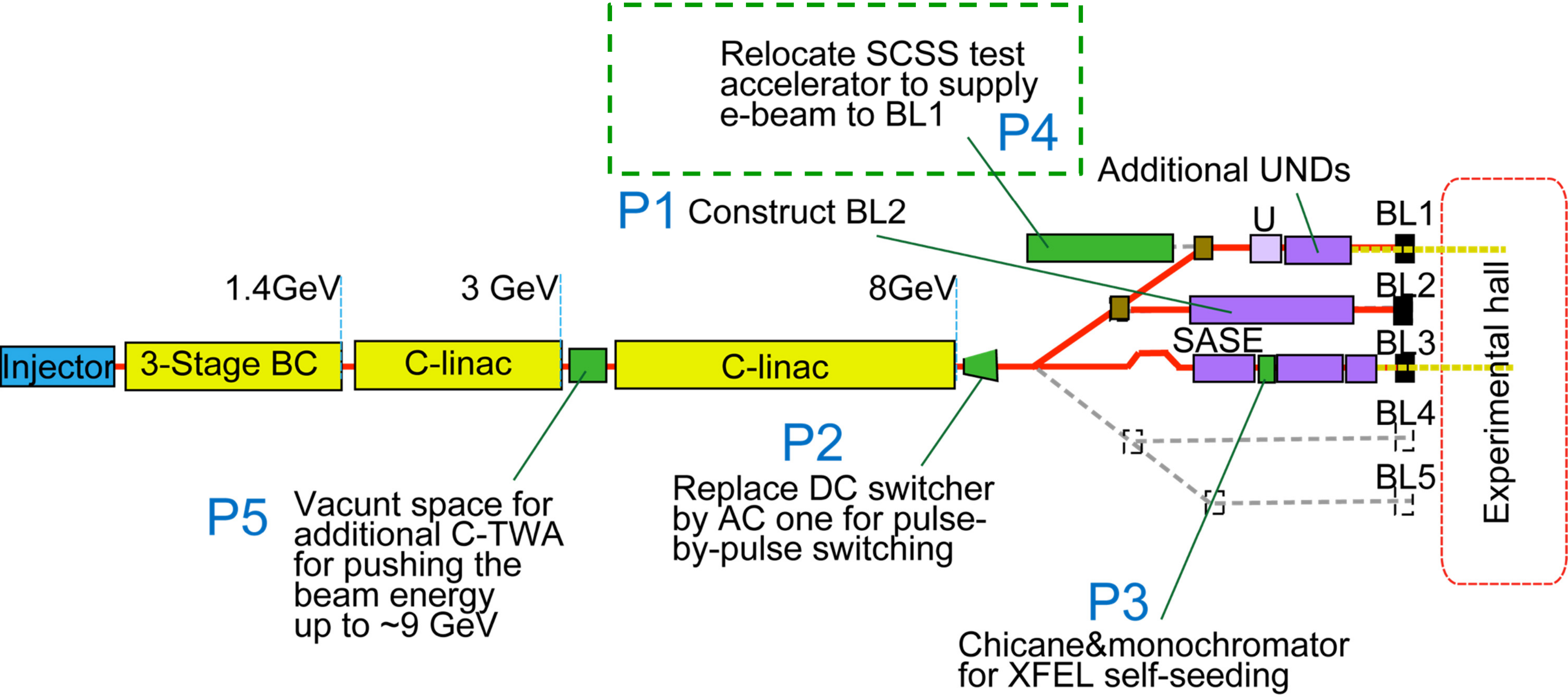
- SCSS test accelerator (e-beam energy 250 MeV) was a prototype for SACLA
  - Stable EUV FEL (200–50 nm)
  - HHG seed 61.5 nm
  - Shut down in May 2013

- Relocation to the SACLA undulator hall is in progress
- SCSS becomes a dedicated electron beam driver for BL1
- Initial beam energy ~450 MeV
- Potentially up to ~1.4 GeV
- Capability for EUV to soft X-rays

Outline of upgrade projects

Hitoshi Tanaka

SXR undulator period 18 mm
Wavelength range 15 – 60 nm initially
Date of SX FEL operation: Autumn 2015



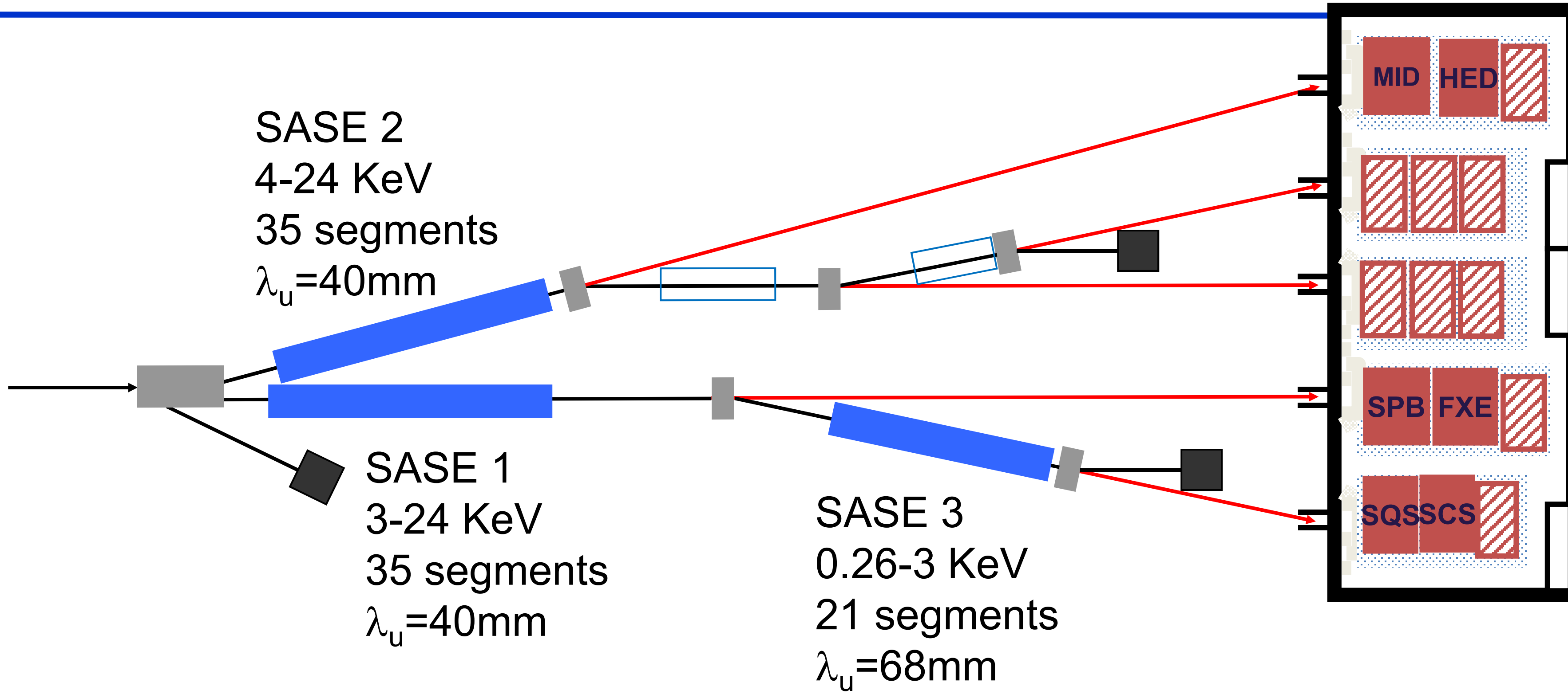
European XFEL project

Winfried Decking

- **Built by 12 European Nations at DESY, Hamburg**
- **Up to 17.5 GeV SC Linac, 27000 pulses per second**
- **Three moveable gap undulators for hard and soft X-rays**
- **Initially 6 equipped experiments**

XFEL Undulator Systems

Winfried Decking

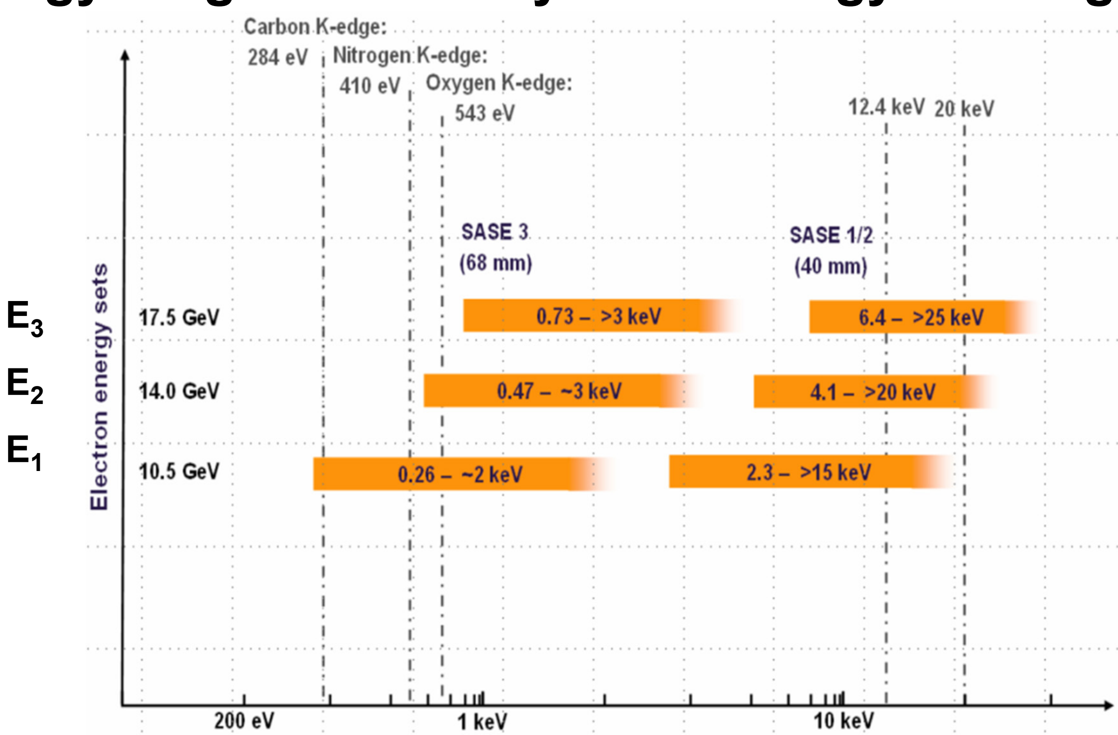


- **Flexible beam distribution with simultaneous operation of 3 experiments**
- **Up to 27000 bunches/second in 10 Hz bursts**
- **SASE3 (soft X-ray) operates either with ‘spent’ beam or ‘fresh bunch technique**
- **Fast variation of e-beam properties under investigation**

Soft X-ray capabilities

Winfried Decking

- **Baseline layout pure SASE**
- **68 mm period, tunable PM undulators**
- **Recent studies show potential to obtain 10 TW radiation at 3-5 keV with strong compressed bunches**
- **Self-seeding options and helical 'after-burner' under study (funding …)**
- **Photon energy range covered by three energy working points and gap movement**



Status

Winfried Decking

Civil Construction

- Underground construction finished
- Surface buildings construction on-going

Technical Infrastructure

- Injector building and accelerator tunnel finished by 9/2013
- Remaining installation ongoing till 2015

Industrial production and treatment of SC cavities (as of 05.08.2013)

- ~100/800 cavities delivered, > 60 cavities tested in vertical test stand
- ‘useable’ gradient 29 MV/m (23.5 MV/m required)

Assembly of 103 cryo-modules

- 2 of 3 pre-series modules assembled
- Series assembly to start late summer 2013

High Power RF components (modulator, pulse transformer, connection module klystron) delivered to about 50%

Undulator series production in full swing, about 40 of 91 units delivered, tuning on-going

About 50 % of 800 warm magnets produced

Warm vacuum beam line (about 3.3 km) series production started

Schedule

Winfried Decking

- High power rf-gun test – 10/2013
- First beam through injector – 09/2014
  - Challenging because of cryo components availability
- All infrastructure ready – 04/2015
- Start beam commissioning (T0) – 07/2015
  - Challenging because of module assembly, test and installation schedule
- First lasing possible @ SASE 1 (T0 + 6 month) – 12/2015
  - Challenging because of short commissioning time

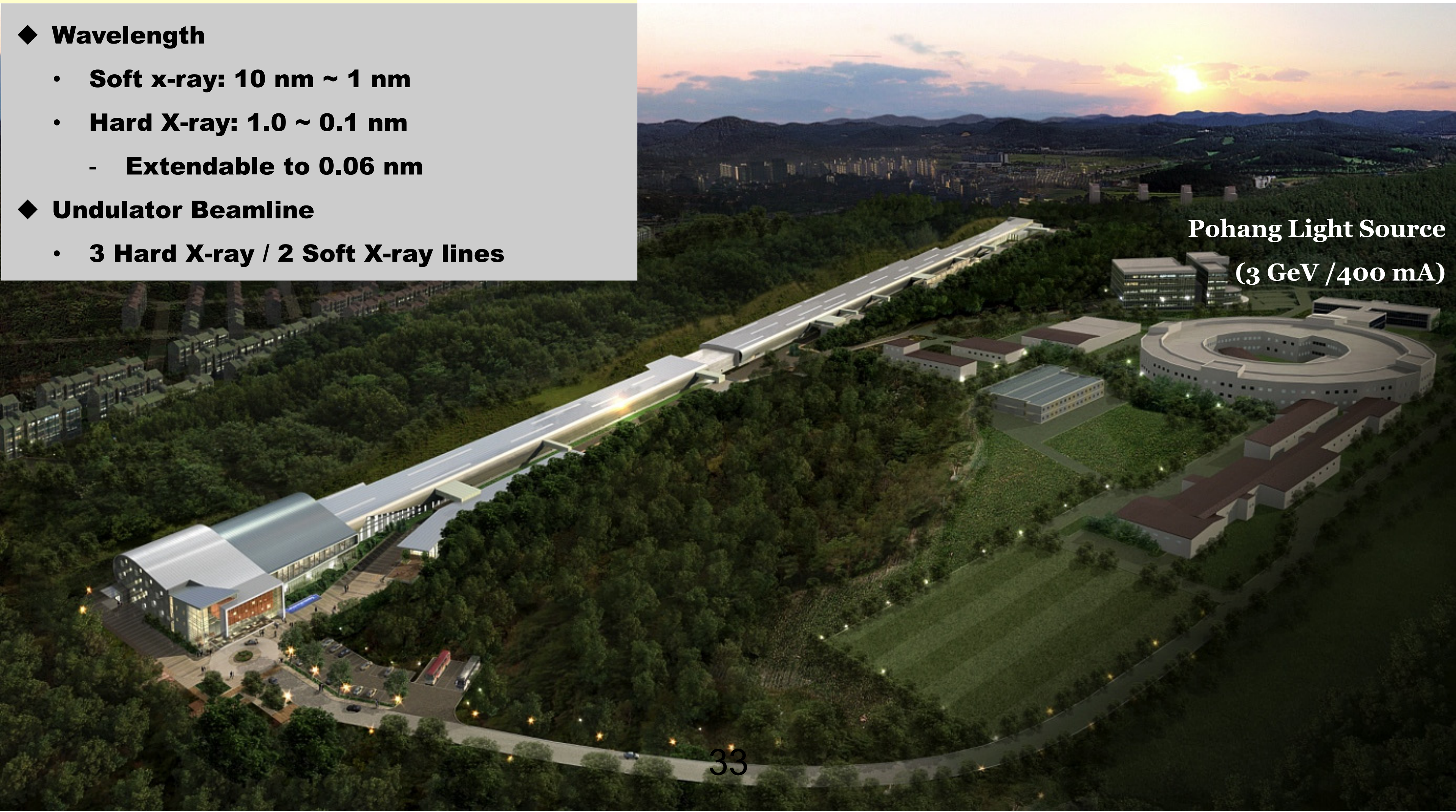
Korean 4-th generation Light Source: PAL-XFEL

Heung-Sik Kang

0.1-nm Hard X-ray 10-GeV XFEL

- **S-band linac, 1.1 km**

- **Wavelength**
  - **Soft x-ray: 10 nm ~ 1 nm**
  - **Hard X-ray: 1.0 ~ 0.1 nm**
    - **Extendable to 0.06 nm**
- **Undulator Beamline**
  - **3 Hard X-ray / 2 Soft X-ray lines**



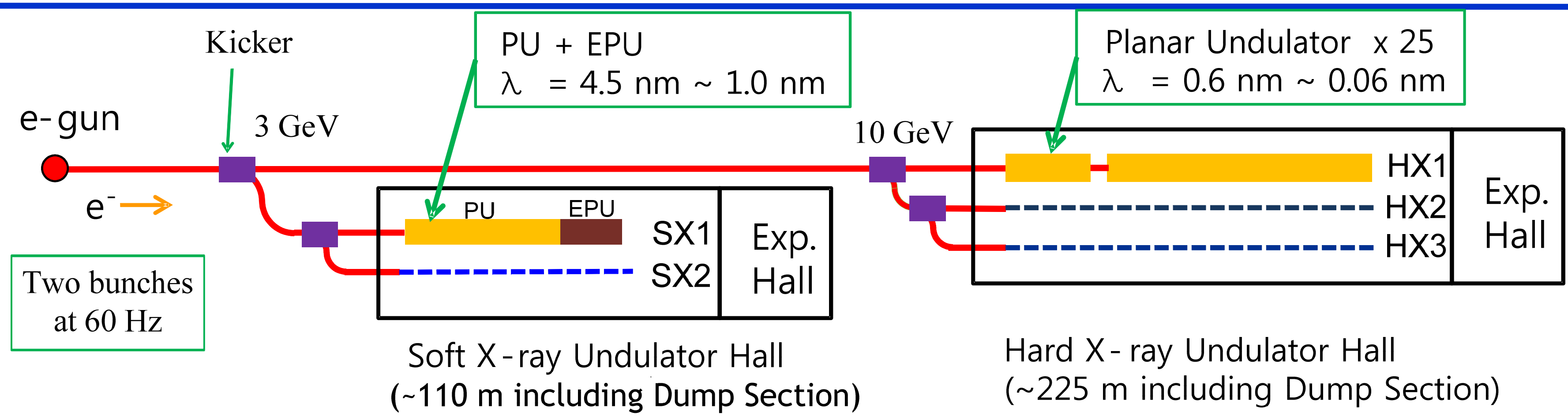
PAL-XFEL site May 2, 2013

Heung-Sik Kang

FEL commissioning and first experiments planned for 2016

Two undulator lines for Phase 1

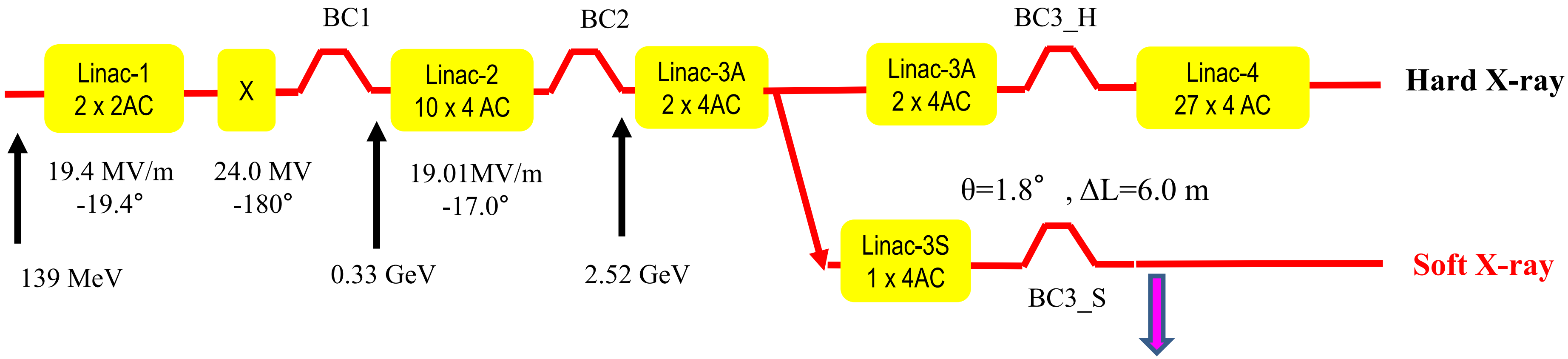
Heung-Sik Kang



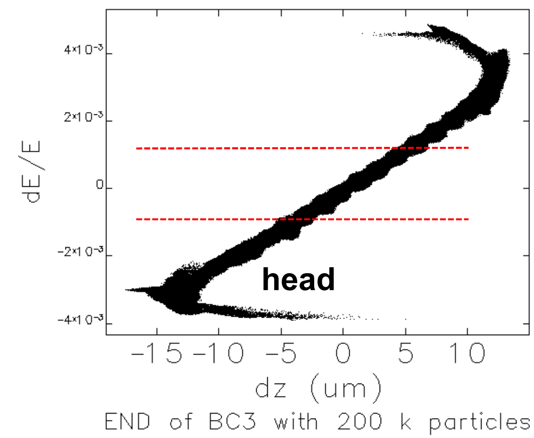
Undulator Line	SX1
Wavelength [nm]	**1 ~ 4.5**
Beam Energy [GeV]	**3.15 (2.55)**
Wavelength Tuning [nm]	**3 ~ 1 (Undulator gap) 4.5 ~ 3 (Beam Energy)**
Undulator Type	**Planar + APPLE II**
Undulator Period [cm]	**3.4**
Undulator Gap [mm]	**8.3**

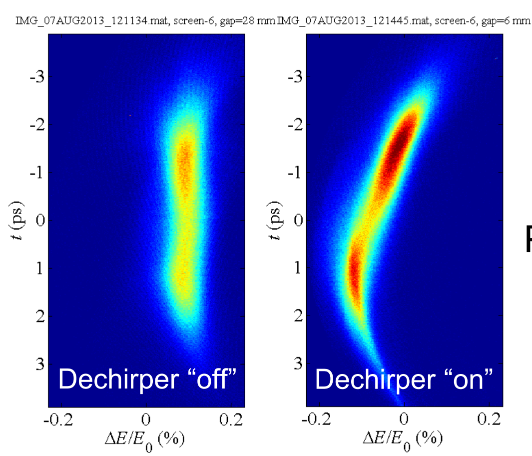
Need "dechirper" for longitudinal phase space control in soft X-ray beamline

Heung-Sik Kang



- Energy chirp is larger than FEL parameter
- Need strong longitudinal wake
- "Dechirper"
  - Experiments at PAL-XFEL injector test facility confirm performance

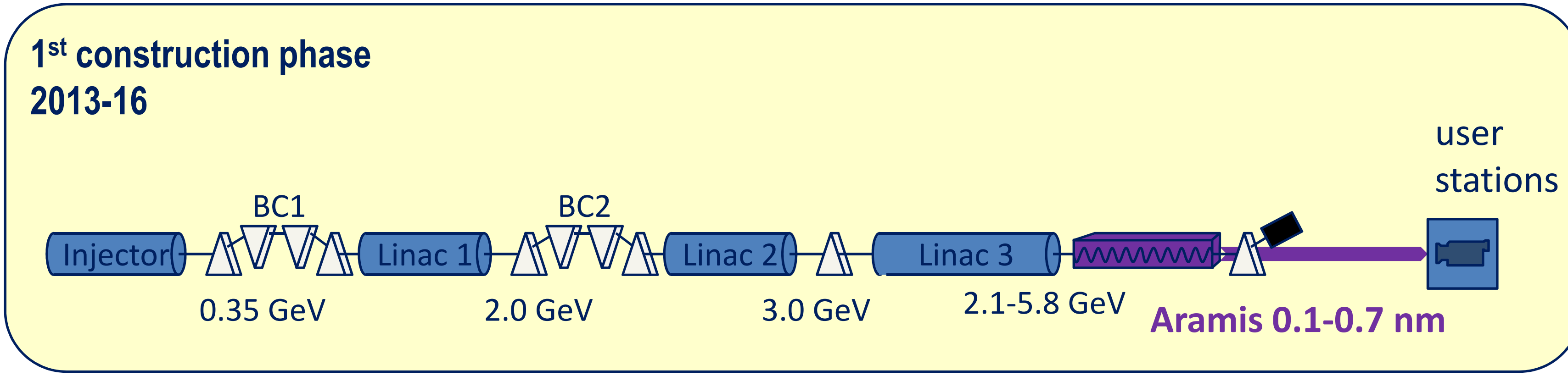




P. Emma

SwissFEL layout

Sven Reiche



- **S-band RF photo-electron gun, injector, 100 Hz**
- **C-band linac up to 6 GeV**
  - **Fewer RF stations, less real estate and electrical power than S-band**
- **Branch line for future Athos (SXR FEL)**
  - **40 mm period APPLE-II type variable gap undulators with polarization control**
  - **Self-seeded**
    - **PSI, SLAC, LBNL on soft X-ray seeding experiment in LCLS scheduled for end 2013**
- **2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz**

SwissFEL layout

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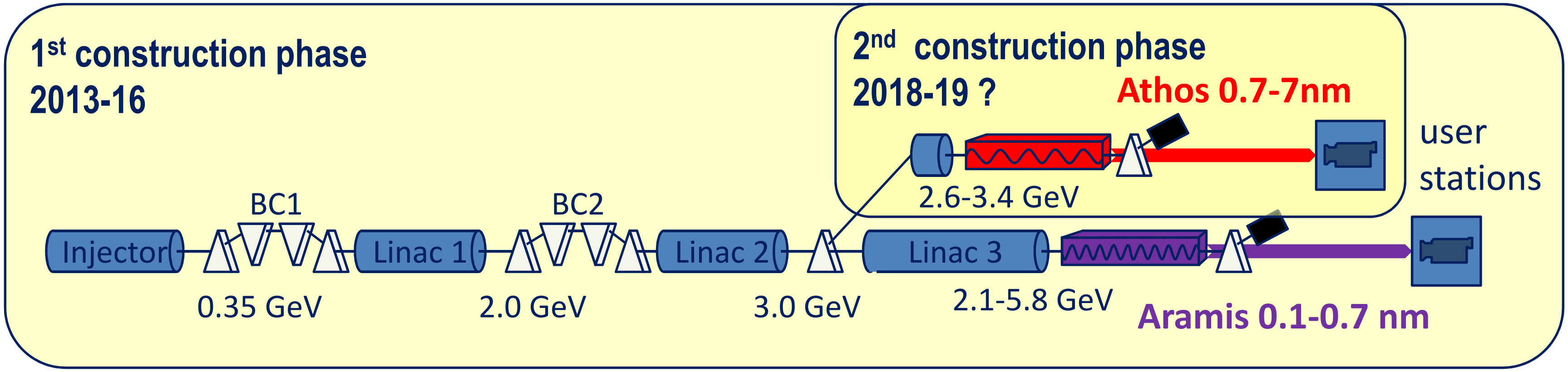

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SwissFEL construction site 27 June 2013

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PSI
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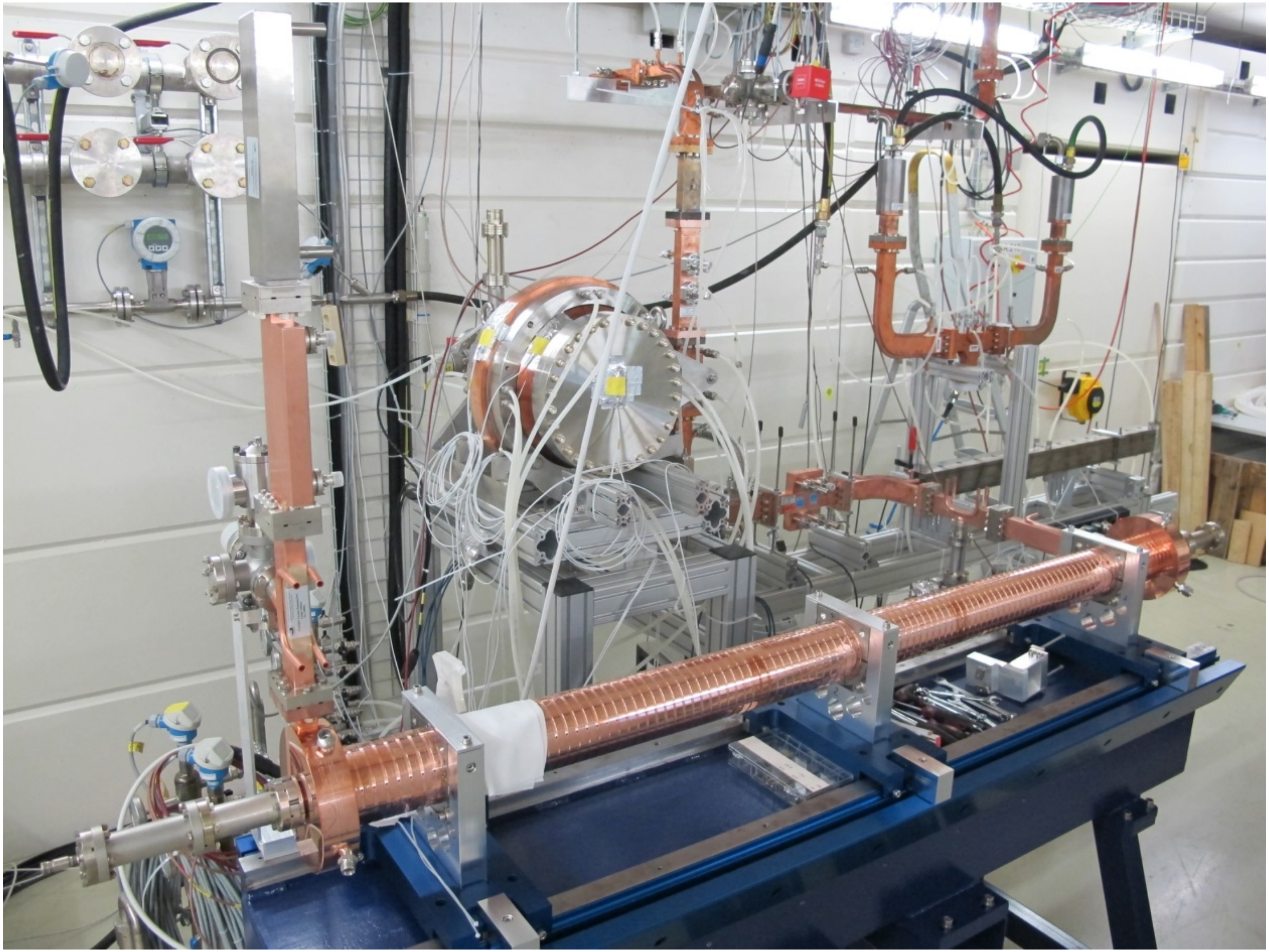
C-band structure under test

Sven Reiche



SwissFEL schedule

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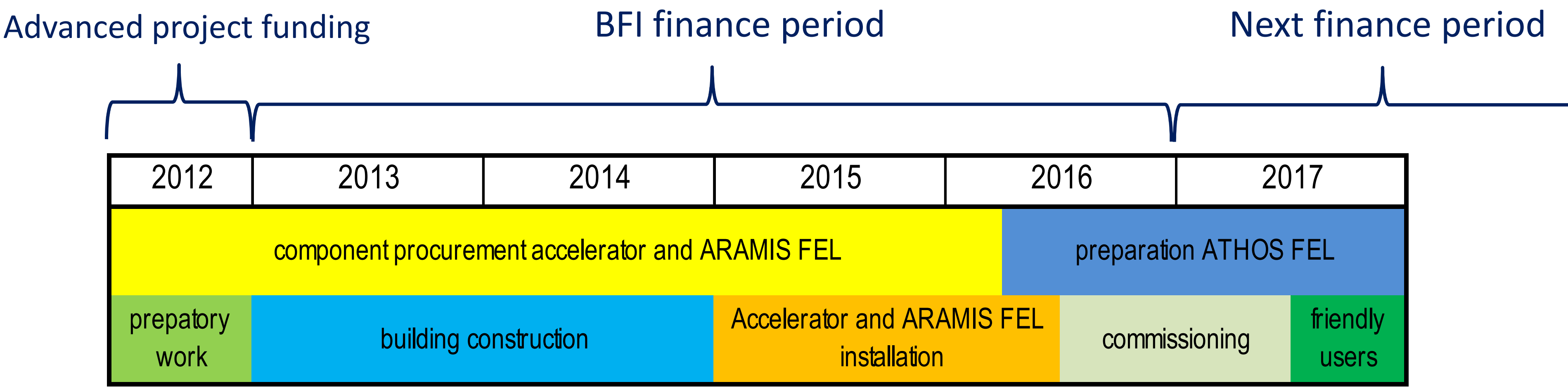

- **For seamless continuation of SwissFEL efforts towards ATHOS additional funds need to be secured for 2017-20 period**
- **May be difficult before presentation of first ARAMIS results**

Summary: many exciting developments in soft X-ray FELs

- **Several operational: upgrades to enhance performance and capacity**
  - FLASH: FLASH2 adds capacity, tunability, and seeding (2014)
  - FERMI@elettra: FEL-2 longitudinal HGHG at 4 nm; higher rep-rate (2014)
  - SACLA: Upgrades to improve stability, add soft X-ray capability with SCSS (2015)
  - LCLS: LCLS-II adds CW SCRF, high rep-rate, high average power, and capacity (2020)

- **Several new projects are at various stages of development**
  - XFEL: 17.5 GeV SRF linac, SXR and HXR capability; high-power beams (SASE, 2015)
  - PALFEL: compact 10 GeV HXR, 3.15 GeV branch line SXR (SASE, 2016)
  - SwissFEL: compact 6 GeV (2017), SXR future (3 GeV branch line, self-seeded, 2019?)

- **Several facility proposals**
  - IRIDE, NGLS, SXFEL, WiFEL ...

- **Many FEL R&D projects and facilities**
  - APEX, ATF, CLARA, JLAB, LUNEX-5, MAX-IV, NLCTA, SCSS, SDL, SDUV FEL, SPARC, WiFEL, ...

Summary: many exciting soft X-ray FEL projects

Facility / Project	Maximum electron beam energy	Main linac type	X-ray pulse time structure	FEL type and tuning range	Radiator undulator period, type
FLASH	1.2 GeV	Superconducting L-band	Burst, flexible, up to ~500 bunches separated by ≥ 0.33 μs per pulse, 10 Hz burst rate	SASE: 4.2–40 nm	27.3 mm, fixed gap PM
FLASH-II	1.2 GeV	Superconducting L-band	Burst, flexible, bunches separated by ≥ 1 μs per pulse, 10 Hz burst rate	SASE: 4–40 nm HGHG: UV seed, 20–40 nm	31.4 mm, variable gap PM
sFLASH	1.2 GeV	Superconducting L-band	Burst, flexible, bunches separated by ≥ 0.33 μs per pulse, 10 Hz burst rate	HGHG: UV seed, ≤60 nm (cascade for shorter wavelength) HHG 38.2 nm seed EEHG, LSCA options under study	31.4 mm + 33 mm, variable gap PM
LCLS	15 GeV	Normal conducting S-band	120 Hz CW	SASE: 0.12–4.5 nm Self-seeded HXR: 0.16–0.18 nm	30 mm, fixed gap PM
LCLS-II	4 GeV	Superconducting L-band	100 kHz CW	Self-seeded: 1–5 nm Self-seeded: 0.25–1.2 nm	~40mm, variable gap PM ~26mm, variable gap PM
FERMI@elettra	1.2 GeV	Normal conducting S-band	10 Hz, upgrading to 50 Hz, CW	HGHG; UV seed 20–65 nm (FEL1) HGHG 2-stage cascade; UV seed, 4–20 nm (FEL2)	55.2 mm, variable gap APPLE-II PM 55.2 mm + 34.8 mm variable gap APPLE-II PM
SACLA	8.5 GeV (SCSS: 0.45 – 1.4 GeV)	Normal conducting C-band	10 Hz, capable of up to 60 Hz, CW	SASE: 0.6 Å Self-seeded SXR planned: 15–60 nm	18 mm in-vacuum variable gap PM
EuXFEL	17.5 GeV	Superconducting L-band	Burst, flexible, up to ~2700 bunches separated by ≥ 0.22 μs per pulse, 10 Hz burst rate	SASE: 0.5–4 Å SASE: 0.4–4.5 nm	40 mm, variable gap PM 68 mm, variable gap PM
SwissFEL	5.8 GeV	Normal conducting C-band	100 Hz, CW	SASE: 1–7 Å Self-seeded SXR planned: 0.7–7 nm	15 mm in-vacuum variable gap PM 40 mm variable gap APPLE-II PM
PAL-XFEL	10 GeV	Normal conducting S-band	60 Hz, CW	SASE: 0.6–6 Å Self-seeded SXR planned: 1–4.5 nm	24.4 mm variable gap PM 34 mm variable gap APPLE-II PM

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Thank you for your attention!