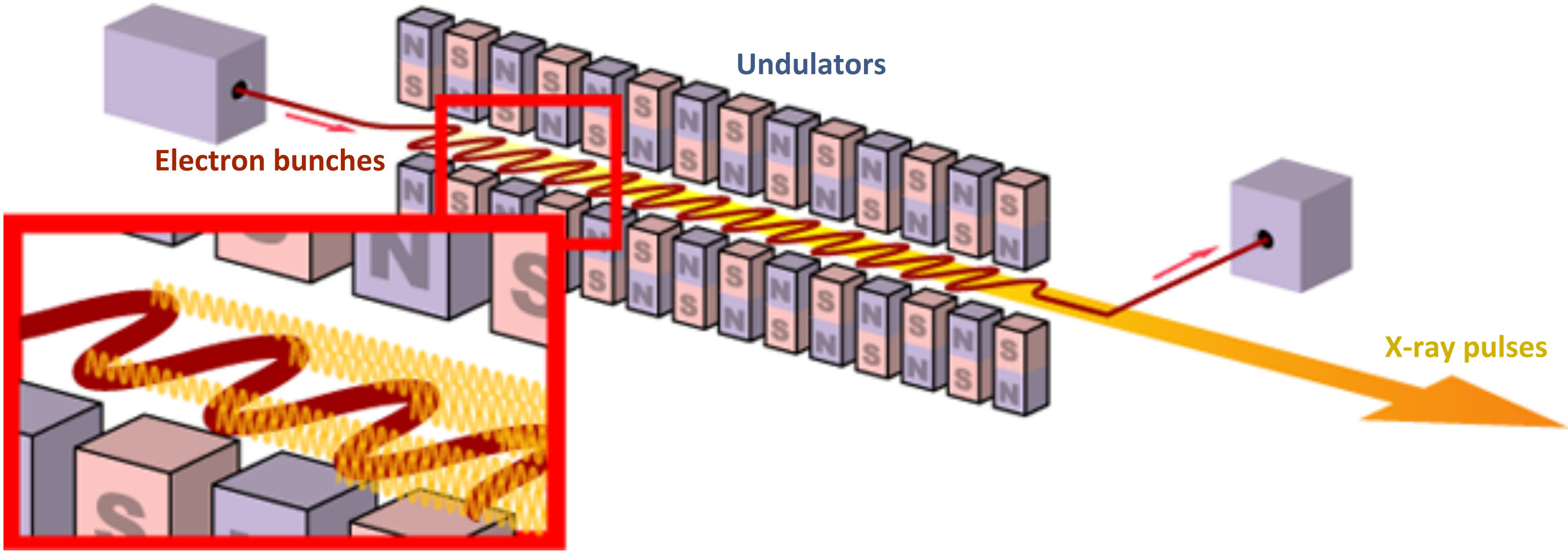
Review of X-ray FEL Projects

John Corlett
LBNL

LINAC 2012
Tel Aviv, September 2012

FEL process

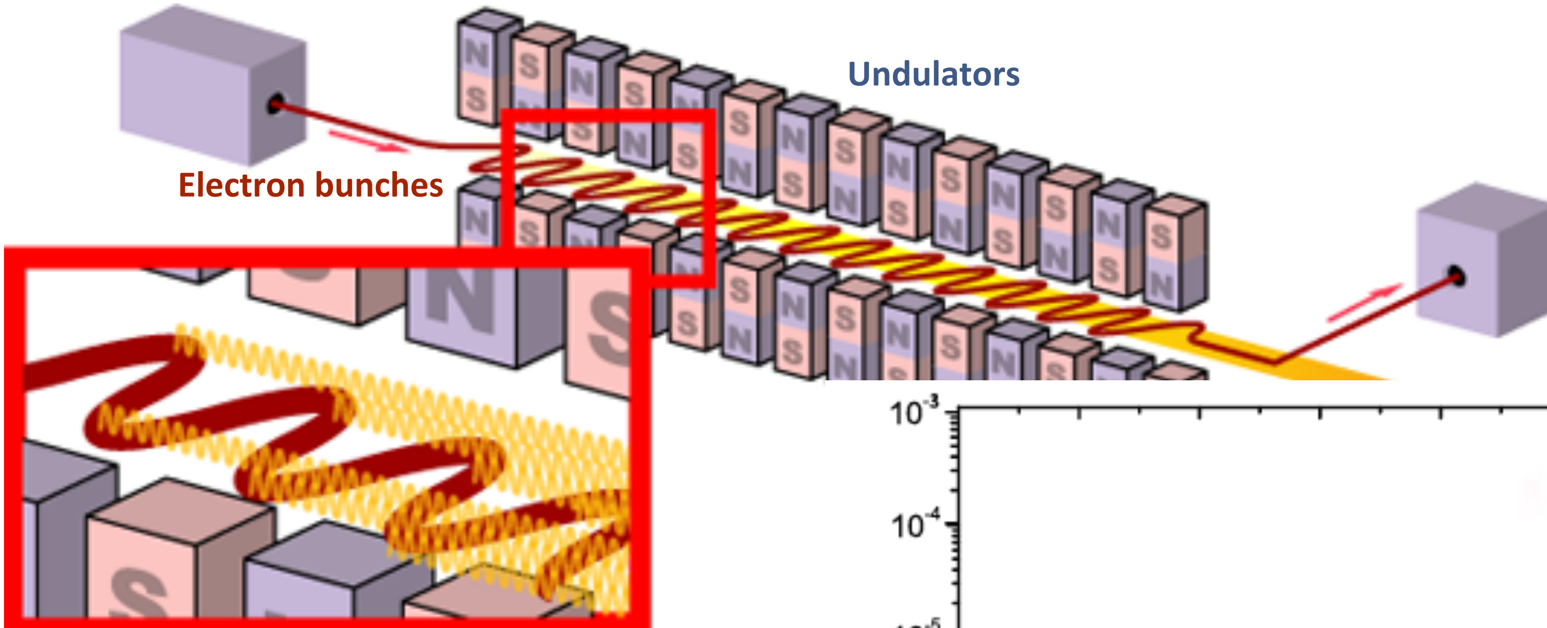


$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{eB_0\lambda_{undulator}}{2\pi mc}$$

***and* high-brightness beam to support the FEL interaction at X-ray wavelengths**

FEL process



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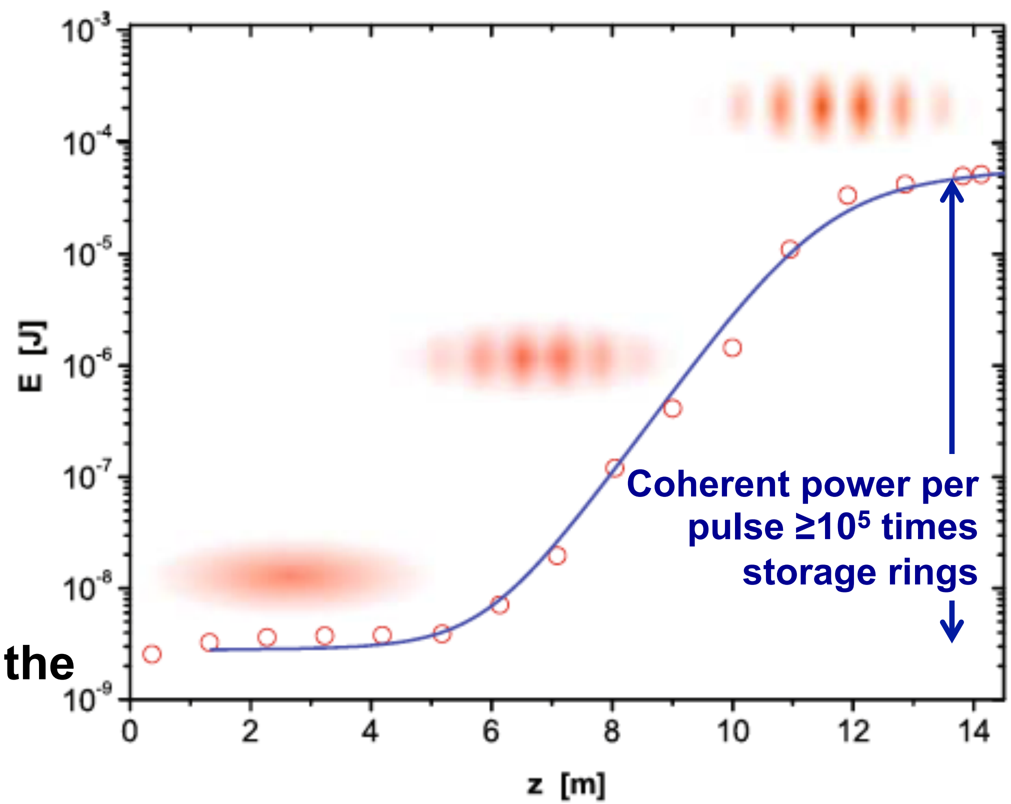
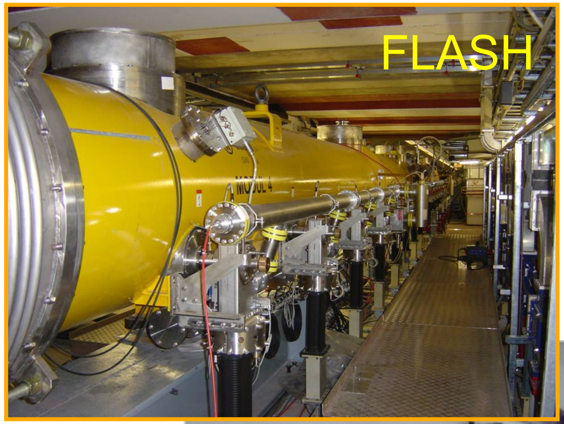


and **high-brightness beam to support the FEL interaction at X-ray wavelengths**

The X-FEL revolution with linac-driven FELs

- **Linac beam quality now allows FELs to operate at wavelengths in the hard X-ray regime**
- **FLASH set the stage with a VUV FEL, now upgraded to reach ~4 nm**
- **LCLS and now SACLA have demonstrated hard X-ray production ~1Å and less**
- **FERMI@elettra is the world's first seeded FEL soft X-ray user facility**
- **LCLS now offers enhanced temporal coherence through self-seeding**
- **Extraordinary power, coherence, and time resolution are now available from X-ray FELs**
- **New projects offer even greater capabilities for X-ray science**



X-ray FEL activities

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

Overview of this talk

- Existing X-ray FEL user facilities and their upgrade projects
  - FLASH
  - LCLS (TU2A03)
  - FERMI@elettra
  - SACLA (TU2A02)
- Under construction and planned user facility projects
  - European XFEL (MO1A02)
  - SwissFEL
  - PAL-XFEL
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FLASH at DESY in Hamburg

Siegfried Schreiber

- **Single-pass high-gain SASE Free-Electron Laser**
  - SASE = self-amplified spontaneous emission
- **Superconducting TESLA linac technology**
- **FEL user facility since Summer 2005**
- **sFLASH is developing HHG seeded FEL operation**
- **Second undulator beam line (FLASH2) under construction**
- **FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)**

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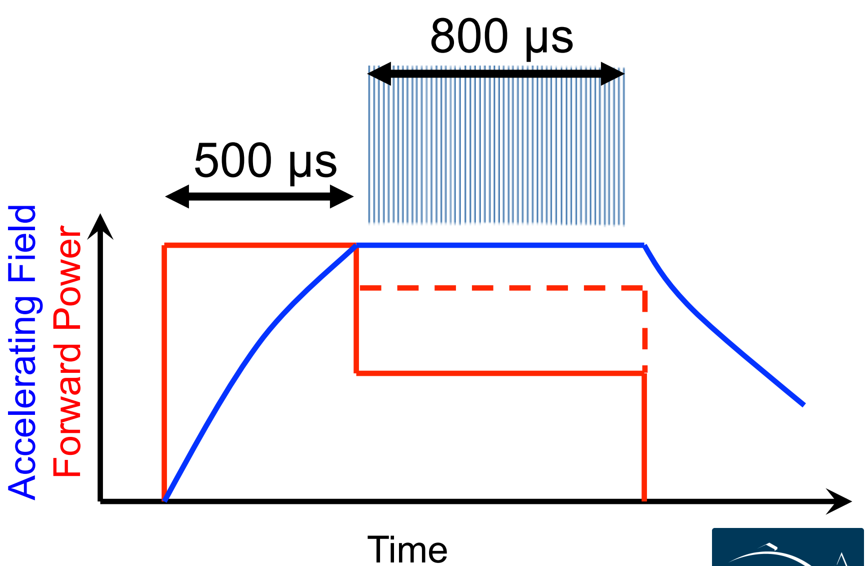
9-cell superconducting cavities @ 1.3 GHz

Burst mode: acceleration for 800 μs at 10 Hz

Efficient acceleration due to high Q ~ 10^{10}

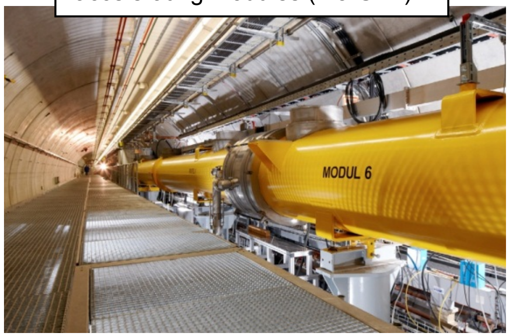
Energy gain ~25 MV/m



FLASH layout

Siegfried Schreiber

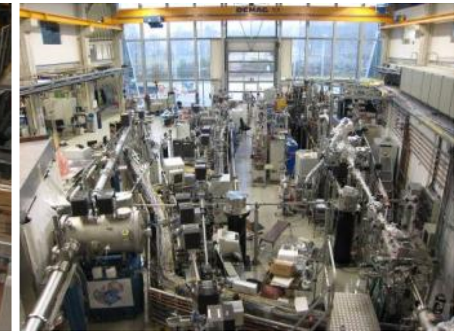
> TESLA type superconducting accelerating modules (1.3 GHz)

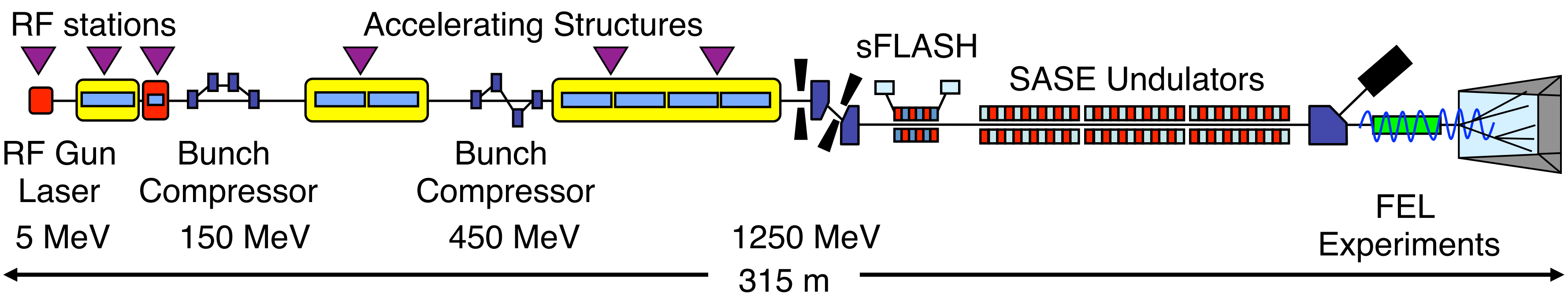


> 3rd harmonic module (3.9 GHz)

> Variable gap sFLASH undulators

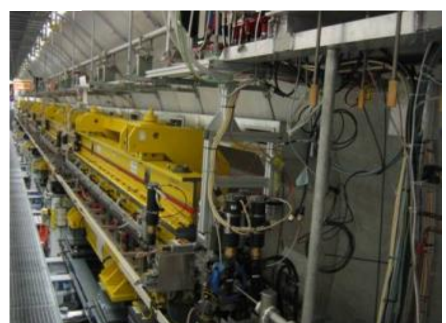
> FEL Experimental Hall





> Normal conducting 1.3 GHz RF gun
> Ce2Te cathode
> Nd:YLF based ps photocathode laser

> Diagnostics and matching

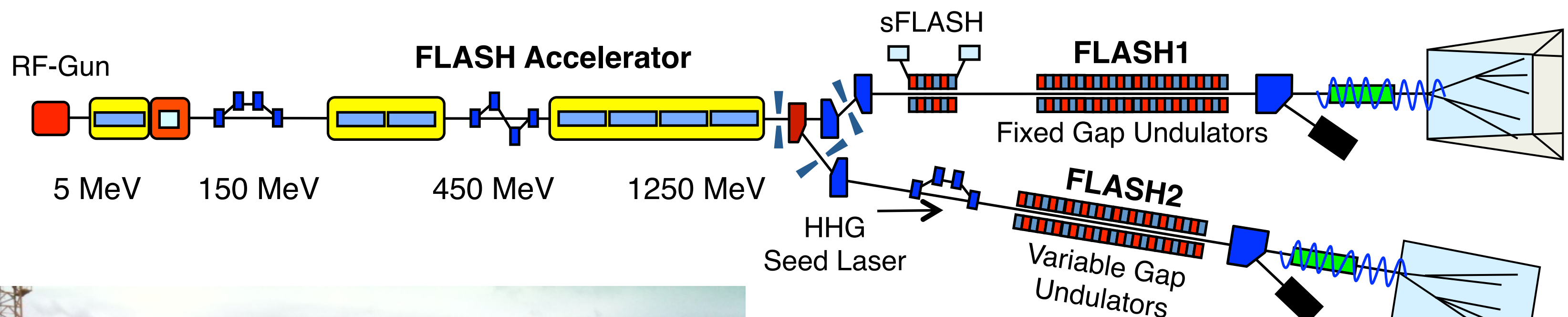


> Fixed gap SASE undulators
> Length ~ 27 m

FLASH2 upgrade project

Siegfried Schreiber

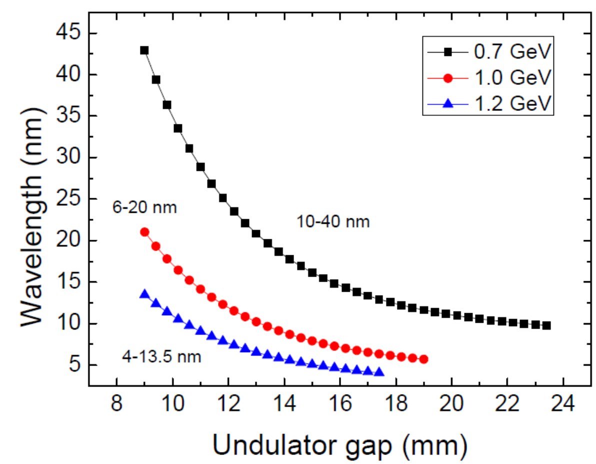
- Second FEL undulator line with variable gap undulators in a separate tunnel
- Second experimental hall for photon beamlines and experiments
- Implementation of seeding schemes for improved radiation properties
- Under construction; first beam expected late summer 2013



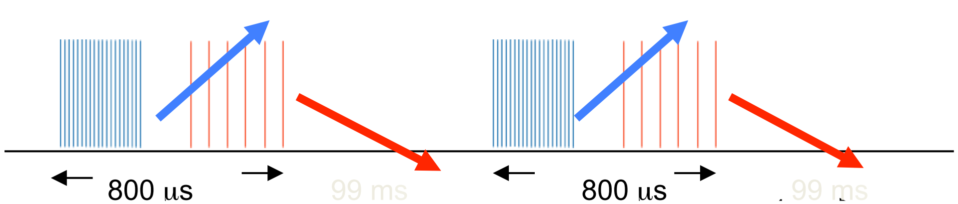
FLASH2 design goals

Siegfried Schreiber

- **Goals**
  - **Increase beam time for user experiments**
  - **Simultaneous operation of different user experiments at FLASH1 and FLASH2**
  - **Improved photon beam quality**
  - **Faster tuning**
- **Beam energy fixed by FLASH1 wavelength, FLASH2 wavelength adjusted by the undulator gap**



- **Separate bunch train to FLASH1 and FLASH2**
  - **With different bunch pattern**
  - **Stable operation of kicker – septum system**
  - **Operation with two injector laser systems**
  - **Operation of (slightly) different bunch charges**



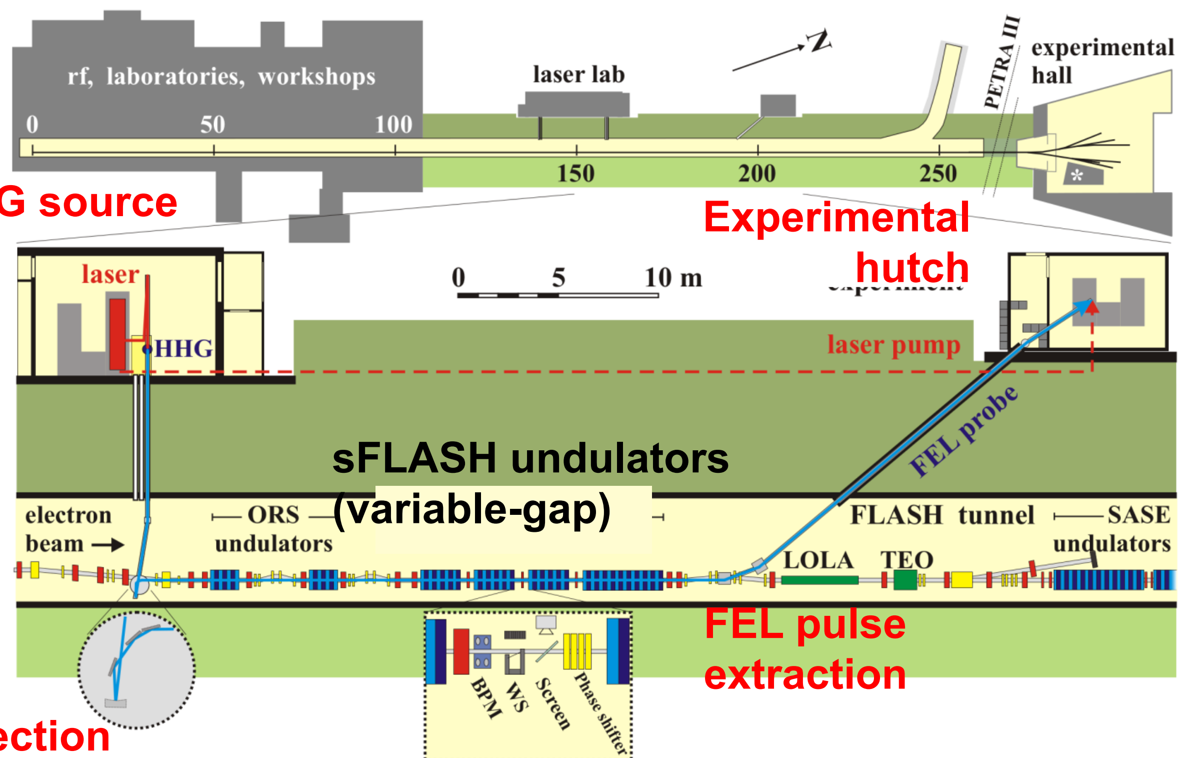
sFLASH: the seeding experiment at FLASH

Christoph Lechner

Superimpose electron bunch with HHG radiation in the undulator ("seeding")

- Electron bunch as amplifier
- Combines stability (HHG) and high peak power (FEL)
  - Longitudinal coherence
  - Stable pulse spectrum and energy
  - Stable arrival time synchronized to laser (goal 10 fs)

- Demonstrated HHG seeding at 38 nm
- Stable seeding at 38 nm into dedicated beamline with GW peak power
- Goal of 40 – 10 nm seeding in FLASH2



FELs at DESY in Hamburg

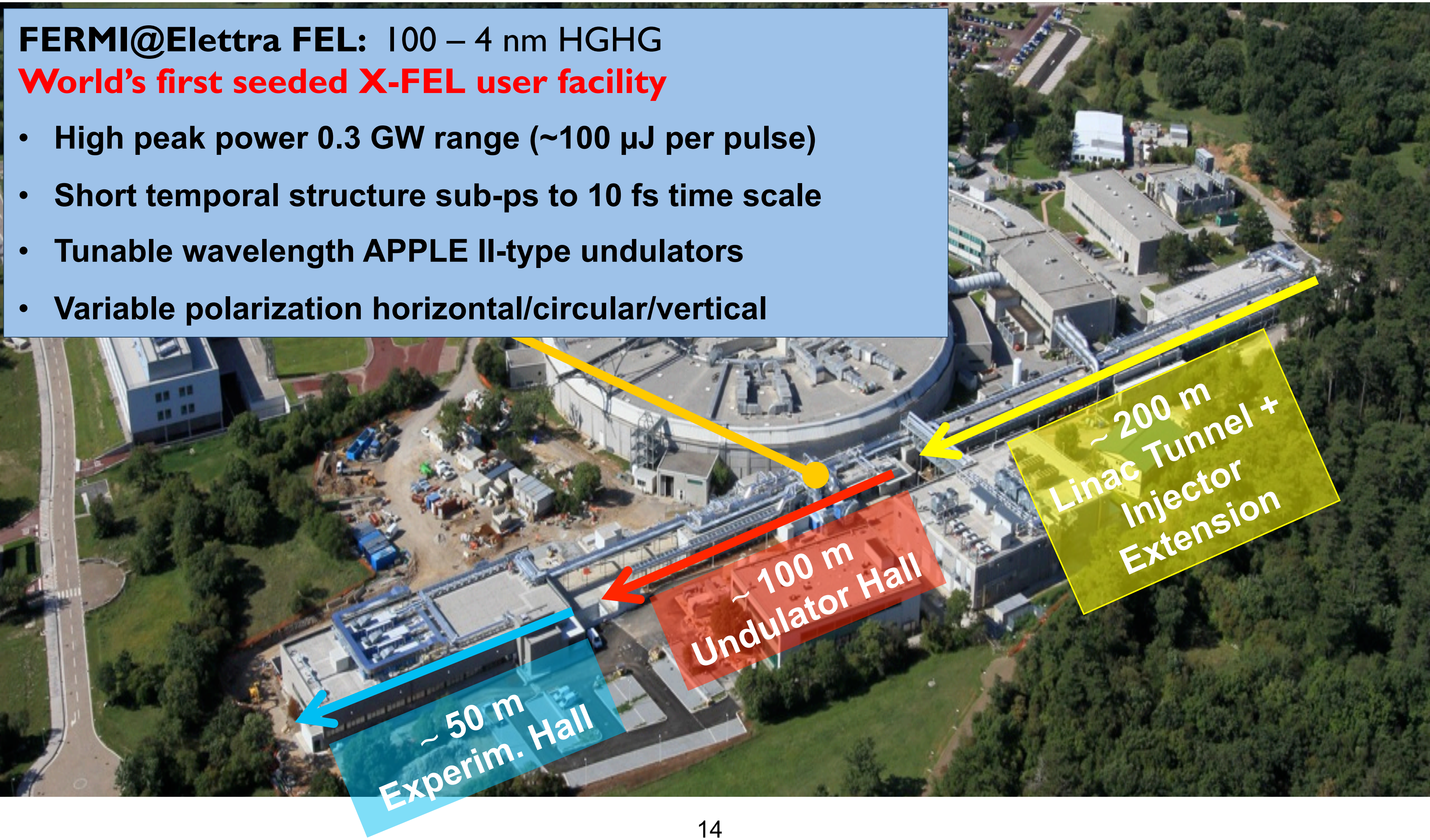
Siegfried Schreiber

FERMI at Sincrotrone Trieste

FERMI@Elettra FEL: 100 – 4 nm HGHG

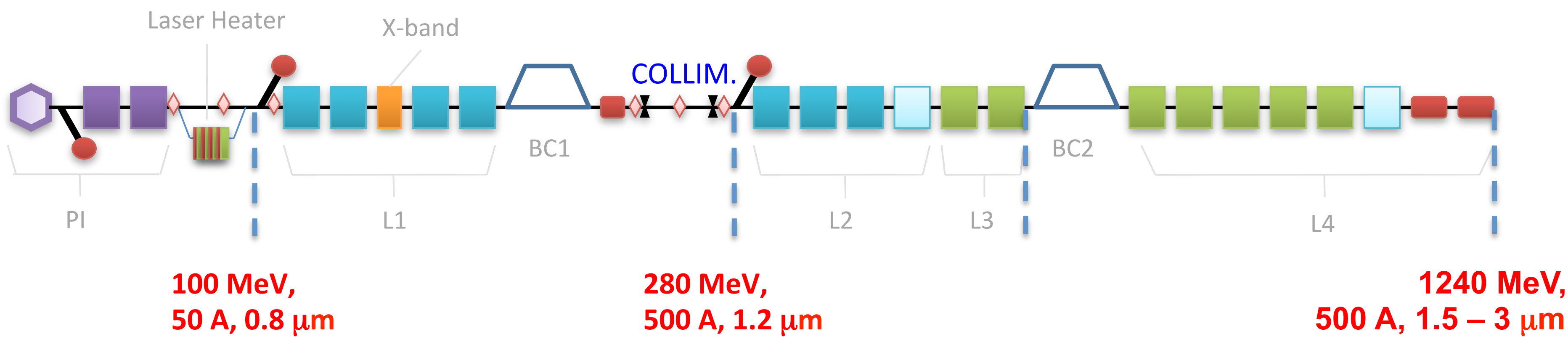
World's first seeded X-FEL user facility

- 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

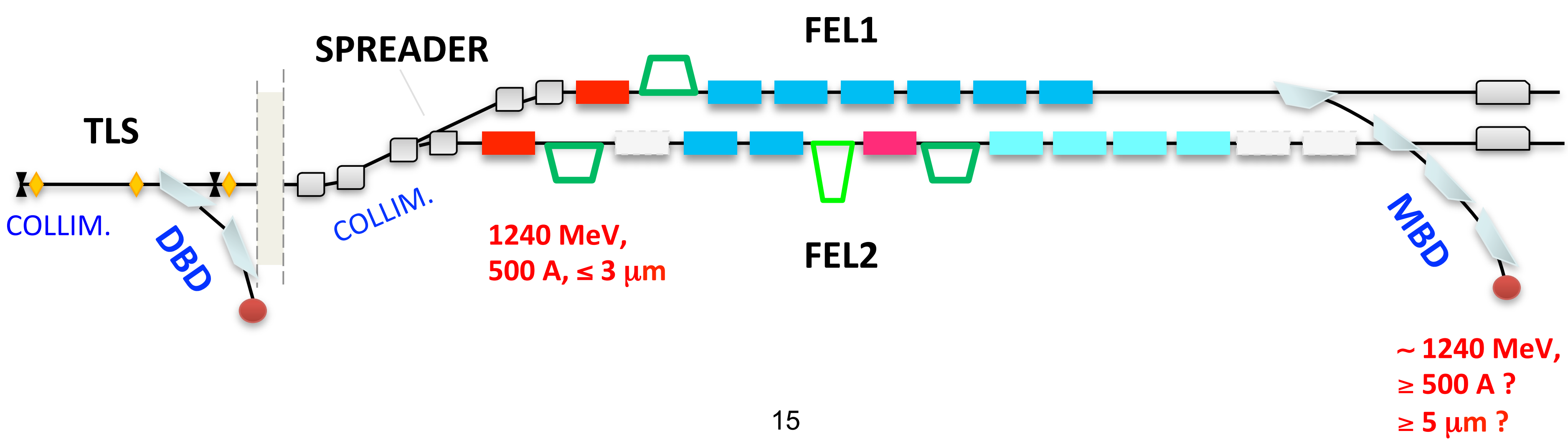


FERMI@elettra layout

FERMI Commissioning Team

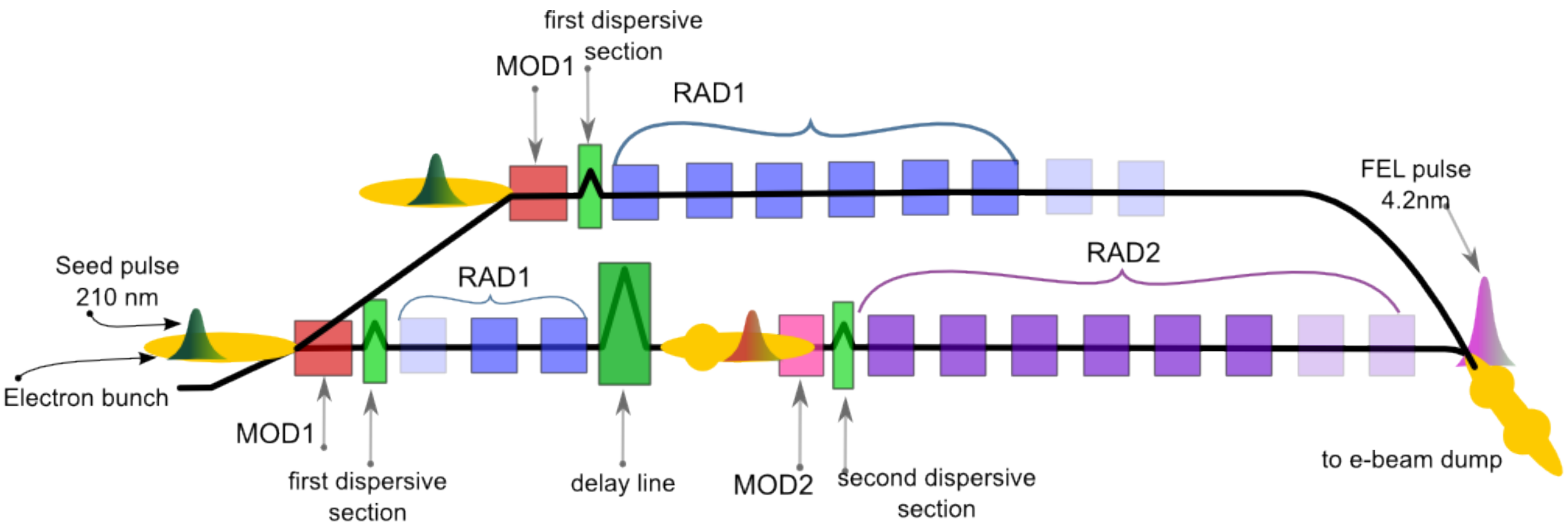


- **1.2 GeV S-band normal-conducting copper linac**
- **100 pC, pulsed 10 Hz**



FERMI's two seeded FELs

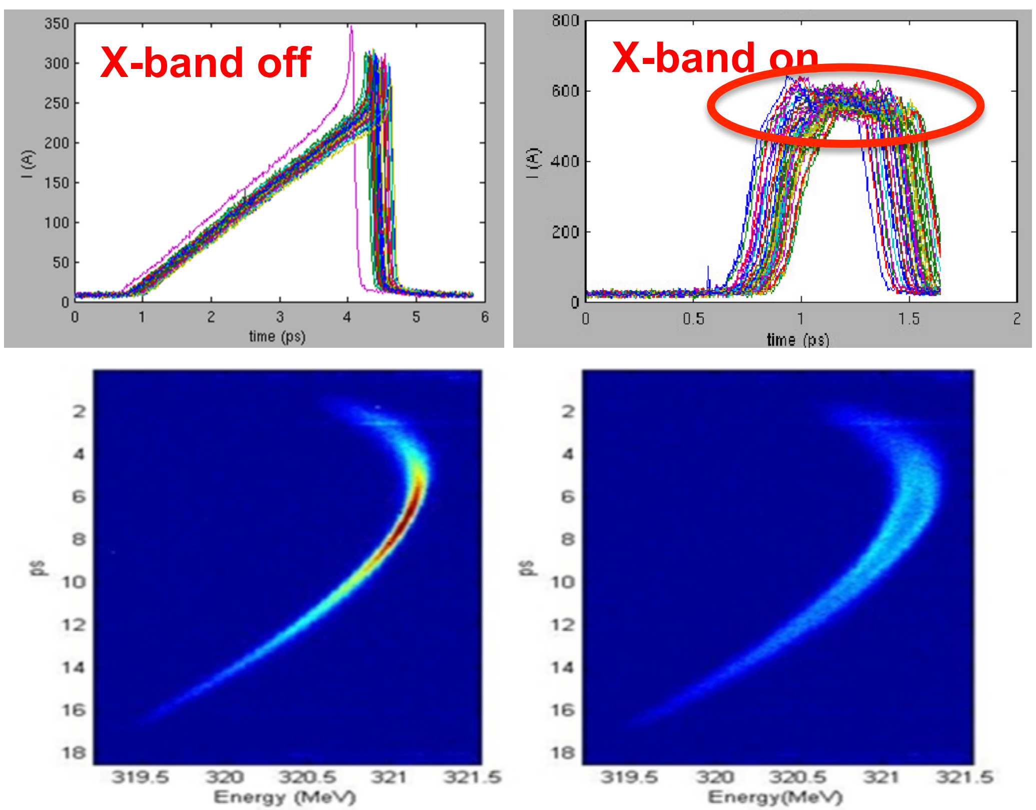
FERMI Commissioning Team



- **FEL-1: single stage high gain harmonic generation (HGHG) from UV laser seed**
  - **Spectral range from ~80 nm down to 20nm**
- **FEL-2: double cascade HGHG**
  - **Spectral range from 20 to ~4 nm**
  - **Fresh bunch technique**

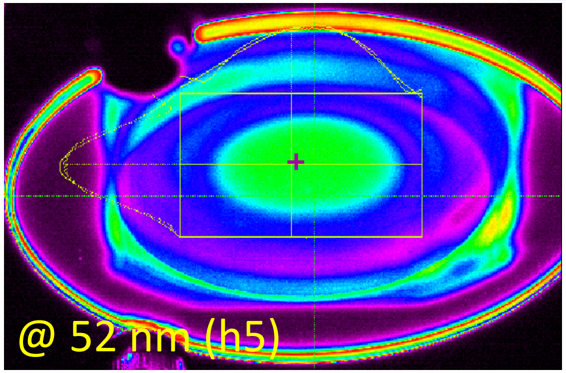
Recent developments

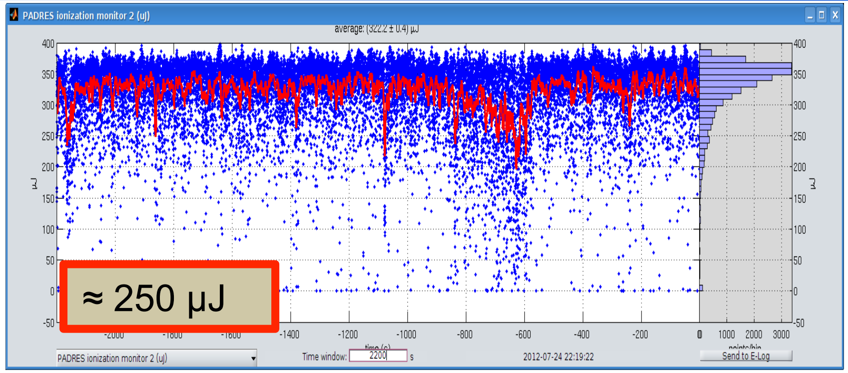
- **New systems and instrumentation installed and commissioned for control and diagnostics of longitudinal phase space**
  - **High energy RF deflector**
  - **Laser heater**
  - **X-Band cavity for phase space linearization**

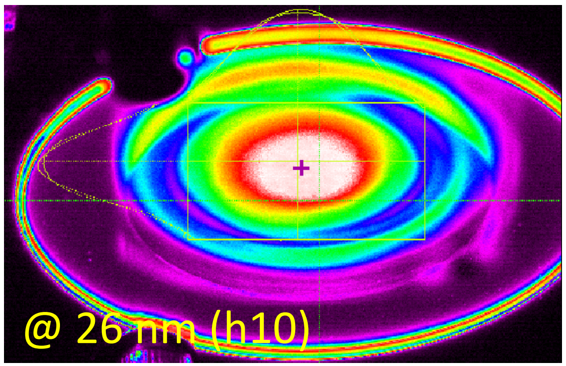


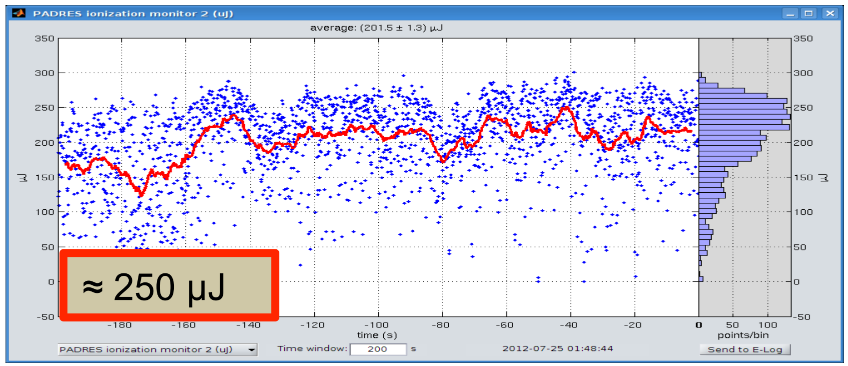
- **X-band linearizer allows to compress more efficiently the electron beam**
- **Laser heater is efficiently used to suppress the micro-bunching that develops with high current beams**

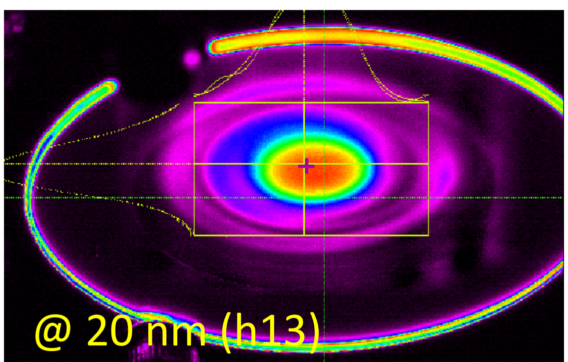
Recent FEL-1 results

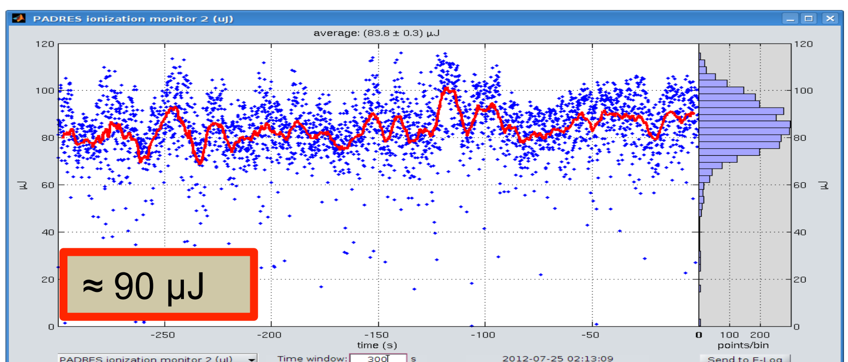










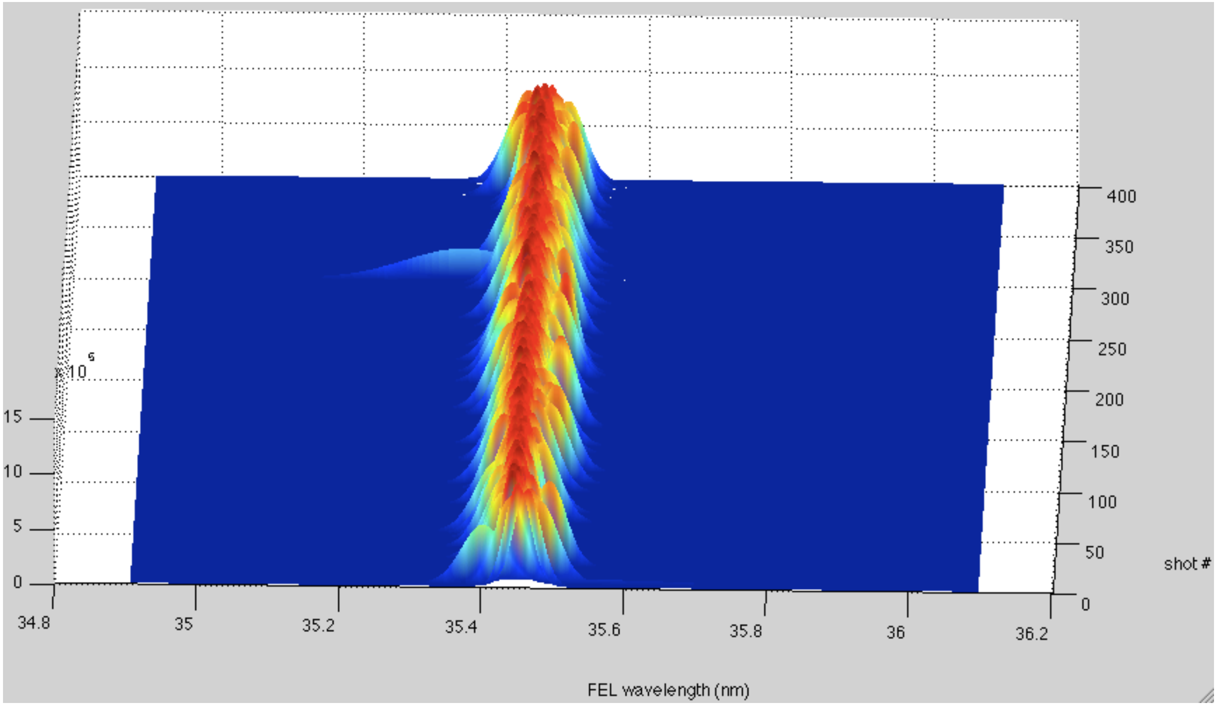


With compression using the x-band linearizer, FEL power increased significantly in all the FERMI FEL-1 spectral range

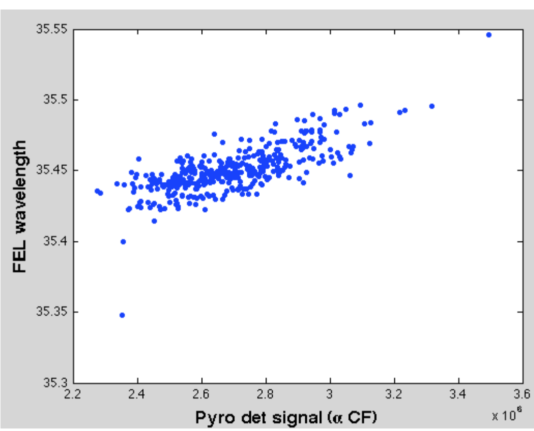
About 100 μJ has been achieved in the 65-20 nm spectral range

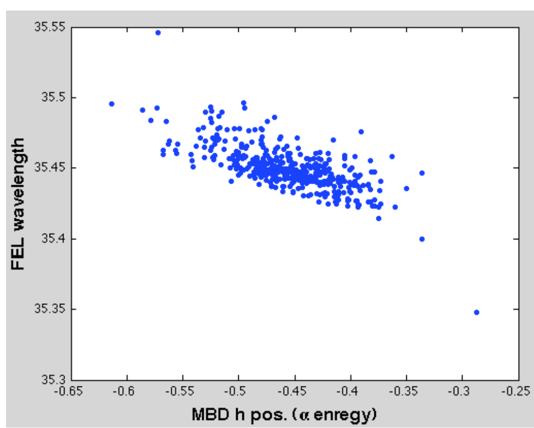
FEL-1 demonstrates excellent wavelength stability

FERMI Commissioning Team



Wavelength =	**35.4 nm (35.0 eV)**
Lambda jitter =	**0.046 %**
Bandwidth = (rms)	**22.0 meV ($6.2x10^{-4}$)**
Bandwidth = jitter	**0.0065 nm (29 %)**





- **Wavelength fluctuations are strongly correlated with beam properties fluctuations:**
  - **After bunch compression (bunch length/peak current)**
  - **In main beam dump (energy)**

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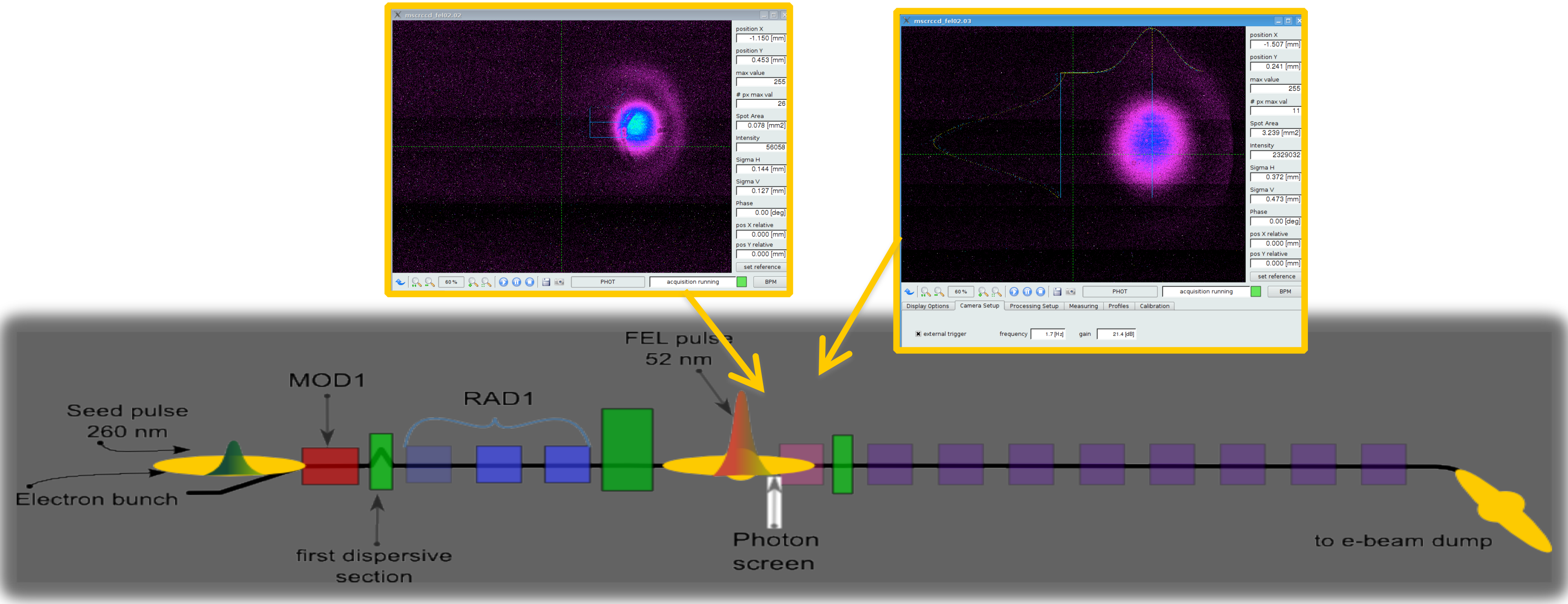
FEL-2 first stage initial lasing

FERMI Commissioning Team

- **52 nm FEL output on diagnostics screens after the radiator of the first stage of FEL-2**
- **5th harmonic in first stage of cascade HGHG**

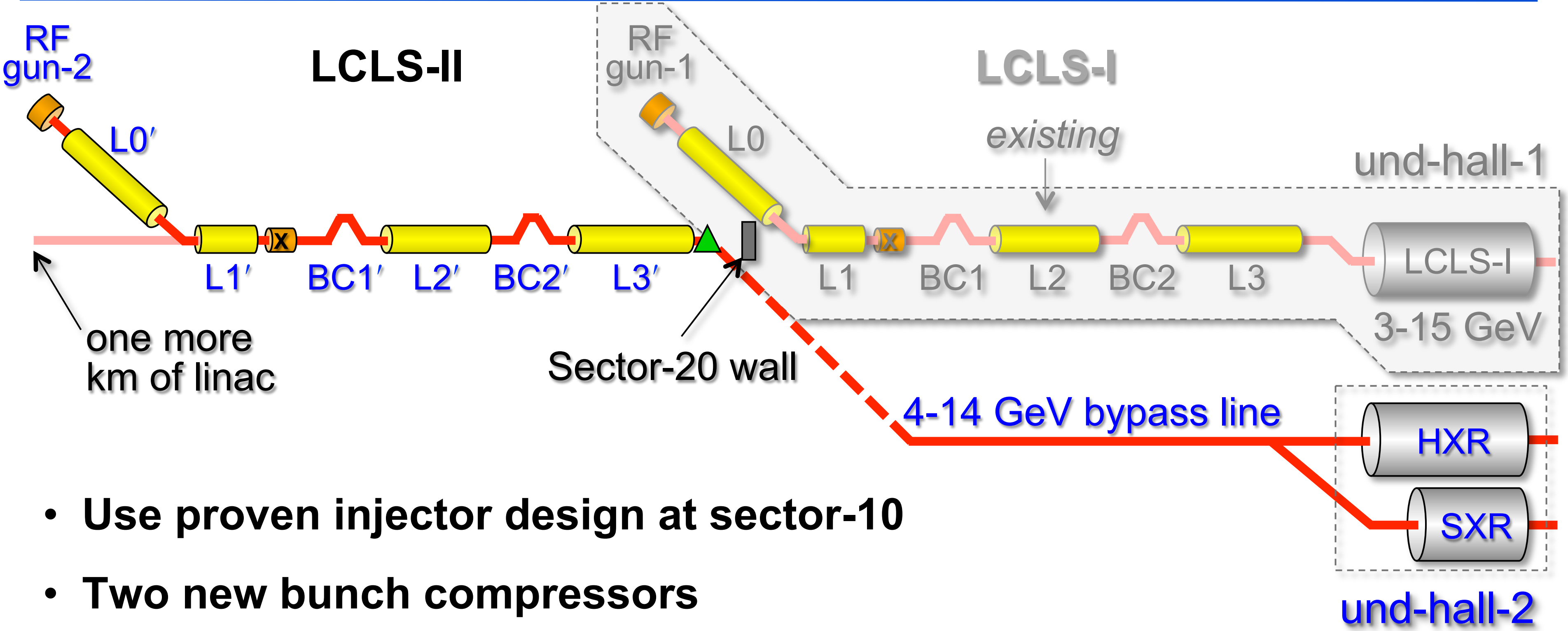


FERMI@elettra near-term plans

- October 2012
  - Commissioning of FEL-2 double stage HGHG cascade
- October-November 2012
  - Installation in the gun test facility of the new 50 Hz gun and start of gun commissioning
- December 2012
  - First run fully dedicated to external user experiments on FEL-1
- March-May 2013
  - Linac energy upgrade to 1.5 GeV and 50 Hz operation
- Fall 2013
  - First tentative user experiments on FEL-2

Tor Raubenheimer

LCLS-II layout
Builds on success of first hard X-ray FEL (1.2 Å)



- **Use proven injector design at sector-10**
- **Two new bunch compressors**
- **14 GeV S-band linac**
- **1200-m long bypass (old PEP-II line) goes around LCLS-I**
- **Two variable-gap undulator SASE FELs (HXR & SXR) in new tunnel**
- **Baseline is 60 Hz in each undulator**

SACLA XFEL at RIKEN
Shortest wavelength FEL, 0.63 Å

TU2A02

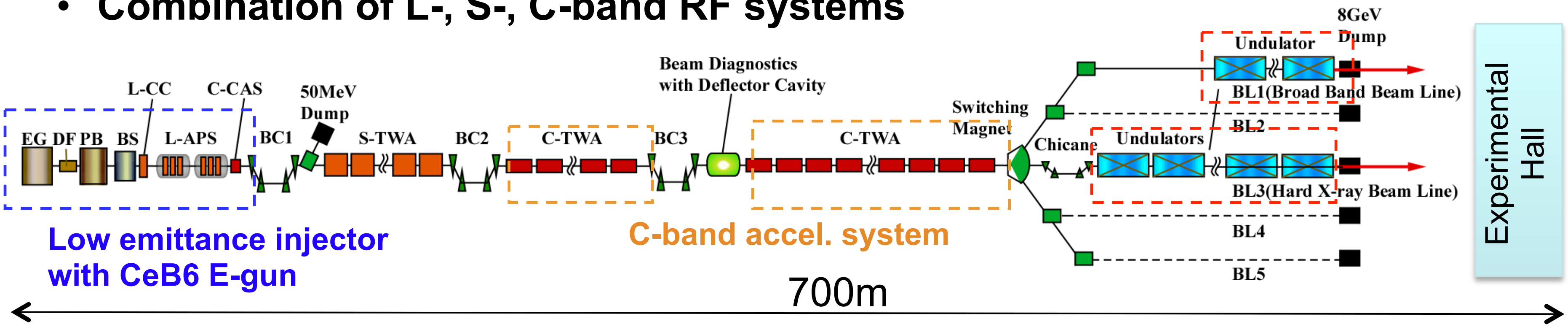
Hitoshi Tanaka

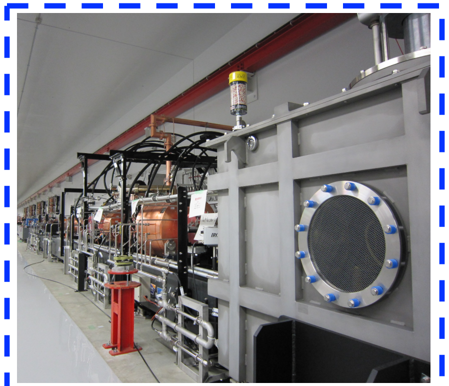
SACLA layout

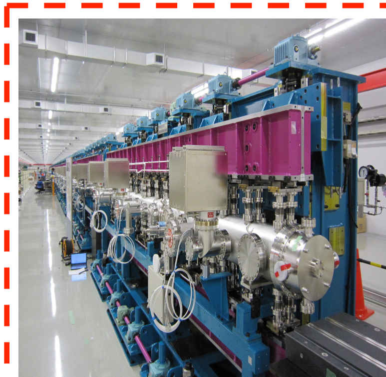
Hitoshi Tanaka

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

Short-period (18 mm) in-vacuum undulators SASE FELS



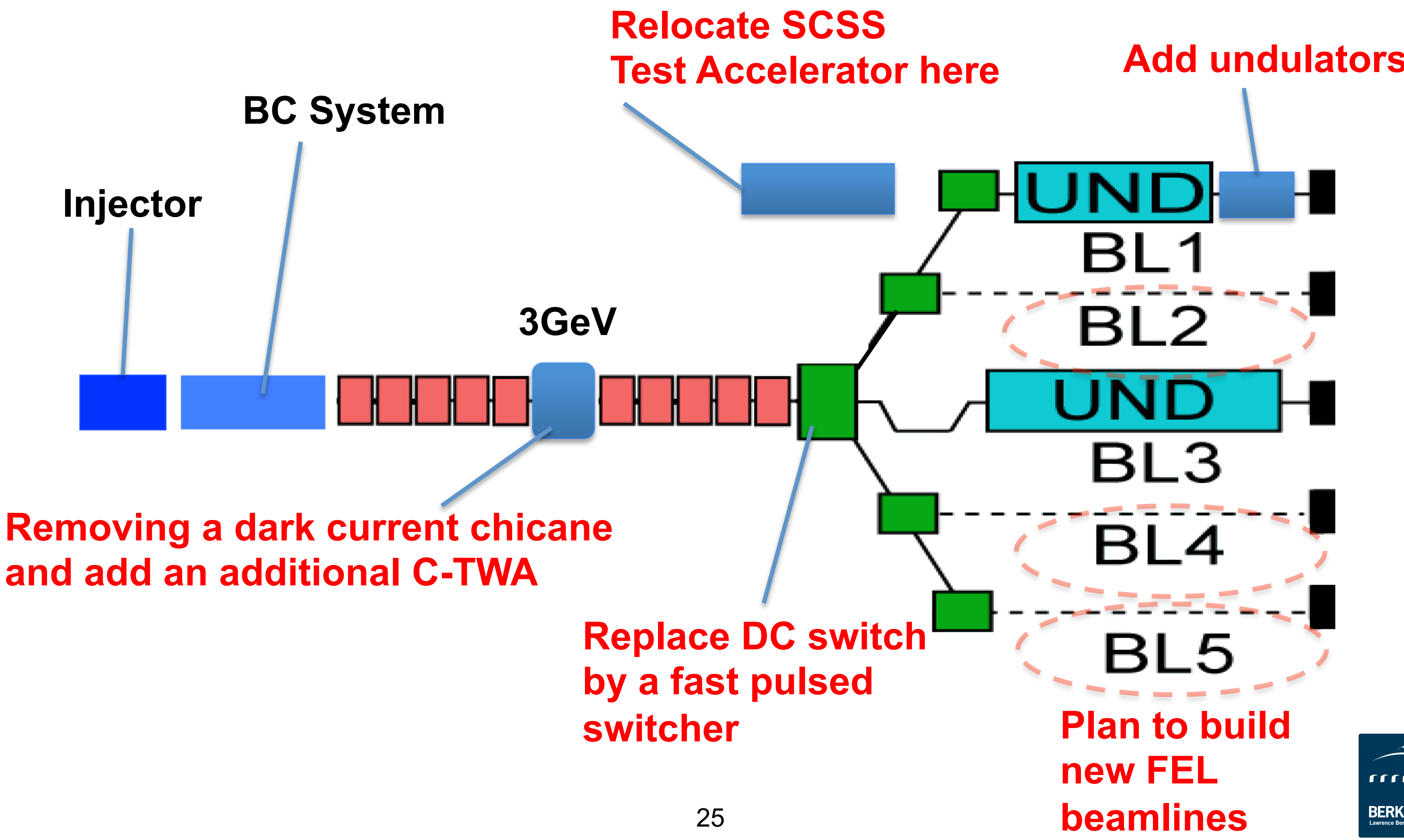




SACLA XFEL upgrade plans

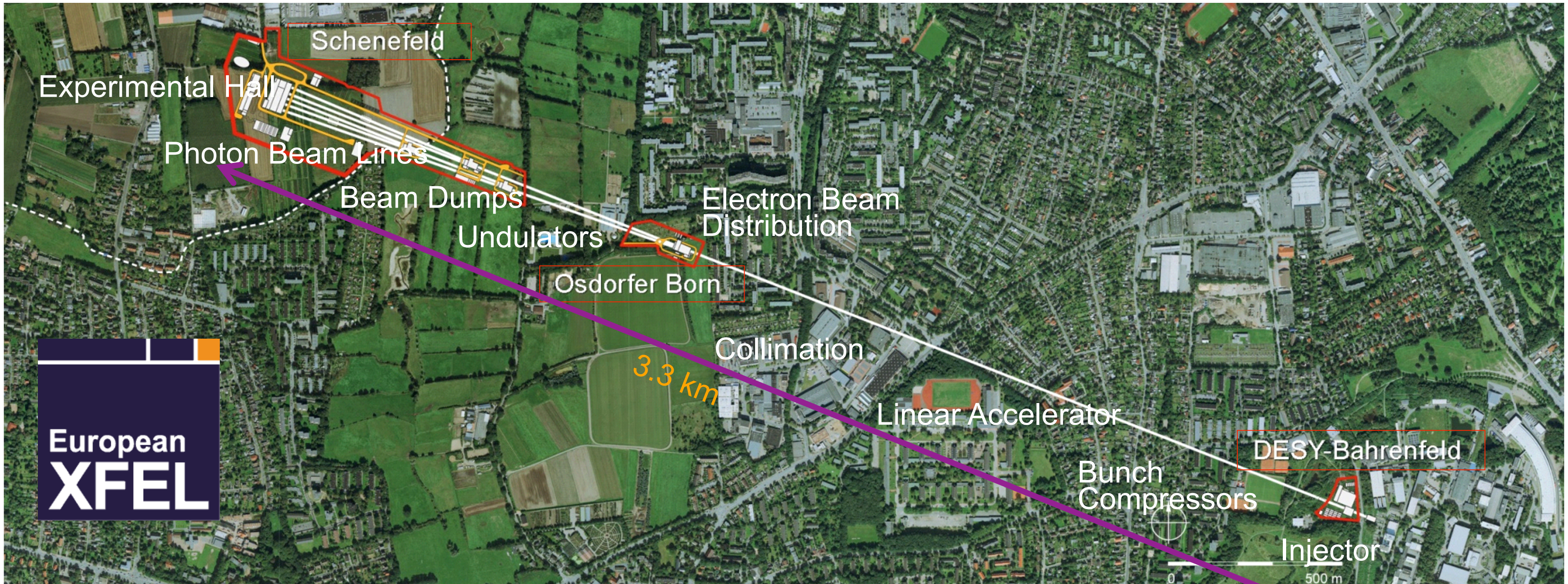
Hitoshi Tanaka

Broader wavelength range
Higher efficiency and reliability



European XFEL project

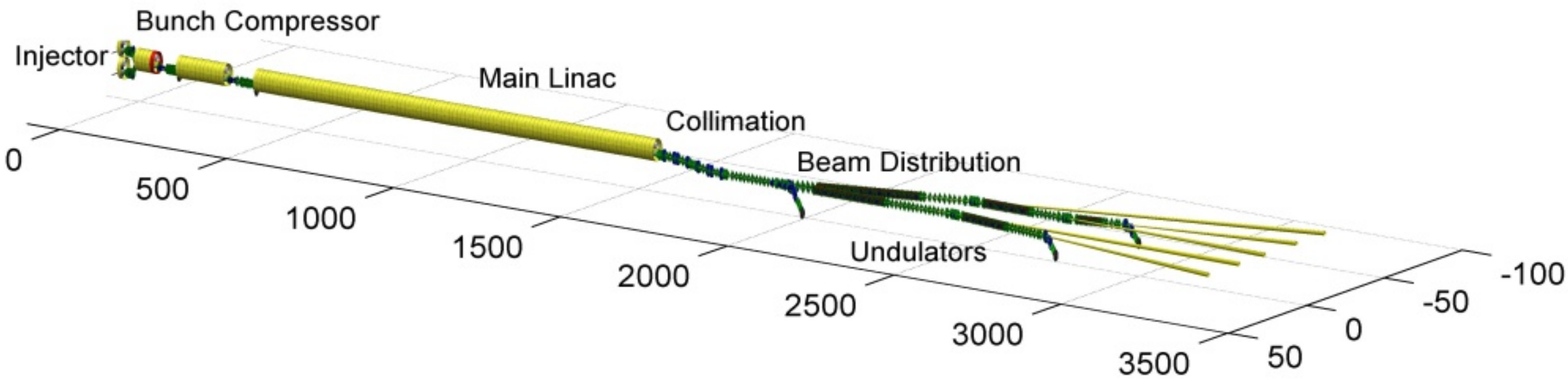
Winfried Decking



- **Under construction by 12 European Nations at DESY, Hamburg**
- **5 FEL tunnels**
- **Initially 3 moveable gap undulators for hard and soft X-rays**
- **SASE FEL wavelength 4 – 0.05 nm**

European XFEL layout

Winfried Decking

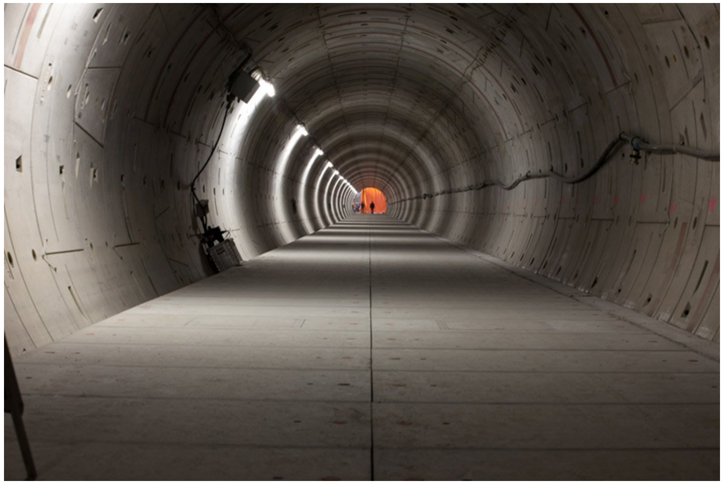


- **Warm L-band RF gun**
- **Up to 17.5 GeV superconducting linac**
- **23.6 MV/m accelerating gradient**
- **0.02 – 1 nC charge per bunch**
- **10 Hz, 600 µs macropulse, 4.5 MHz bunch rate within pulse**
- **27000 pulses per second**
- **500 kW beam power**

European XFEL status & schedule

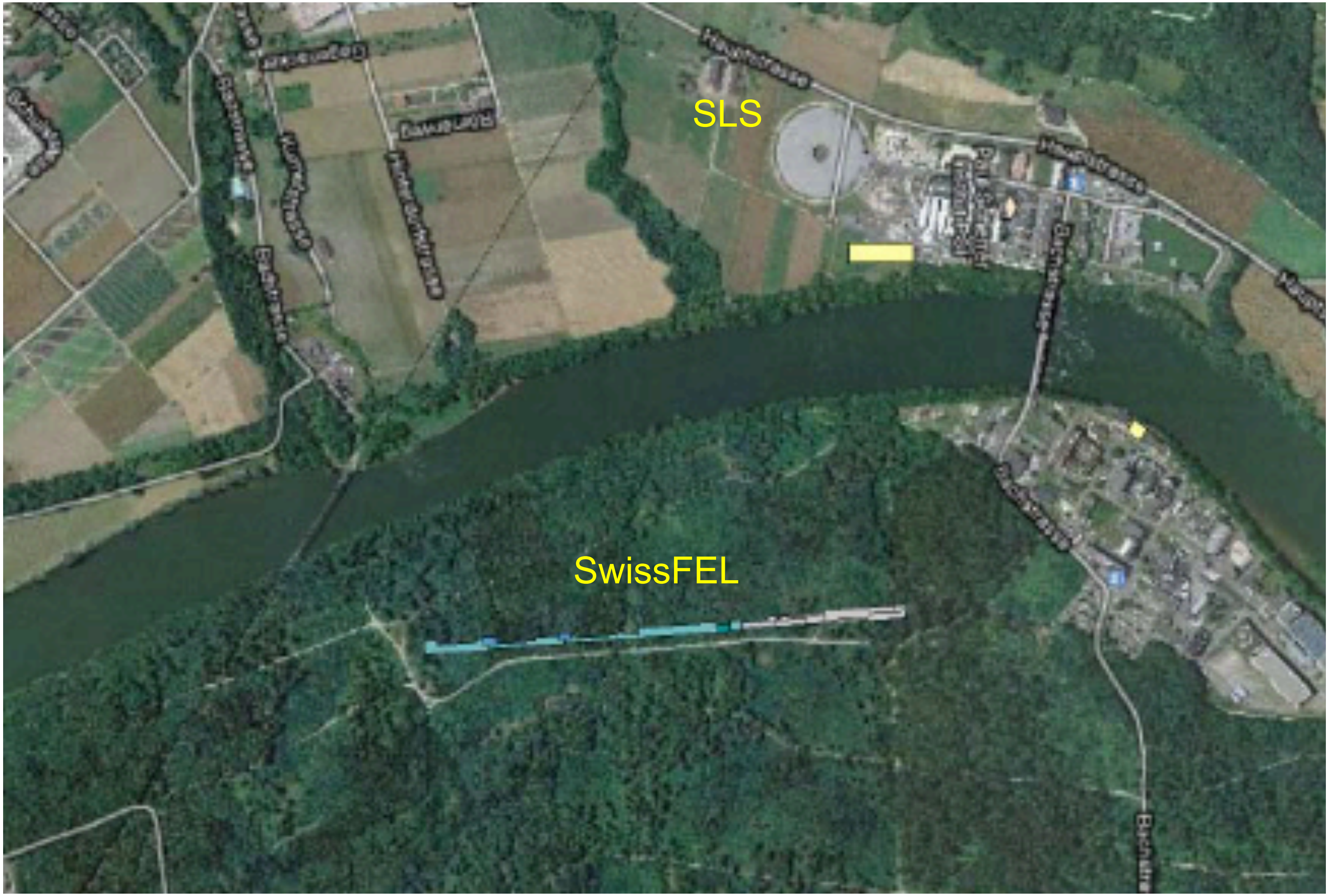
Winfried Decking

- Boring of 5.8 km of tunnel finished June 2012
- Civil construction of underground and surface buildings ongoing
- Orders for major accelerator parts placed, series production started
- Installation of tunnel infrastructure started
- First accelerator components into tunnel mid 2013
- First beam in injector mid 2014
- Tunnel closed and linac cool down mid 2015
- First lasing possible end of 2015



SwissFEL proposed construction site

Sven Reiche



SwissFEL compact footprint

Sven Reiche

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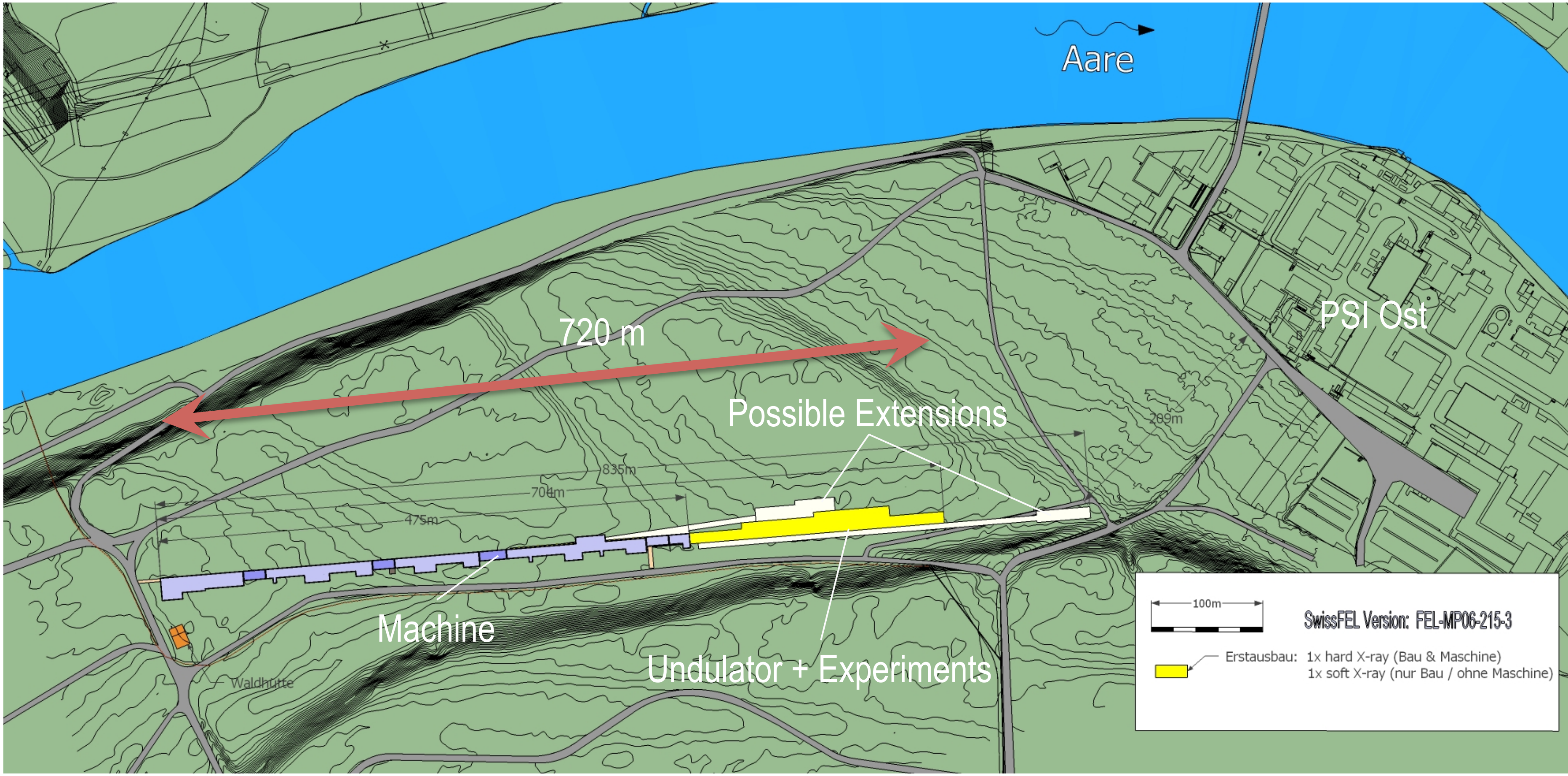

- **2 initial SASE / self-seeded FELs**
  - **"Aramis" HXR: 0.8 – 7 Å**
  - **"Athos" SXR: 0.7 – 7 nm**

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SwissFEL layout

Sven Reiche
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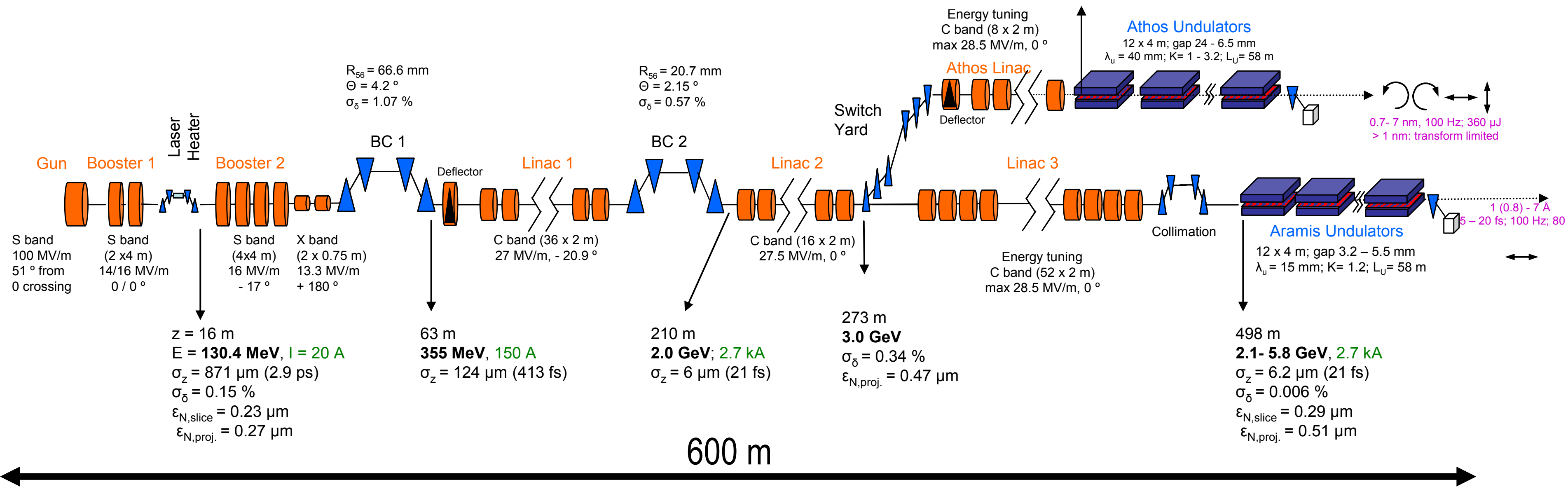
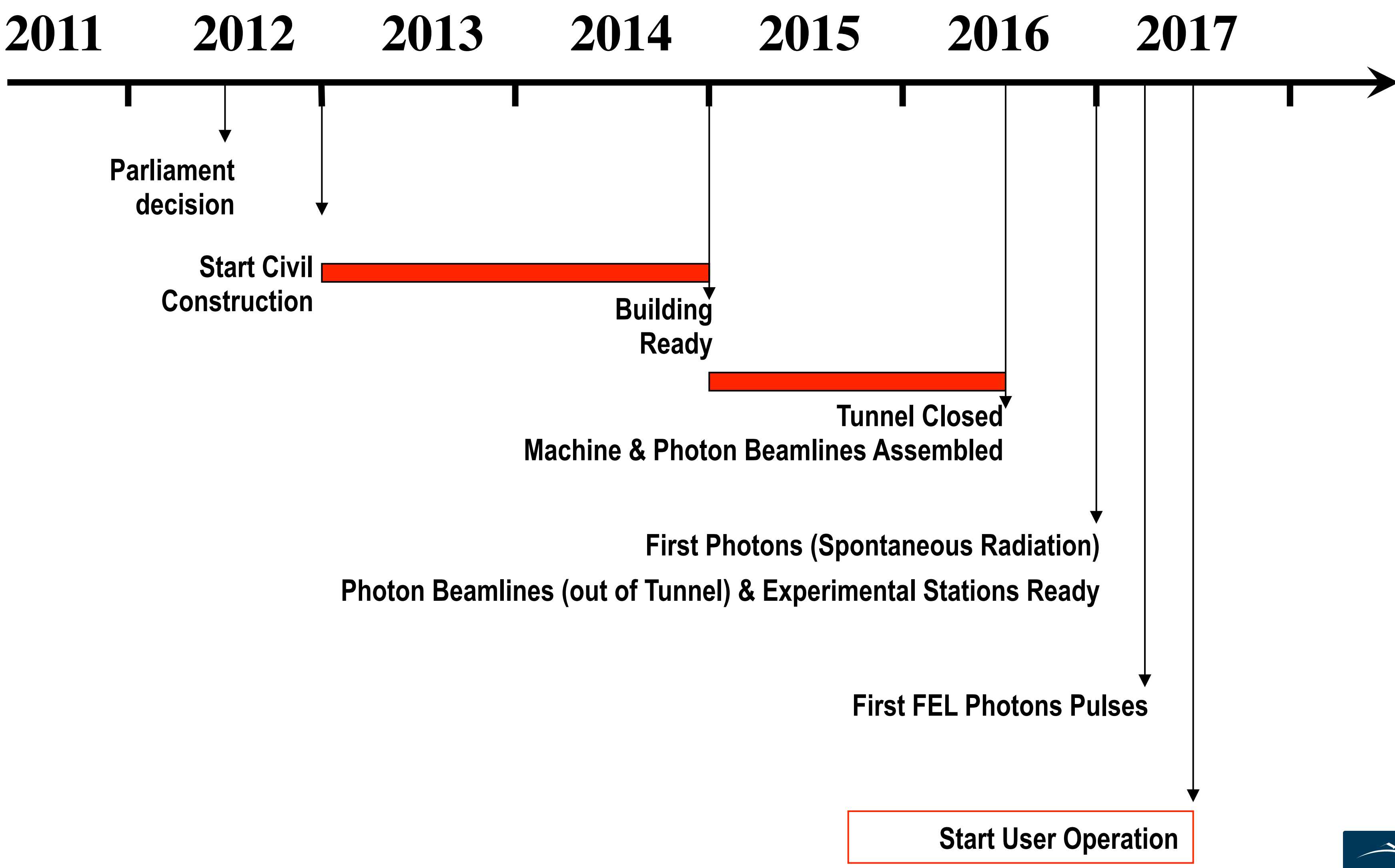


- **S-band RF photo-electron gun, injector, 100 Hz**
- **C-band linac up to 6 GeV**
  - **27 MV/m**
  - **Fewer RF stations, less real estate and electrical power than S-band**
- **Branch line for Athos (SXR FEL)**
- **2 bunch operation (28 ns) with distribution to Aramis and Athos at 100 Hz**

SwissFEL timeline

Sven Reiche



Pohang Accelerator Laboratory XFEL

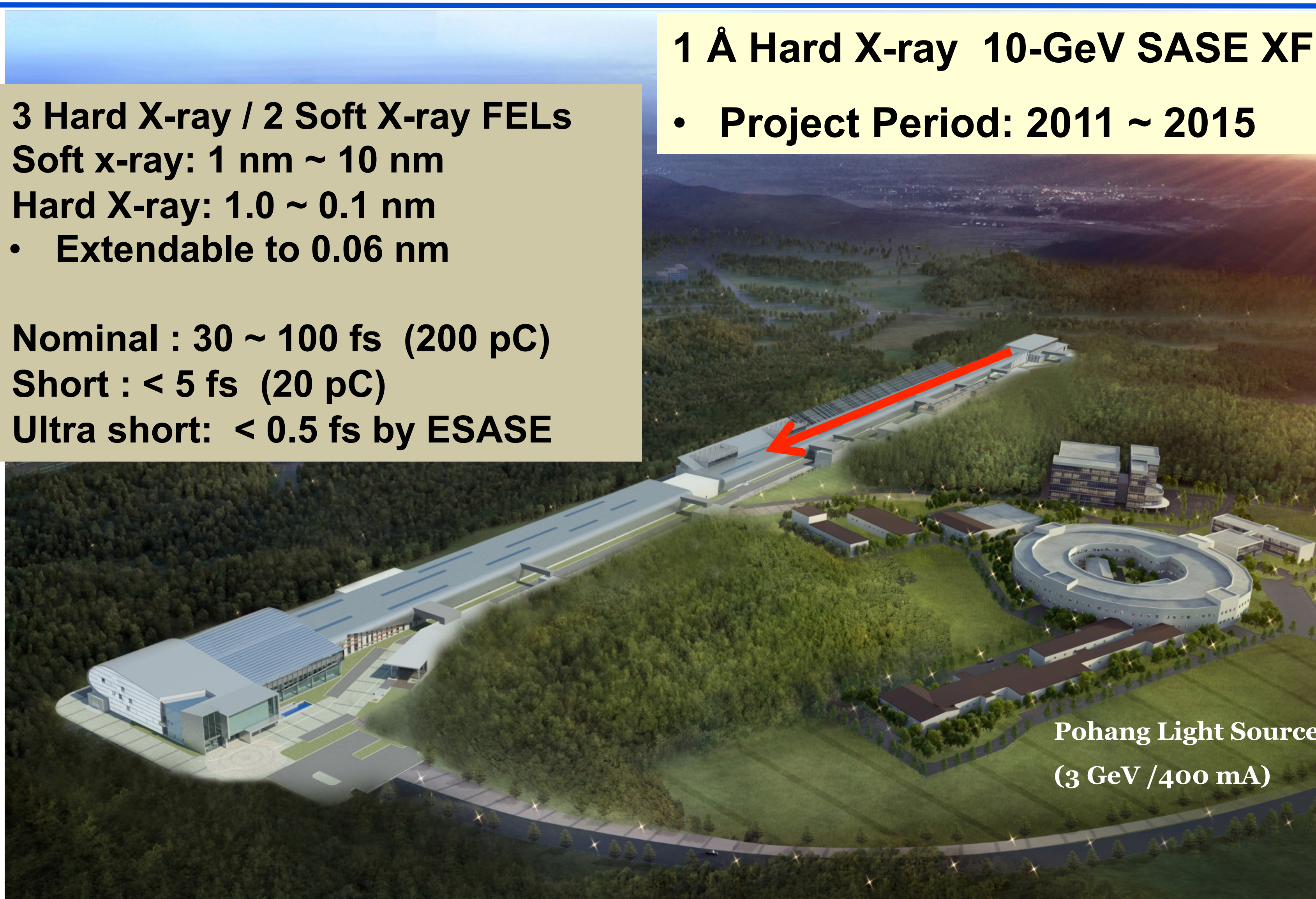
Heung-Sik Kang

1 Å Hard X-ray 10-GeV SASE XFEL

- Project Period: 2011 ~ 2015

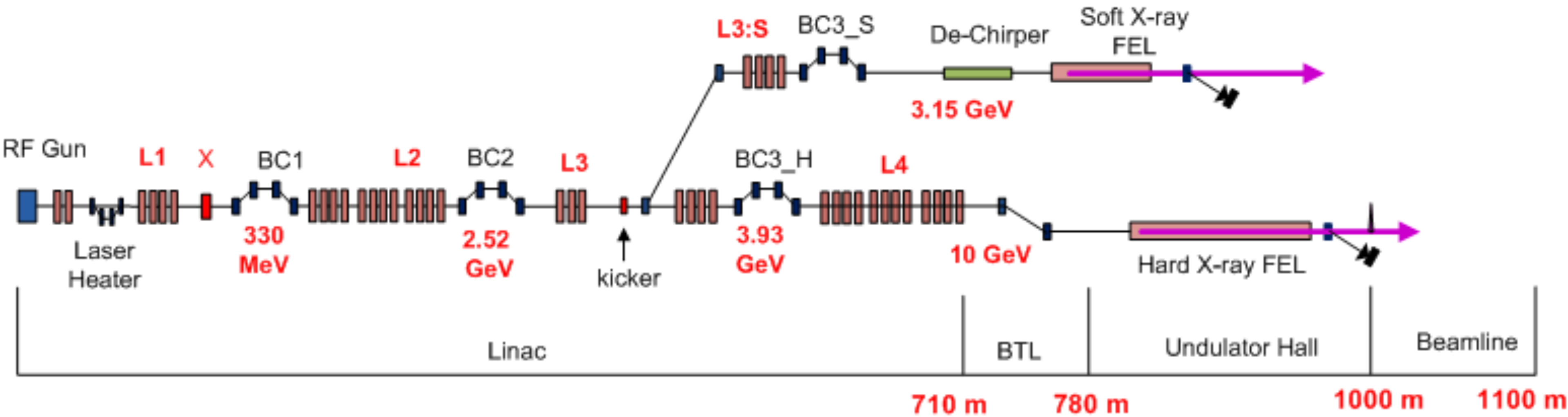
- 3 Hard X-ray / 2 Soft X-ray FELs
- Soft x-ray: 1 nm ~ 10 nm
- Hard X-ray: 1.0 ~ 0.1 nm
  - Extendable to 0.06 nm

- Nominal : 30 ~ 100 fs (200 pC)
- Short : < 5 fs (20 pC)
- Ultra short: < 0.5 fs by ESASE



PAL XFEL design parameters

Heung-Sik Kang



- **S-band linac at 60 Hz**
- **Three bunch compressors for flexibility in beam control**
- **Simultaneous or independent operation of soft X-ray FEL beamline is feasible**
  - **Single bunch: pulse by pulse kick to soft X-ray branch line**
  - **Two bunches (20 ns separation): bunch by bunch kick to soft X-ray line**

Shanghai Soft X-ray FEL (SXFEL)

Zhentang Zhao

SINAP

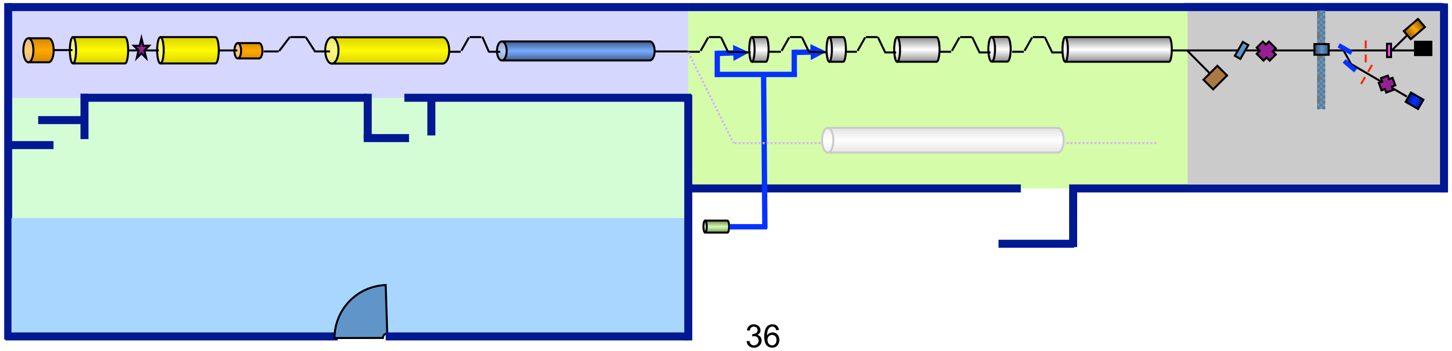
SXFEL concept on the Shanghai Synchrotron Radiation Facility campus

10nm two-stage cascading HGHG FEL demonstrator (3 nm upgrade)
Project approved February 2011
Technical design studies under way
Collaboration with Tsinghua University

SXFEL design parameters

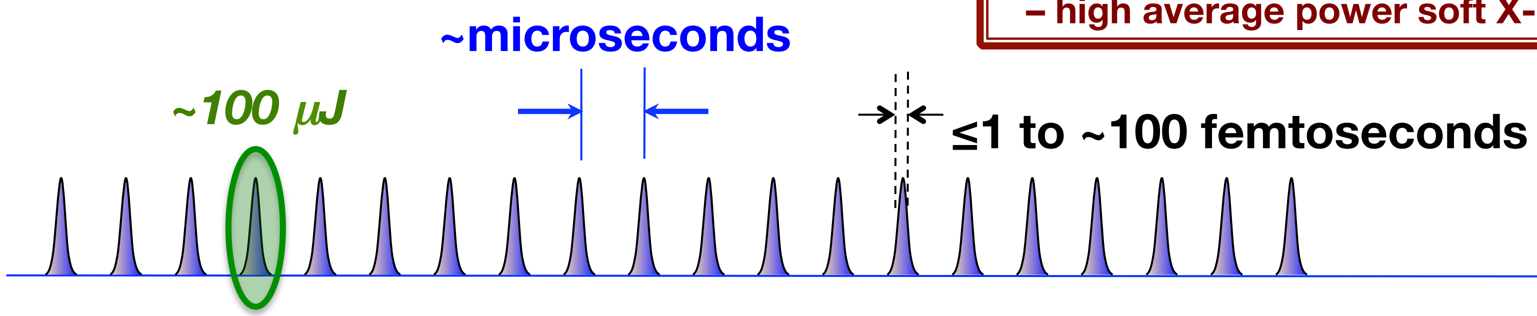
Zhentang Zhao SINAP

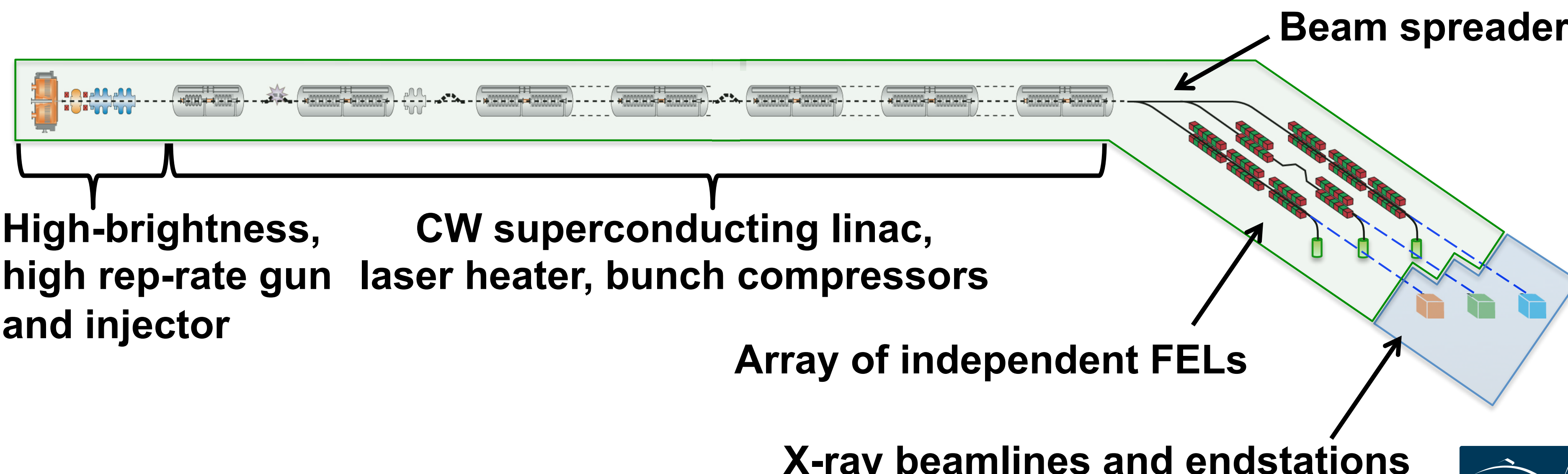
Parameters	HGHG	Upgrade	Unit
Output Wavelength	9	3	nm
Bunch charge	0.5~1	0.5~1	nC
Energy	0.84	1.2~1.3	GeV
Energy spread	0.1~0.15%	0.15%	
Energy spread (sliced)	0.02%	0.03%	
Normalized emittance	2.0~2.5	2.0~2.5	mm.mrad
Pulse length (FWHM)	1.	1	ps
Peak current	~0.5	0.5	kA
Rep. rate	1~10	1~10	Hz



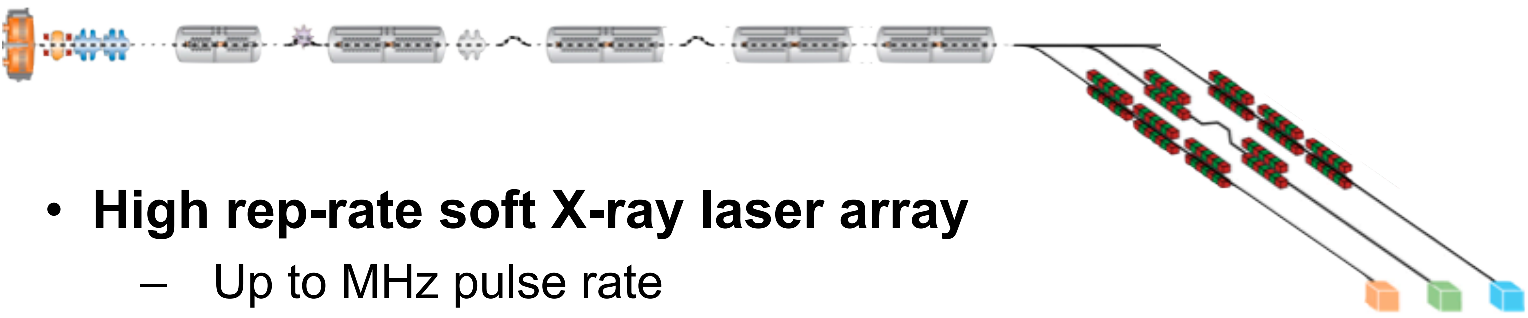
Next Generation Light Source (NGLS)

Intense coherent pulses at high rep rate – high average power soft X-ray lasers



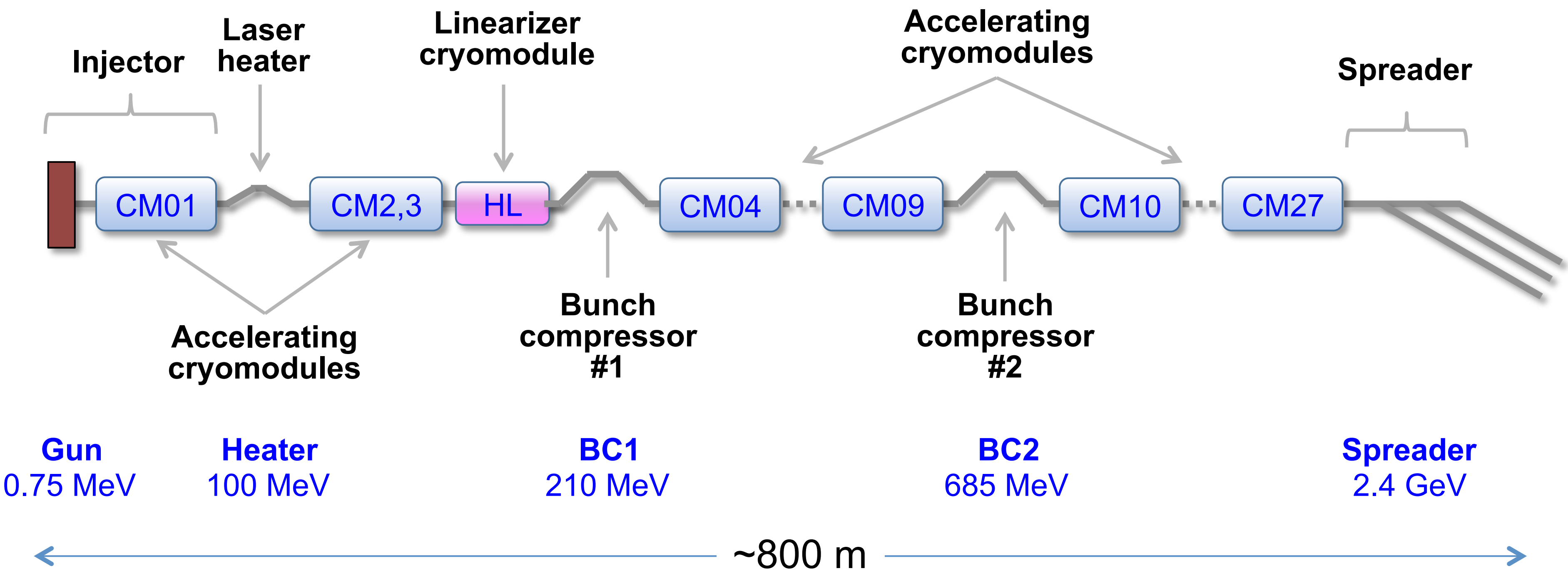


NGLS performance goals



- **High rep-rate soft X-ray laser array**
  - Up to MHz pulse rate
  - Average coherent power up to ~100 W
- **Spatially and temporally coherent X-rays (seeded)**
  - Ultrashort pulses from ≤1 fs to ~300 fs
  - Narrow bandwidth to 50 meV
- **Tunable X-rays**
  - Adjustable photon energy: 0.27 - 1.2 keV (harmonics to 6 keV)
  - Polarization control
  - Moderate to high flux with 10^8 - 10^{12} photons/pulse
- **Expandable in Capability and Capacity**

NGLS layout (concept)



- **30-300 pC bunches**
- **1 MHz bunch rate (+)**
- **2.4 GeV**
- **~750 kW e-beam power**
- **~16 MV/m gradient**
- **TESLA-type cavities operated in CW mode**

- **2 bunch compressors**
- **1 laser heater**
- **3 initial seeded or self-seeded FELs**

NGLS status

- **DOE approved "Mission Need" for the Next Generation Light Source in April 2011**
- **LBNL is performing R&D, design studies, developing the science case, and building partnerships and collaborations**
  - **APEX MHz rate gun**
  - **Photocathodes**
  - **Superconducting undulators**
  - **Soft X-ray self-seeding**
  - **Beam spreader**
  - **Detectors**
  - **Seed lasers**
  - **Linac partnerships being built**

Summary: many exciting X-ray FEL projects

- Several operational: upgrades to enhance performance and capacity
  - FLASH: FLASH2 adds capacity and coherence capability (sFLASH)
  - LCLS: LCLS-II adds capacity and capability in tuning SXR/HXR
  - FERMI@elettra: FEL-2 promises additional coherence at 4 nm; 50 Hz and 1.5 GeV upgrade
  - SACLA: Upgrades to improve stability, add capacity, and extend wavelength range
- Several new projects are at various stages of development
  - XFEL: 17.5 GeV SRF linac; FELs 4 nm to 0.5 Å; high-power beams (2015)
  - SwissFEL: compact 6 GeV facility with SXR and HXR (~1 Å) capability (2017)
  - PALFEL: 10 GeV facility with SXR and HXR (~0.6 Å) (2015)
  - SXFEL: design study for 1.3 GeV seeded SXR FEL
  - NGLS: conceptual design for 2.4 GeV high average power CW SRF, SXR laser facility
- Other proposals under development
  - LUNEX-5, MaRIE / SPARX / ...
- Many FEL R&D projects and facilities
  - APEX, ATF, CLARA, JLAB, MAX-IV, NLCTA, SCSS, SDL, SDUV FEL, SPARC, WiFEL, ...

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Thank you for your attention!