X-ray Free Electron Laser (XFEL)

Part-1: Accelerator

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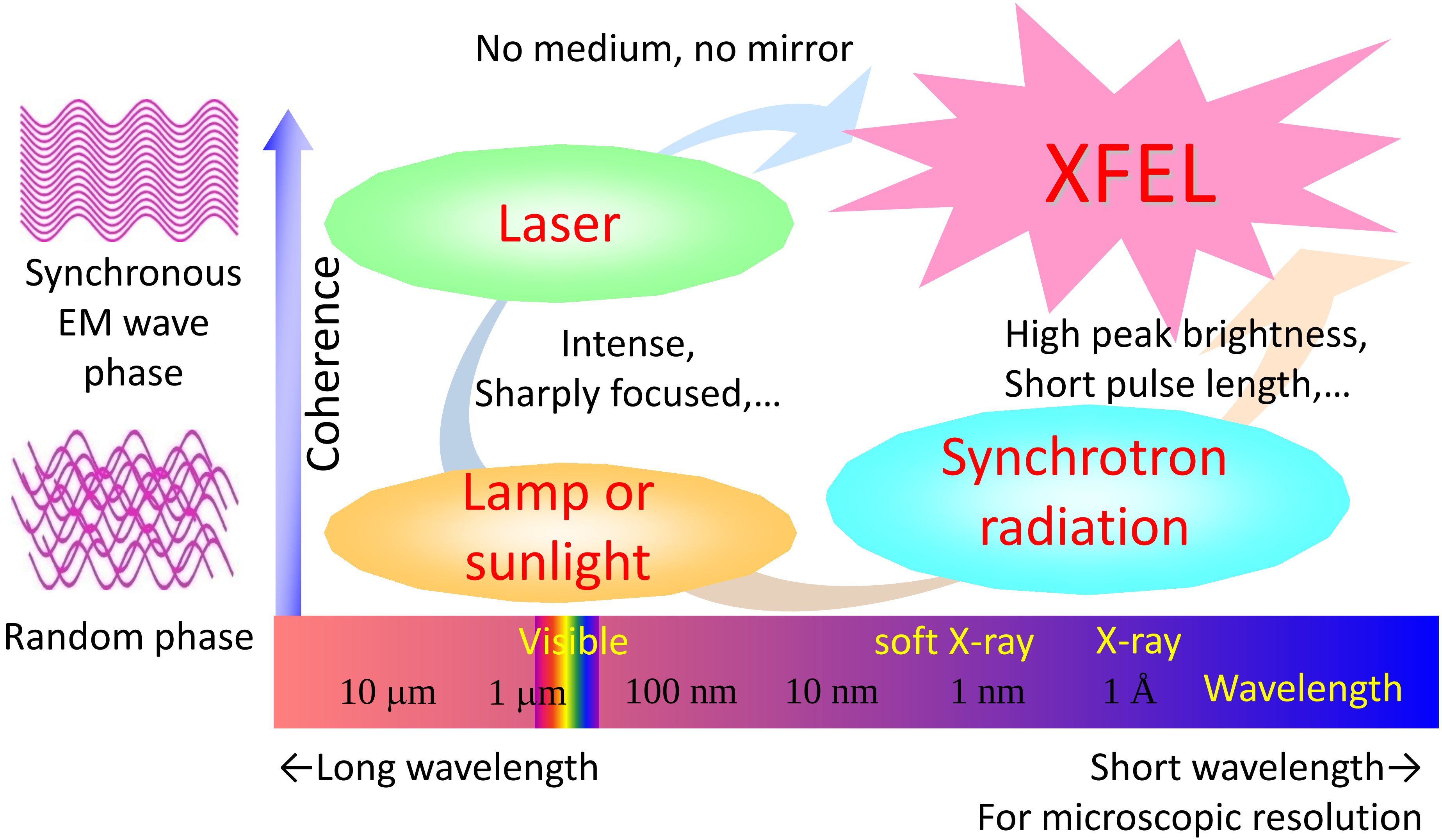
Outline

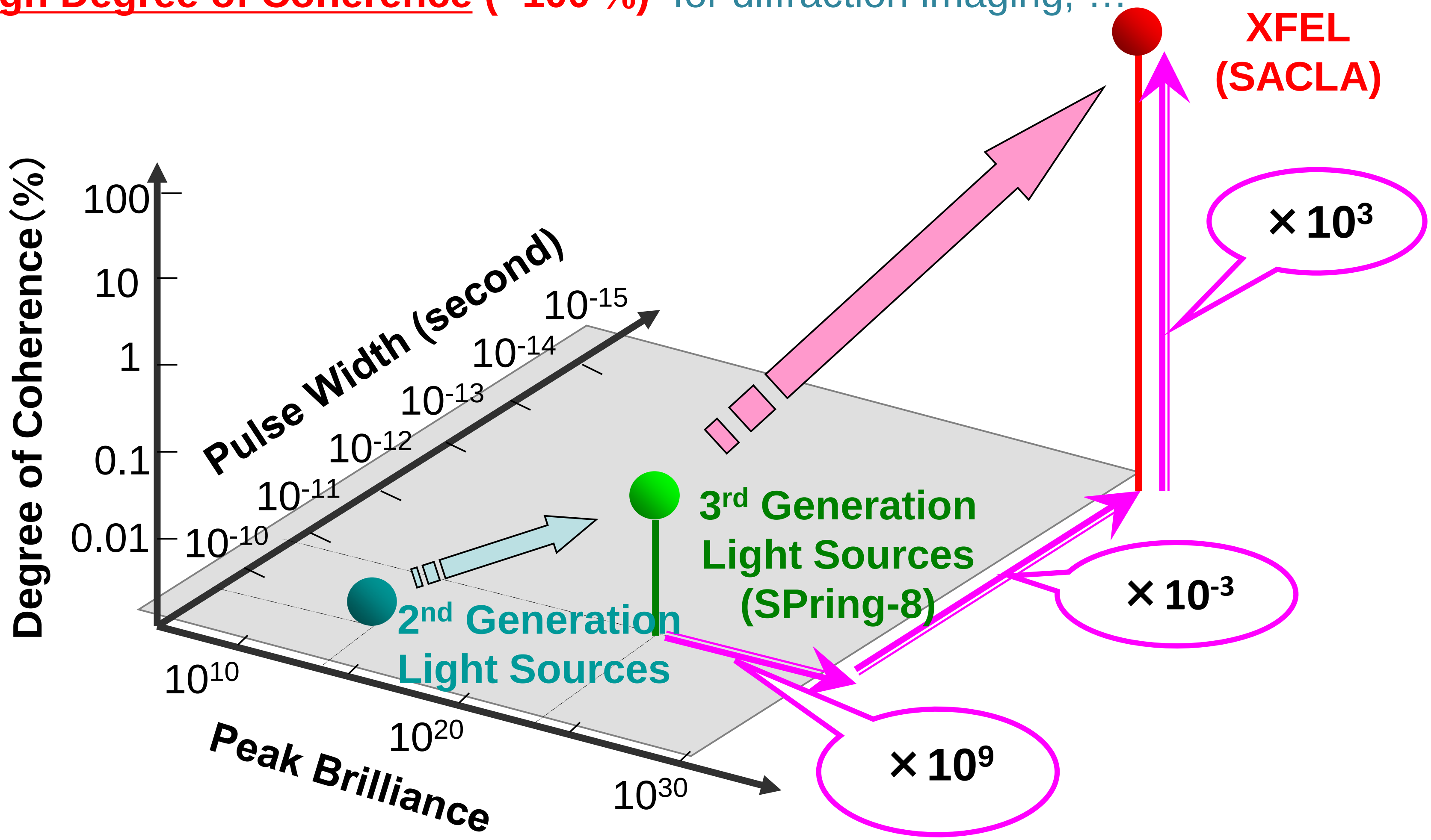
- **Introduction**
- FEL mechanism
- SACLA machine configuration
- Present status and outlook
- Summary

What is X-ray Free Electron Laser (XFEL)?



Remarkable features of XFEL

- **High Peak Brilliance** **(~10^{33})** for physics in extremely intense field, …
- **Narrow Pulse Width** **(~10 fs)** for ultrafast reaction or interaction, …
- **High Degree of Coherence** **(~100 %)** for diffraction imaging, …



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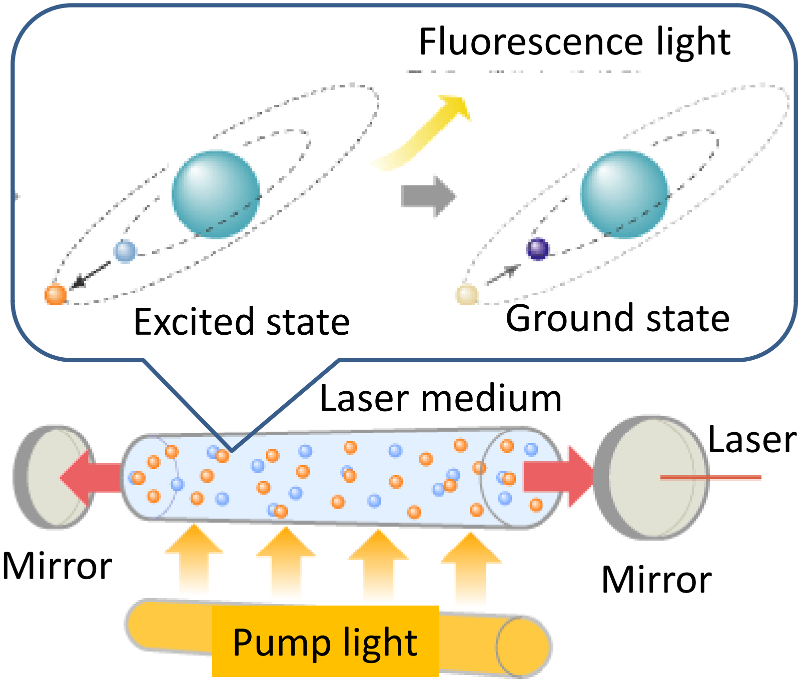
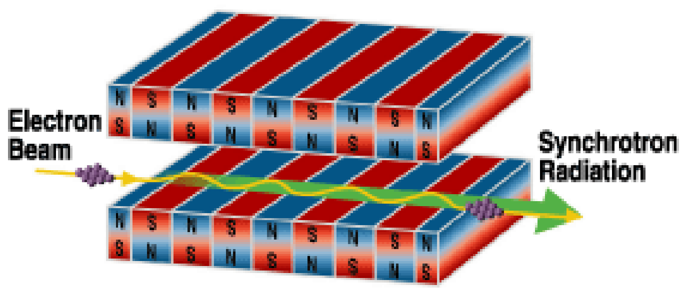
Laser amplification mechanism

- Visible light laser
  - Stimulated photon emission in the laser medium.
  - Amplified by the optical cavity.

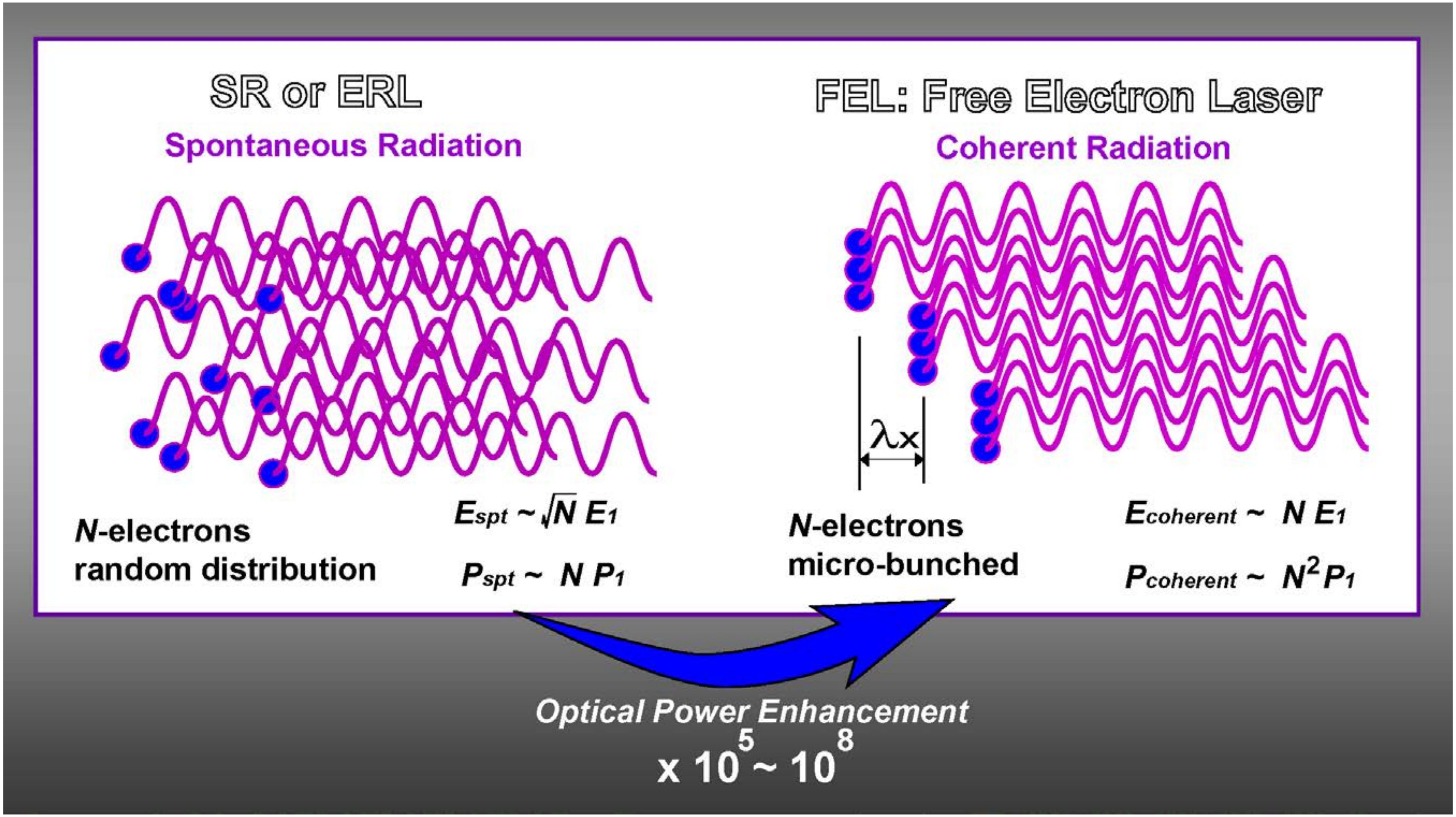


- X-ray
  - Almost transmit the materials.
  - Low interaction to laser medium.
  - No available reflection mirror.

- Free electron laser (FEL)
  - Stimulated synchrotron radiation from the electron beam (free electron) in the undulator.

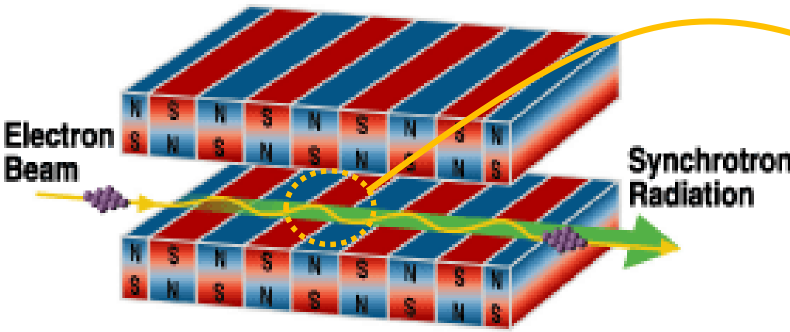


Micro-bunched electron enhances the radiation power



How to make micro bunch in the undulator

Electrons emit undulator radiation



Photon wavelength:

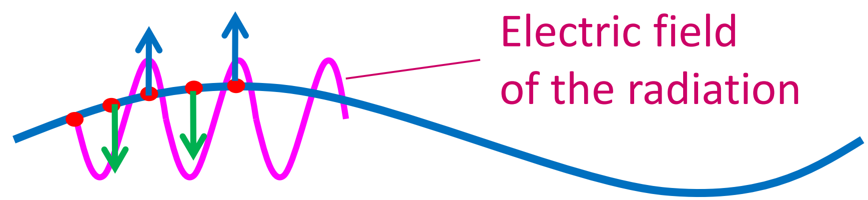
$$\lambda_x = \lambda_u / 2\gamma^2 * (1+K^2/2)$$

Magnet period

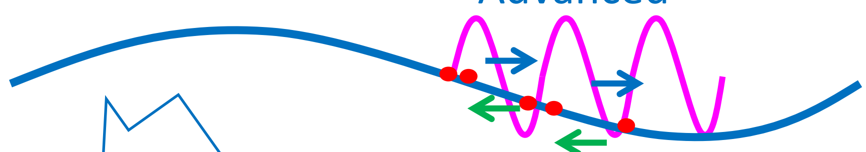
Electron beam energy

Magnetic field strength

Electron's energies are periodically modulated by EM field of the radiation



Electrons are gathered (micro-bunch) in the wavelength intervals

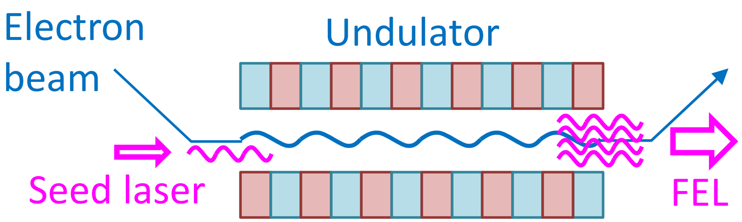


Micro-bunched electrons emit Intense, coherent radiation (laser)

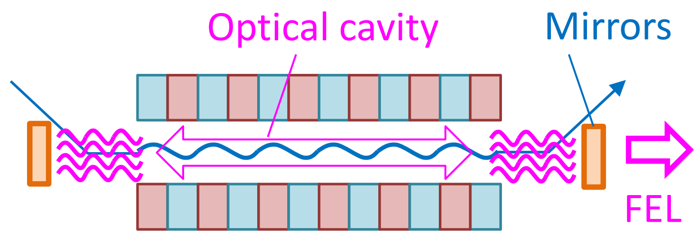
Various type of Free Electron Lasers

- **Seeded FEL**
  - External laser gives initial modulation.
  - Wavelength range is limited by seed laser.
  - 61 nm @SCSS/SPring-8 in 2010.

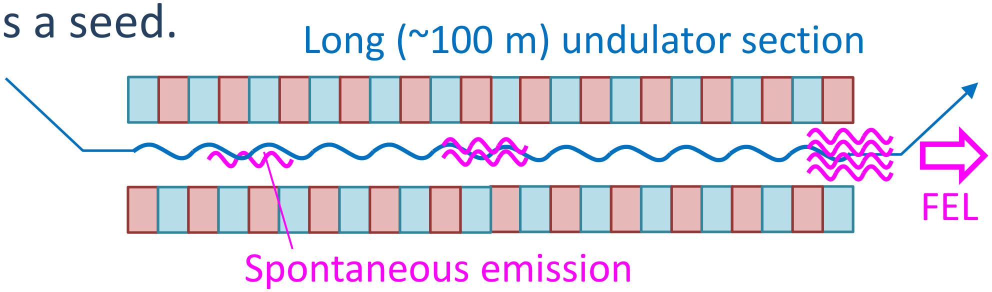
    (T. Togashi et al. Opt. Express, 2011)



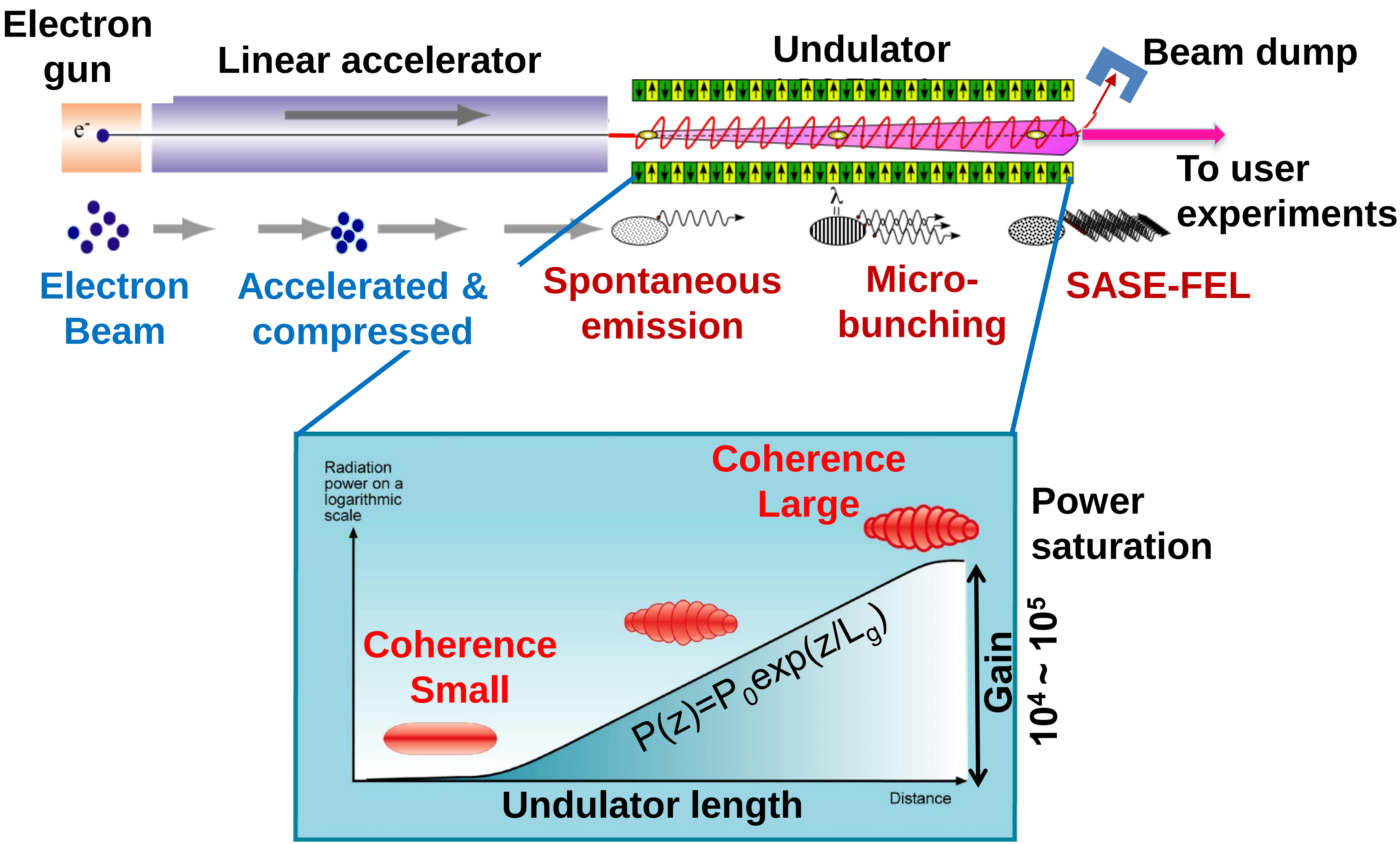
- **Cavity FEL**
  - Long electron pulse length (> several μs).
  - Wavelength range is limited by mirror.
  - Popular for infrared (THz) FELs.



- **Self Amplified Spontaneous Emission (SASE) FEL**
  - Spontaneous emission works as a seed.
  - No limitation for wavelength.
  - Intrinsic fluctuation due to initial spontaneous emission.



SASE-type XFEL schematic

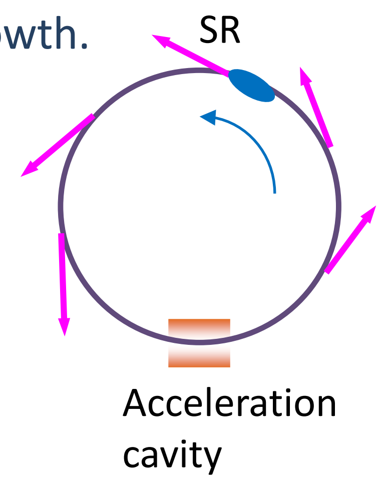


SASE-XFEL, basic formulas (for linear undulator)

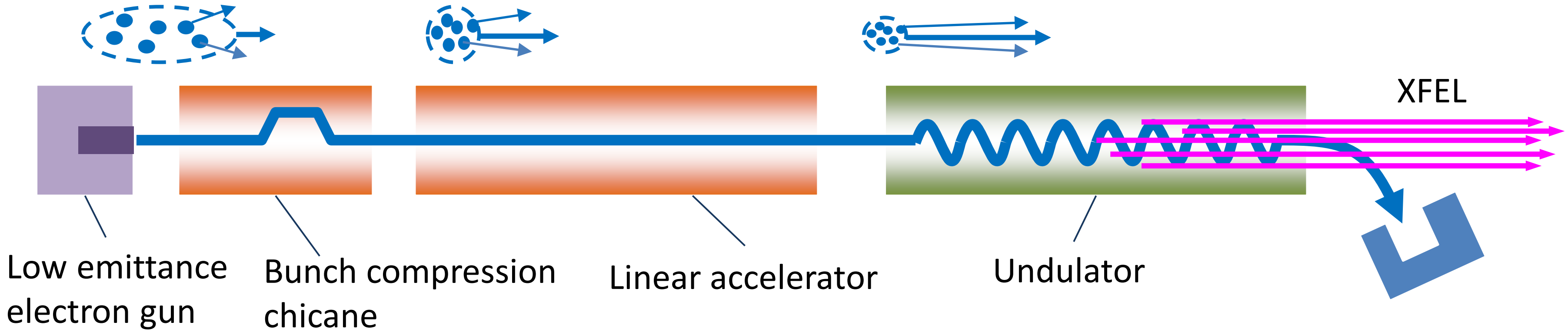
	Formula	Typical parameters at SACLA
• Photon wavelength:	$\lambda_x = \frac{\lambda_u}{2\gamma^2} \cdot (1 + \frac{K^2}{2})$	←X-ray 0.12 nm
– Beam energy: $\gamma \equiv E_e/(m_e c^2)$		←High 8 GeV
– Undulator period: λ_u		←Short 18 mm
• FEL parameter:	$\rho \propto \left(\gamma I_e \cdot \frac{\lambda_x^2}{\sigma_x \cdot \sigma_y} \cdot f(K)\right)^{1/3}$	←High typ. 5×10^{-4}
– Beam current: I_e		←High several~10 kA
– Beam size: σ_x, σ_y		←Small typ. 30 μm
– Undulator parameter: $K \equiv (eB\lambda_u)/(2\pi m_e c)$		←High 2.1
• Gain length (1D approx.):	$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$	←Short typ. 2 m
• Radiation power growth:	$P_x(z) \propto \exp\left[\frac{z}{L_g}\left(1 - \frac{(\Delta\gamma/\gamma)^2}{12\rho^2}\right)\right]$	
– Energy spread: $\Delta\gamma/\gamma$		←Small $<10^{-3}$
• Saturation power:	$P_{sat} \sim \rho P_{beam} = \rho N_e E_e$	←High typ. 500 μJ

XFEL requires high-dense, low-emittance electron beam

- <u>Ring type accelerator</u>
  - Synchrotron radiation causes energy spread and emittance growth.
  - Unable to obtain enough quality beam for XFEL.



- <u>Linear accelerator</u>
  - Low emittance (beam size x divergence) electron gun.
  - Transverse beam size is focused by the beam acceleration.
  - Bunch length compression to several kA.



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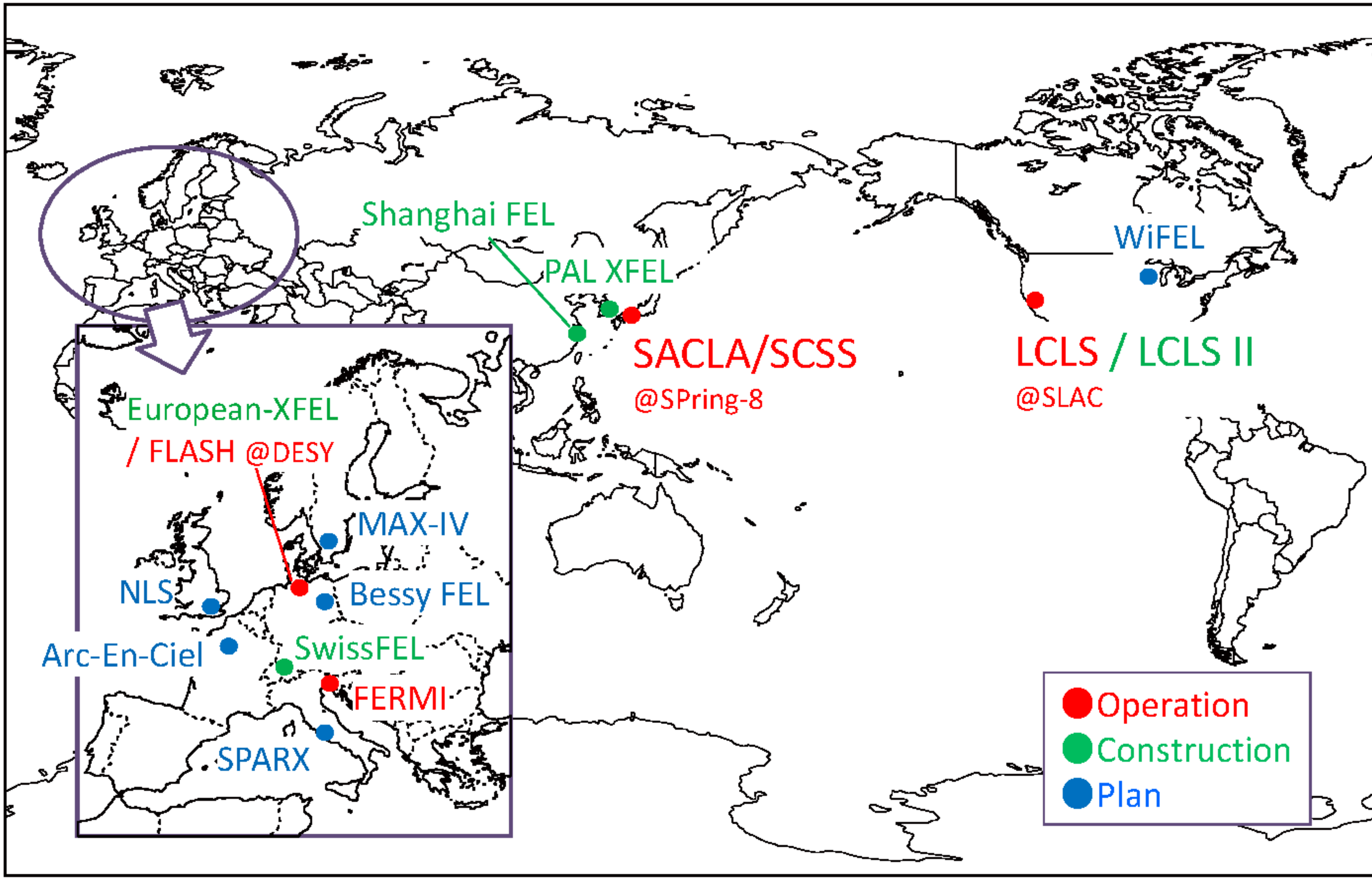
Short wavelength FEL facility in the world （λ_x < 100 nm）



Comparison of three XFELs

Facility	LCLS	SACLA	European-XFEL
Place	SLAC, USA	SPring-8, Japan	DESY, Germany
Length	2 km	**0.7 km**	3.5 km
E-gun	RF gun	Thermionic gun	RF gun
Accelerator	Normal cond. (S-band)	Normal cond. (C-band)	**Super cond.** (L-band)
Undulator	Out-vacuum	In-vacuum	Out-vacuum
Energy	14 GeV	**8 GeV**	17.5 GeV
Wavelength	> 0.15 nm	> 0.06 nm	> 0.05 nm
Const. cost	75 G-yen	**37 G-yen**	150 G-yen
Operation	**2009~**	2011~	2017 ?
	First XFEL	**Compact, low-cost**	**Long pulse, multi bunch**
			

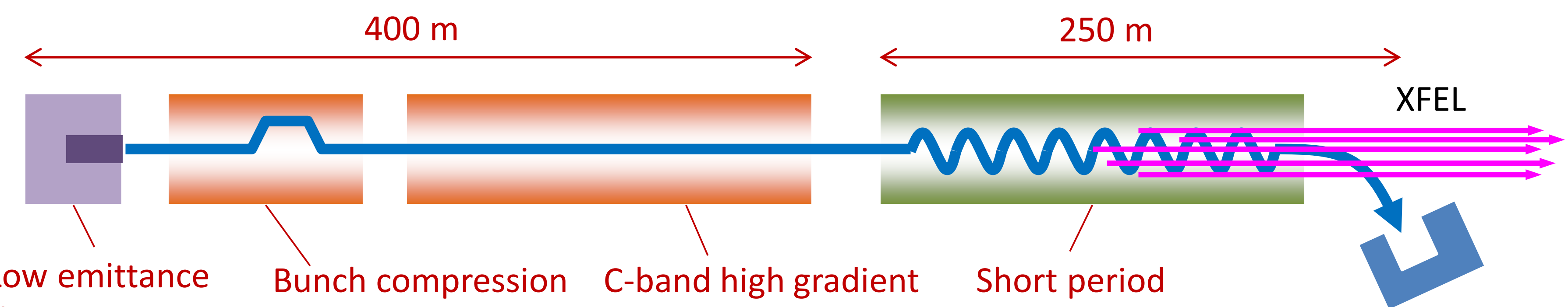
Concept of compact XFEL "SACLA"
(SPring-8 Angstrom Compact X-ray Free Electron Laser)

- Short period undulator → Lower beam energy
  λ_u= 18 mm
- High gradient accelerator → Short accelerator length
  E_{acc}= 35~40 MV/m
- Low emittance e-gun (ϵ_N< 1π μrad) +
  bunch compression → Short saturation length

$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\cdot\left(1+\frac{K^2}{2}\right)$$

$$\rho \propto \left(\gamma I_e \cdot \frac{\lambda_x^2}{\sigma_x \cdot \sigma_y} \cdot f(K)\right)^{1/3}$$

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

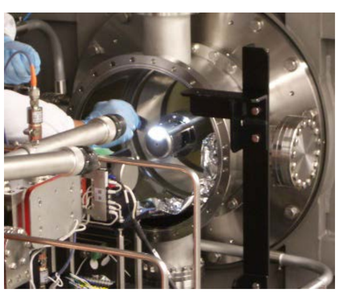


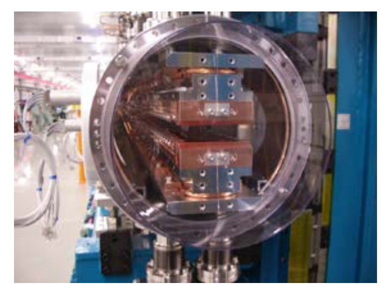
Low emittance thermionic gun

Bunch compression chicane

C-band high gradient accelerator

Short period In-vacuum undulator

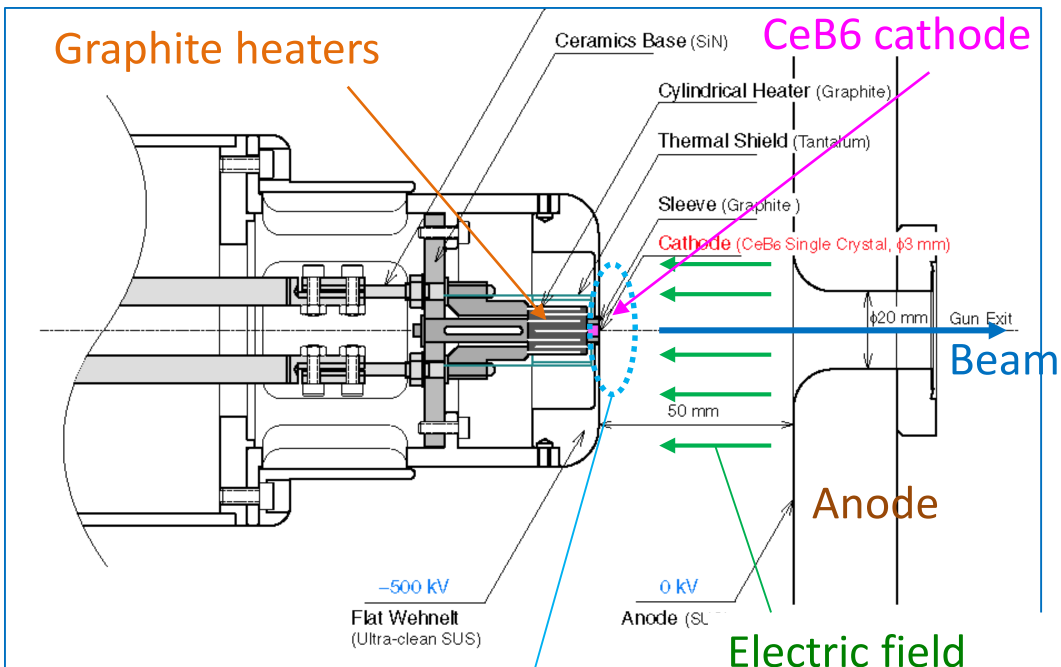


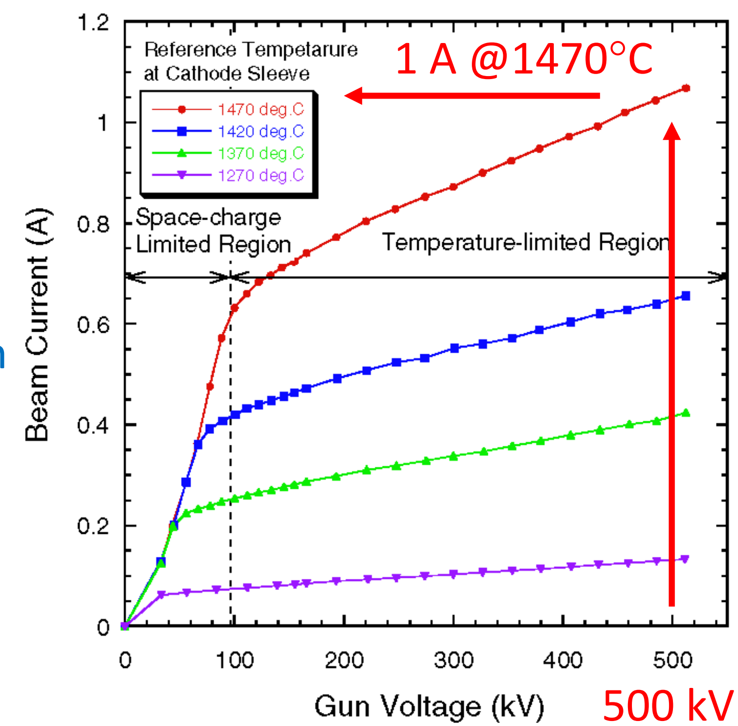


Key technologies of SACLA

Low emittance ($\varepsilon/\gamma < 1\ \pi$ mm*mrad) thermionic gun

- Thermionic gun — Stable, long life, maintenance free
- CeB6 single crystal — Naturally form a flat surface
- Heated to 1500 °C — Intense e-beam (~1 A) from 3 mmϕ cathode
- 500 kV high voltage — Launch to forward direction against space charge.

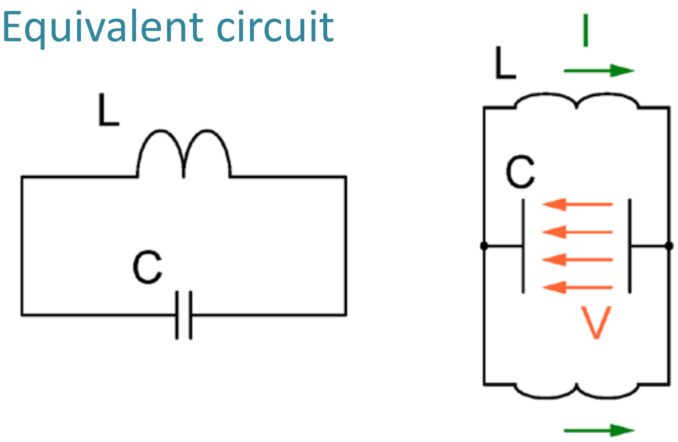


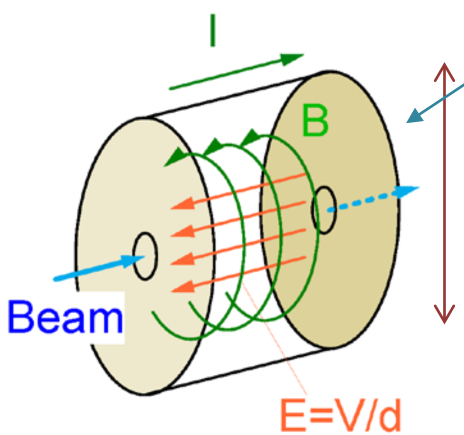


Electron accelerator consists of microwave cavities

- Microwave cavity works as a LC resonator.
- Supplying microwave power for a certain period (so called "filling time"), high electrical field is generated between the gap.
- Electron beam is accelerated with this electrical field.

Equivalent circuit





Resonant frequency: $f = 1/(2\pi\sqrt{LC})$

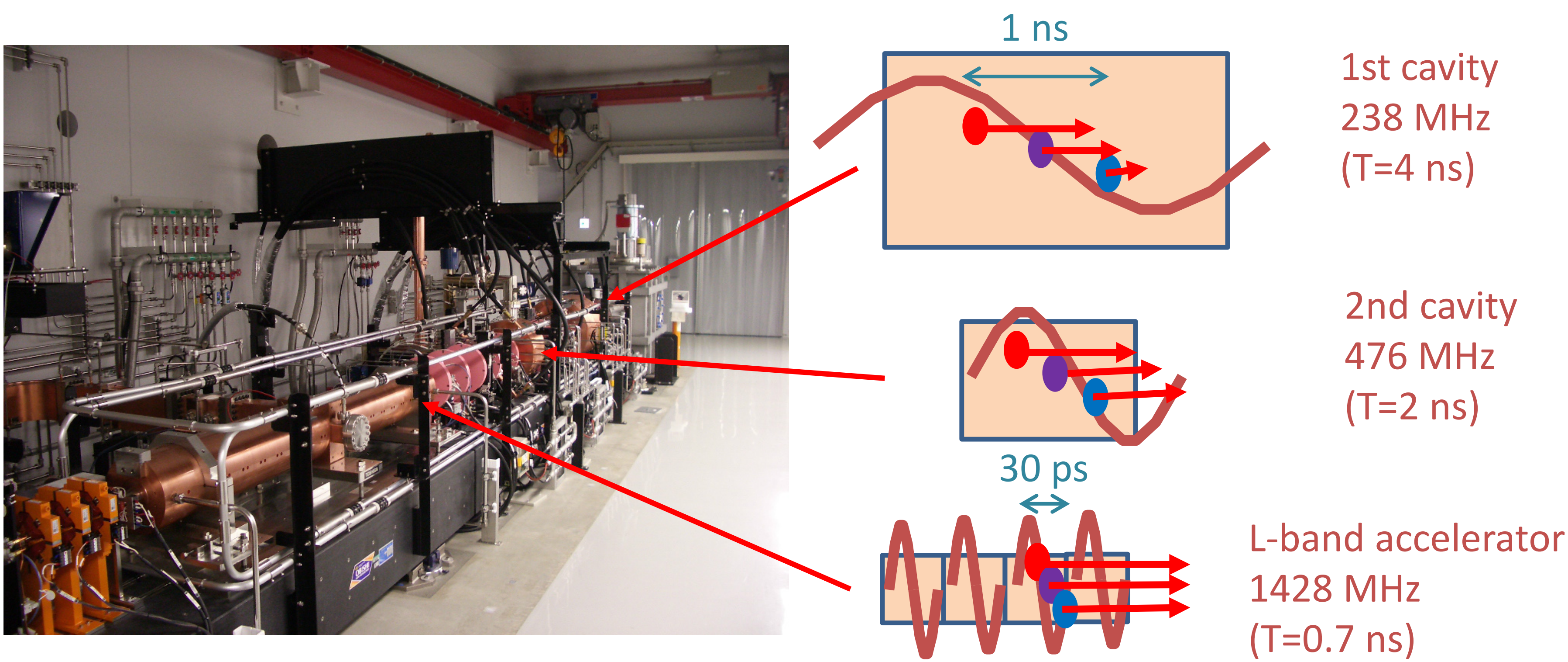
Stored energy: $U = CV_{max}^2/2 = LI_{max}^2/2$

Acceleration voltage:

$$V_{max} = \sqrt{2U/C} = \sqrt{L/C} \cdot I_{max}$$

Velocity bunch compression at “buncher” cavities

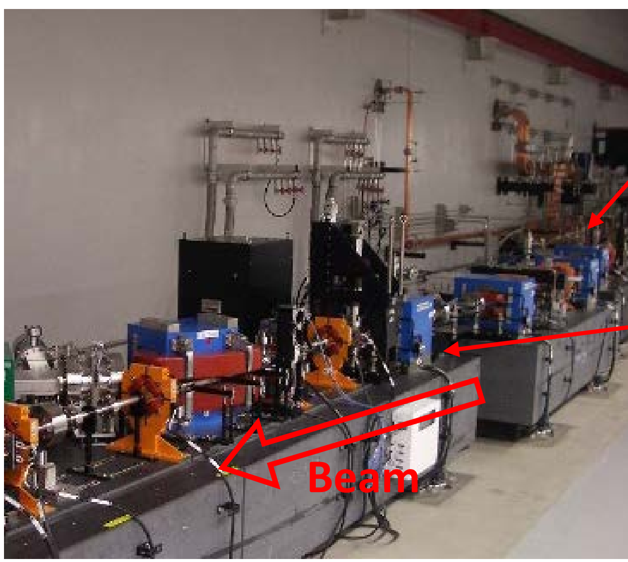
- Electron beam from the gun is accelerated at off-crest phase.
- Due to the velocity difference, electron beam is compressed.
- At the downstream, smaller cavity and higher microwave frequency are used because of the shorter bunch length.

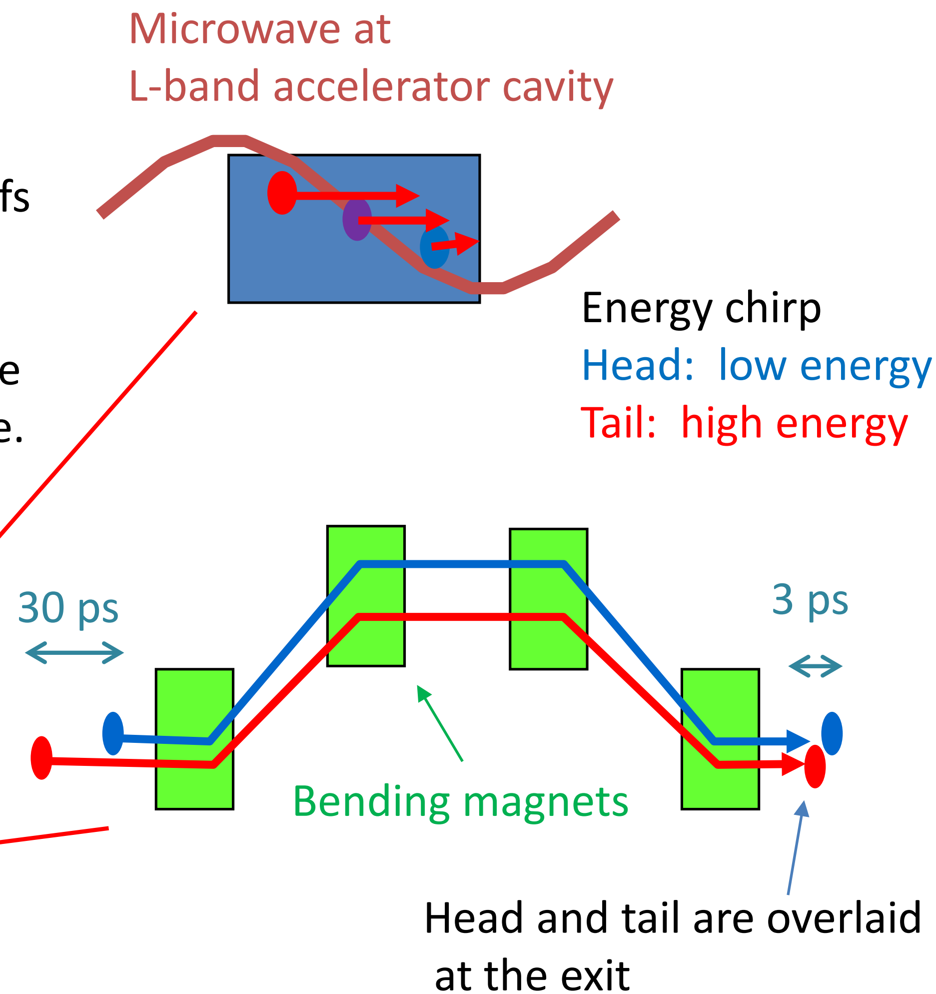


Bunch compression chicane

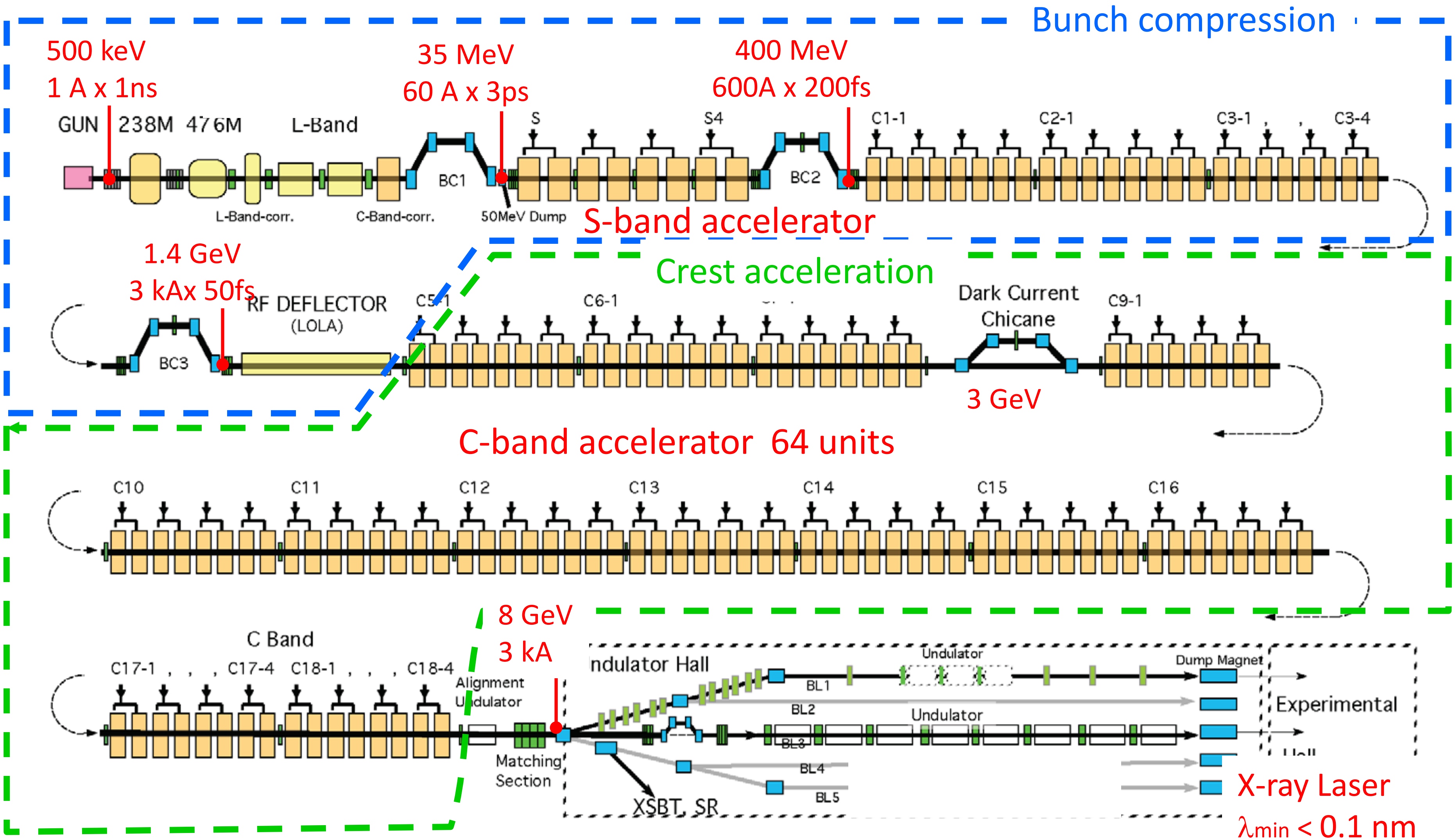
After the L-band accelerator, the bunch length is compressed using a chicane (BC1). In SACLA we use 3 stage compression (BC1, BC2, and BC3) to compress the beam to 50 fs bunch length.

These compression process is quite sensitive to the initial phase of the L-band microwave.
Accuracy ~ 100 fs (0.05° of 1.4 GHz)





SACLA machine configuration

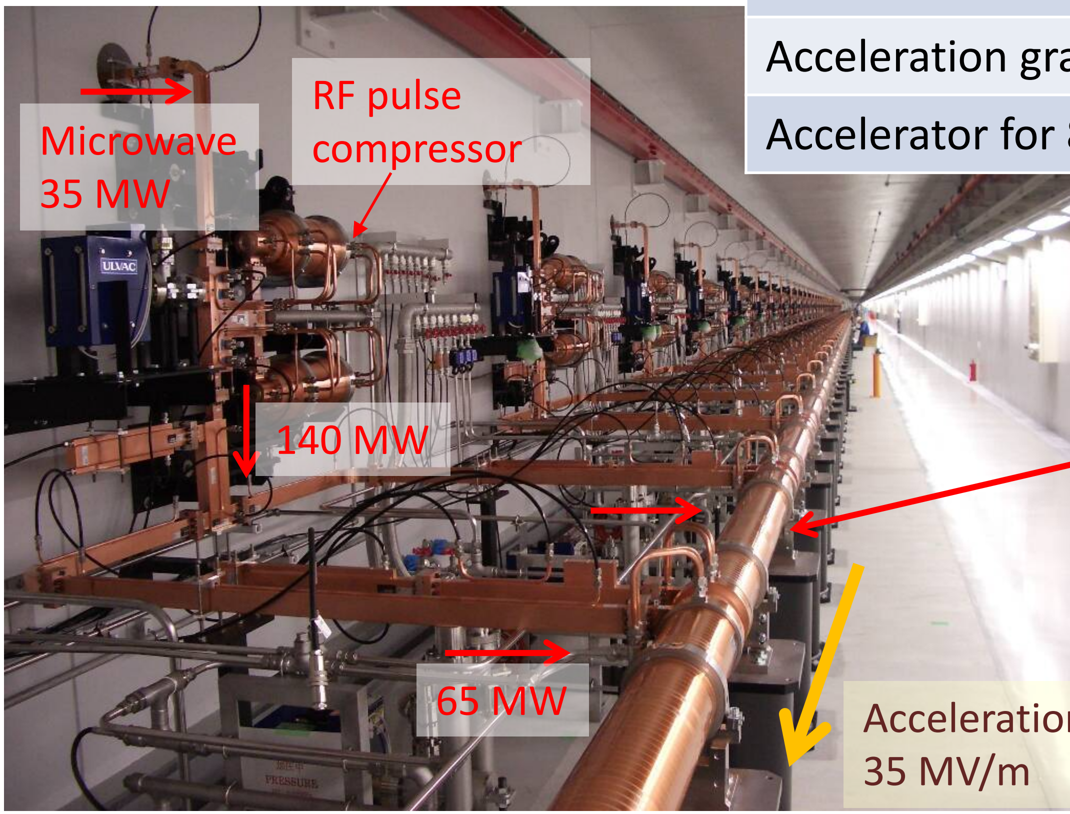


T. Inagaki, PRST-AB 17-080702 (2014)

C-band (5.7 GHz) high gradient accelerator

World first accelerator to use C-band microwave frequency.
The cavity generate twice high gradient than conventional S-band cavity, to make the facility compact.

	SACLA	Conventional
Frequency	5.7 GHz (C-band)	2.8 GHz (S-band)
Cavity size	Compact	Large
Power efficiency	Better	Worse
Acceleration gradient	35~40 MV/m	15~20 MV/m
Accelerator for 8 GeV	230 m	400 ~ 550 m



Each cavity generates 700 kV / 16 mm gap.
Near theoretical limit of arcing at the pure copper surface.

Klystrons (microwave source) and power supplies

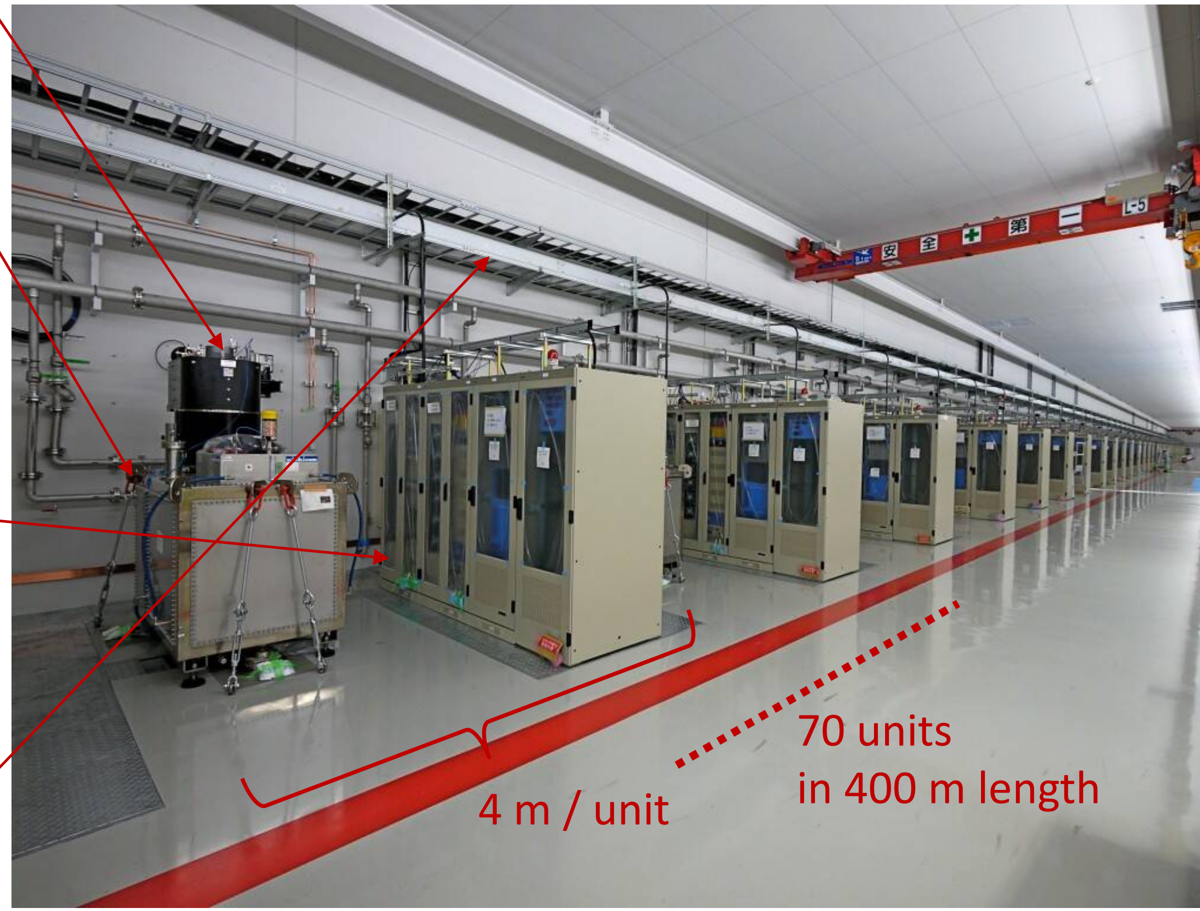
Klystron
50 MW microwave source

Pulse modulator
350 kV pulse generation with very high precision. ($\Delta V/V$~0.001%)

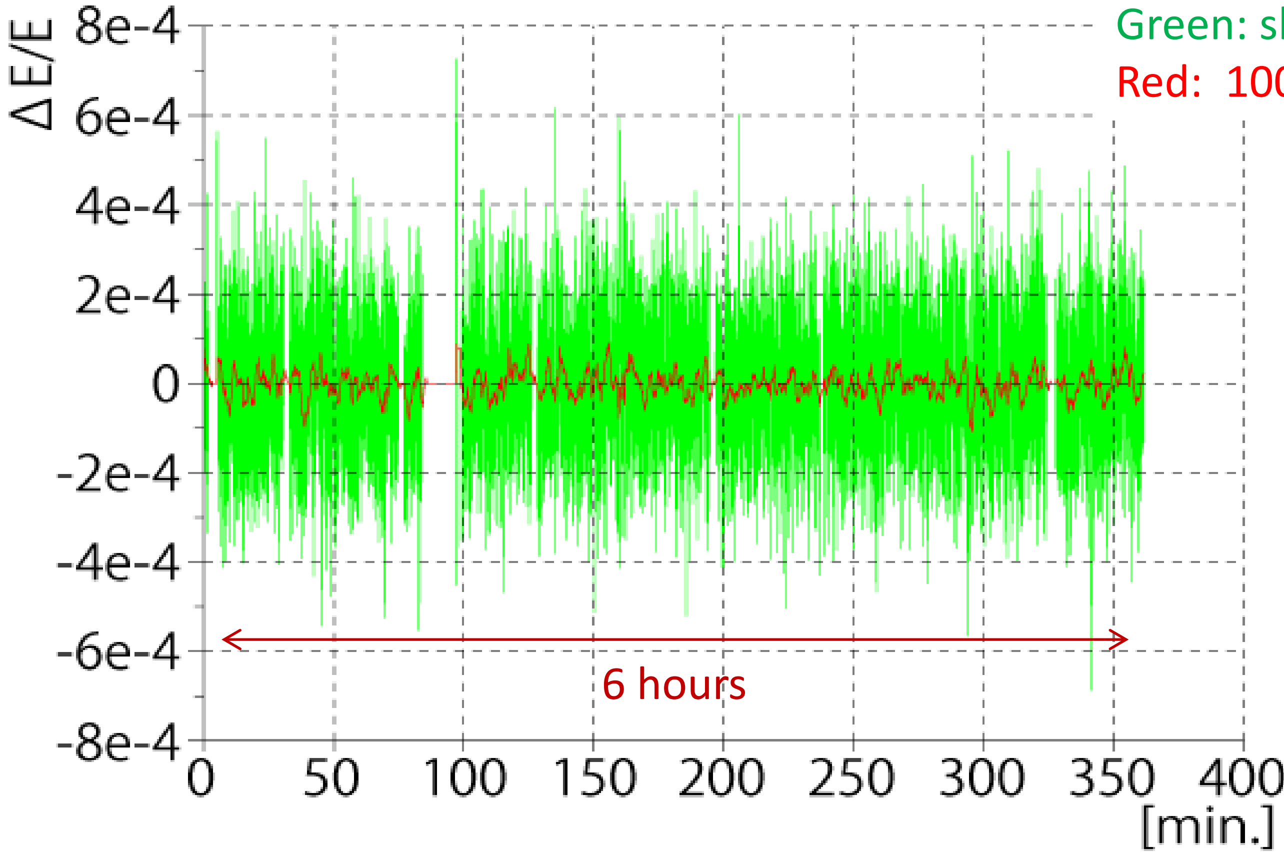
Control cabinet
Microwave phase and amplitude control with <100 fs and <0.1% accuracy and stability.

Timing synchronization optical fiber
Temperature stabilized with <0.1 K by a cooling water.

Supply high power microwave to the accelerator cavity with high accuracy and stability for stable SASE lasing.



Beam energy stability at the accelerator end



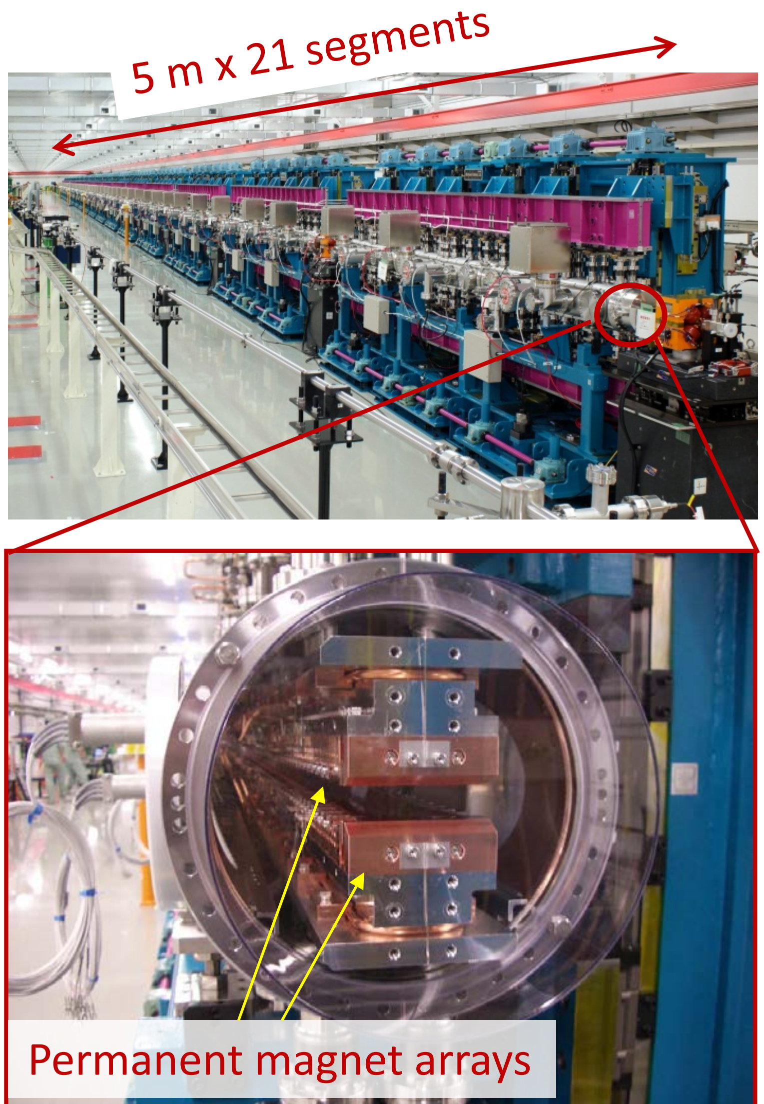
E = 7.0 GeV
Q = 0.1 nC
Repetition = 10 pps
Energy feedback: ON

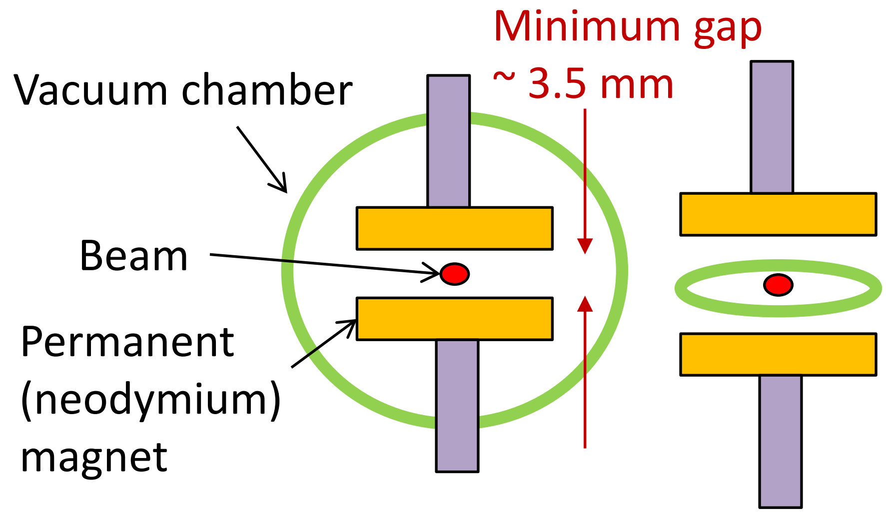
- Stability: **1.4×10^{-4}** (rms of shot-by-shot data)
- Drift: < **1×10^{-4}** (100 s average)

Enough stability for SASE generation.

T. Tanaka, PRST-AB 15-110701 (2012)

In-vacuum, variable-gap undulator





In-vacuum type
Narrow gap
High magnet field

Out-vacuum type
Minimum gap is restricted by chamber.

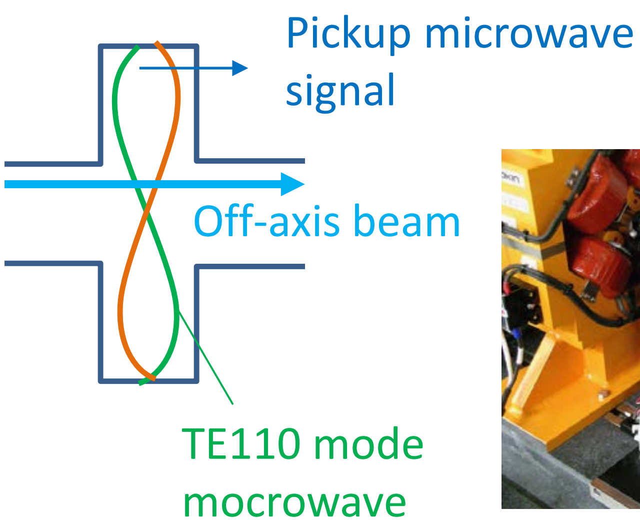
Short period λ_u = 18 mm (half of SPring-8).
Lower beam energy to generate X-ray.
Short undulator length for SASE saturation.

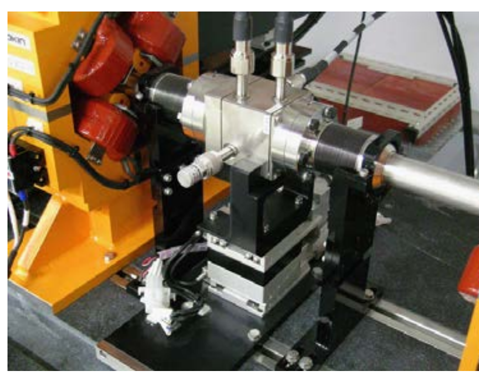
H. Maesaka, NIM A 696 (2012) p66-74

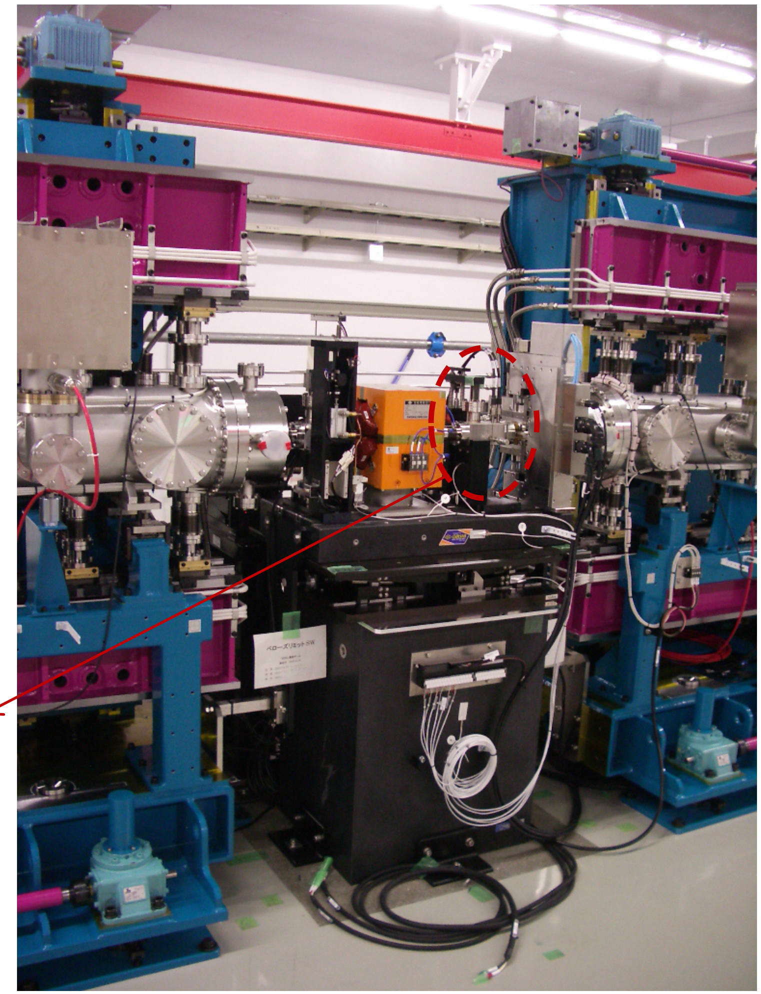
μm level control of electron beam trajectory in the undulator

Electron should sufficiently overlap to SASE radiation in the undulator.
Required accuracy ~ several μm

Cavity-type beam position monitors (BPMs) measure beam position with 0.5 μm accuracy.







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History of SACLA

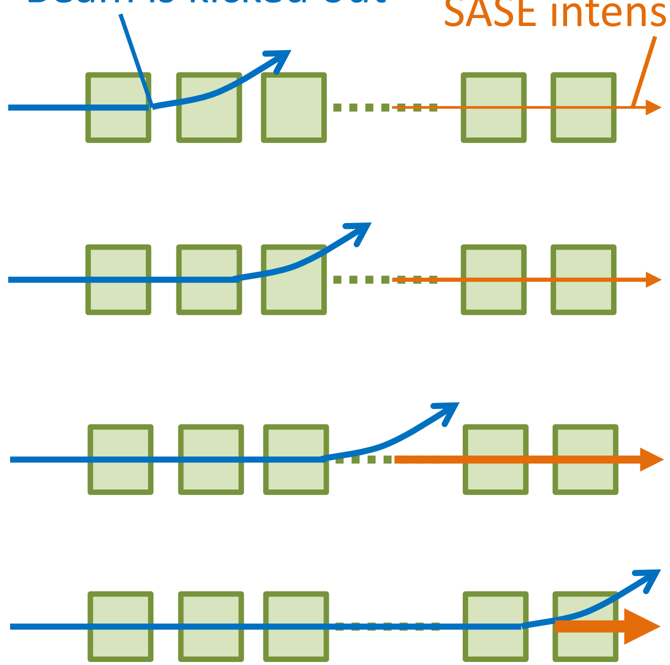
2001	FEL design and development started.
2005	Prototype FEL machine "SCSS" construction.
2006 June	First lasing at 49 nm.
2006~2010	XFEL facility "SACLA" construction.
2011 Feb.	Beam commissioning started.
Jun.	First lasing at 0.12 nm.
Oct.	SASE power saturation achieved at 0.12 nm.
2012 Mar.	User experiments started.
2013 Apr.	2-Color SASE released to user experiments.
Nov.	First experimental symptom of self-seeding observed.
2015 June	Simultaneous operation of 2 BLs demonstrated.

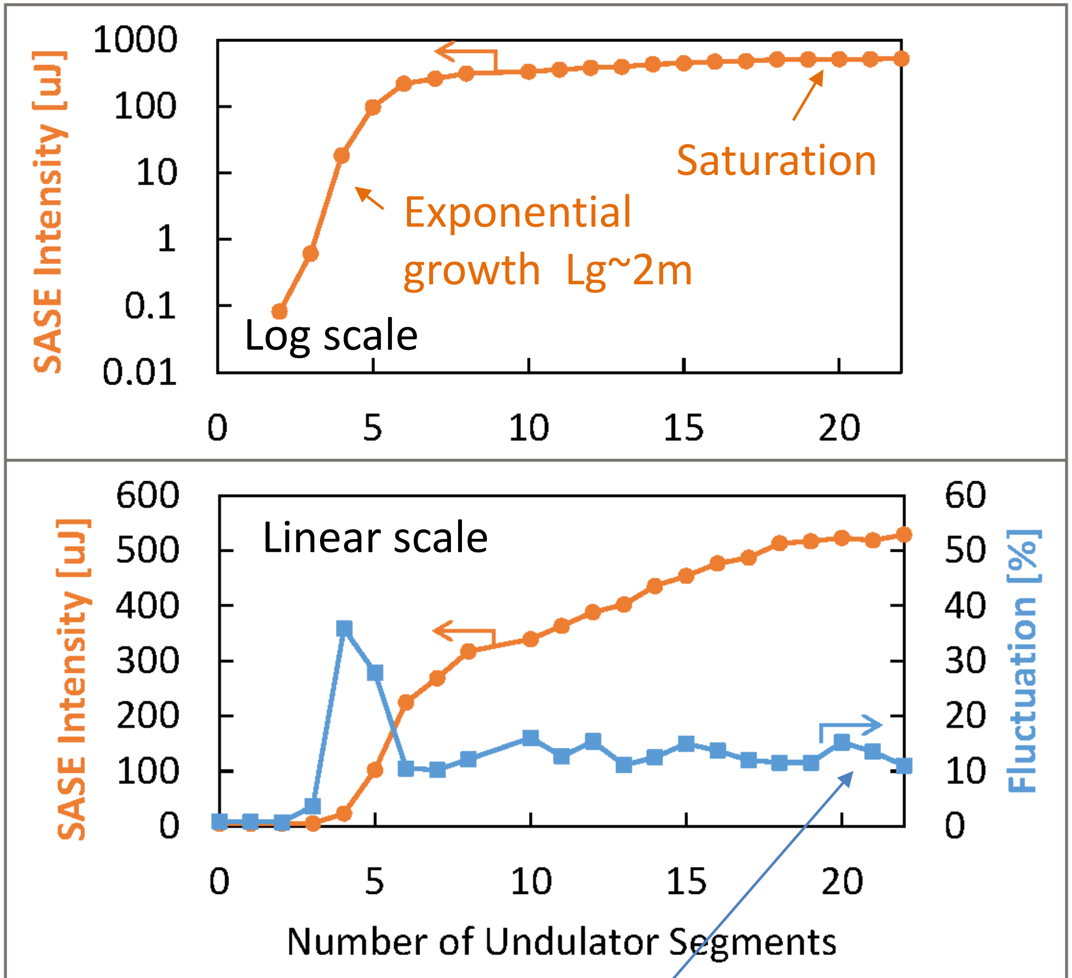
Summary of Present XFEL Performance

Pulse Energy*:	~0.6 mJ@10keV
Peak Power*:	>60 GW (assuming 10 fs pulse)
Pulse duration*:	<10 fs
Intensity Fluctuation*:	~10% (σ)
Lasing Wavelength:	0.83 - 2.8 Å (user operation)
Bandwidth:	~0.5%
Spatial Coherence:	nearly full
Repetition:	30 Hz（Max.60 Hz）
Mean Fault Interval:	~50 min
Operation hour per year:	6300 hours in total
	3600 hours for user operation
Laser availability rate:	93% (2014 user operation)

*It depends on the condition

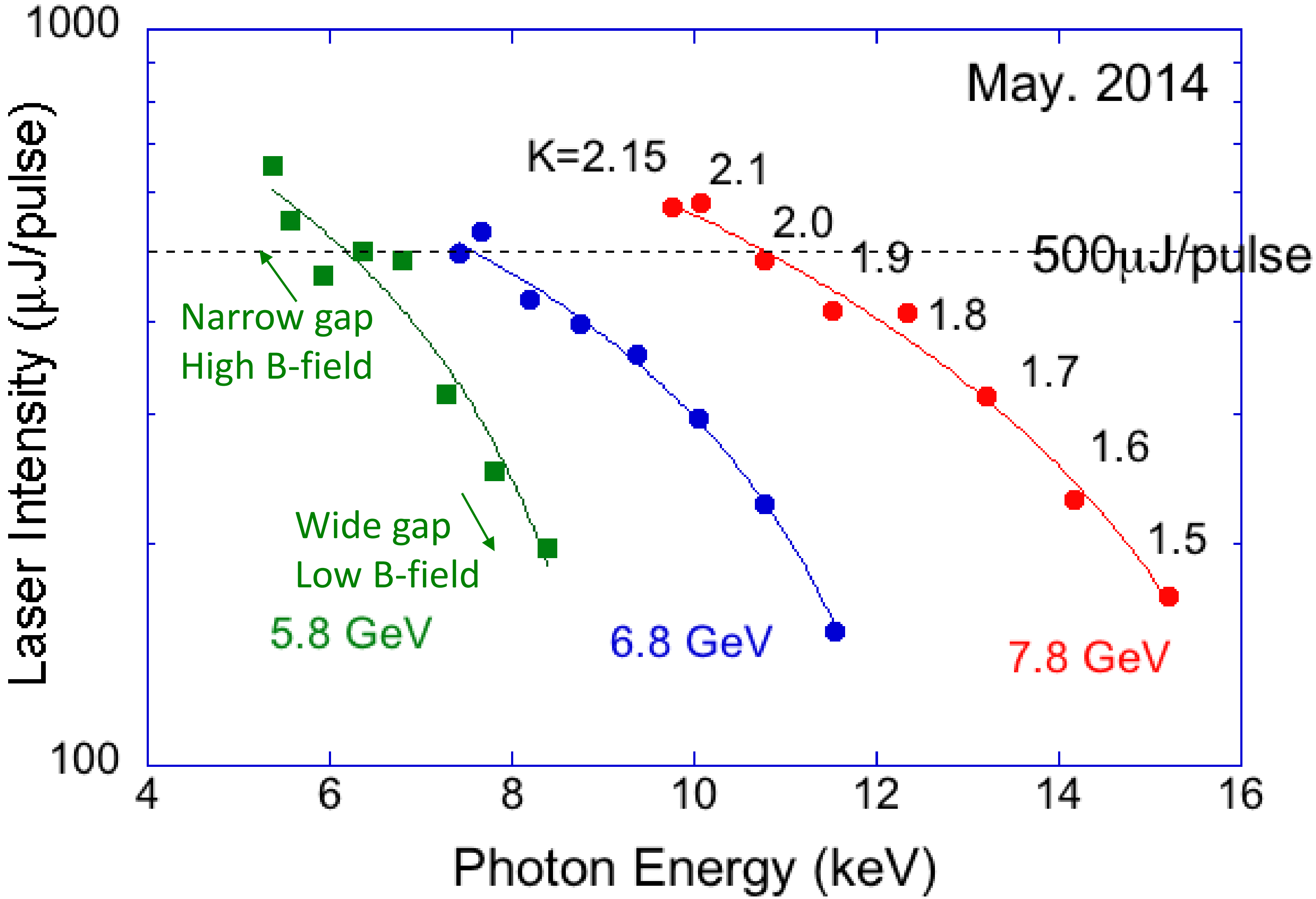
SASE gain curve (July 2015, 10 keV)





Almost fundamental fluctuation of SASE lasing process (statistical fluctuation of shot noise).

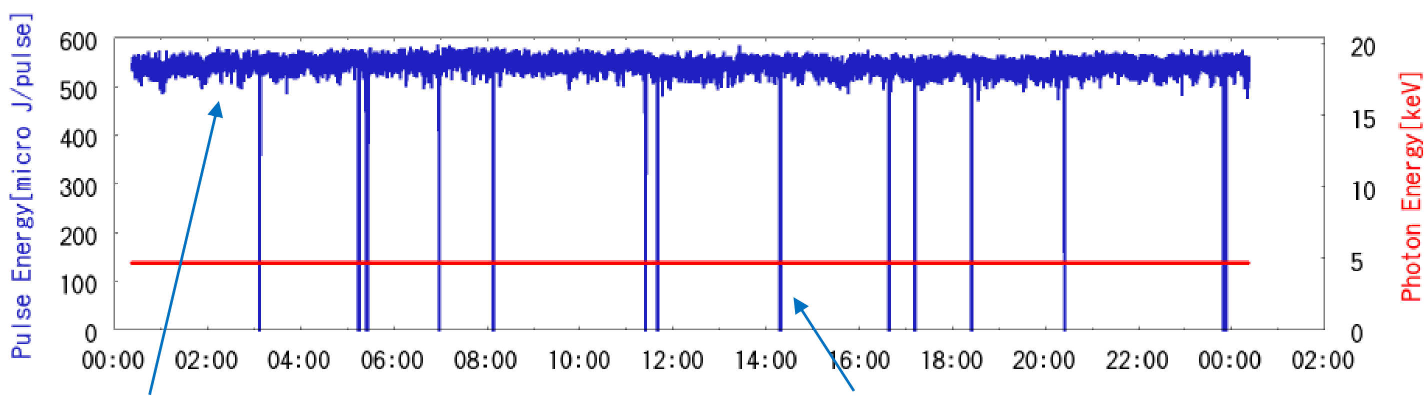
Laser Intensity vs Wavelength



SACLA operation status is available in web: http://sacla-status.spring8.or.jp/

2015/7/11	SACLA Operation Status	00:22:10

Operation Mode	
BL3 User Operation	
Hutch in Use	
BL3 EH4	
Pulse Energy	Photon Energy / Wavelength
538.8 micro J/pulse	4.7 keV / 0.264 nm
Repetition Rate	Intensity Fluctuation in 30 shots (STD)
30 Hz	8.6 %



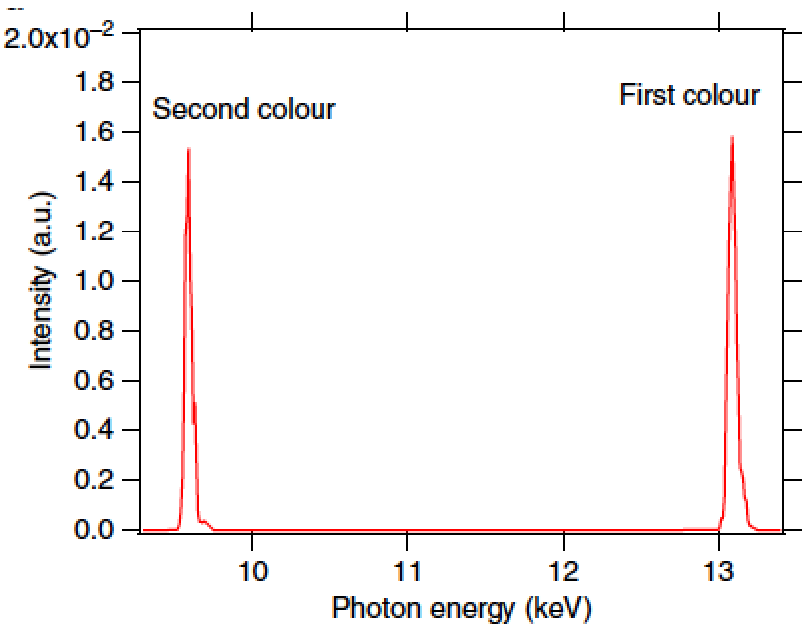
Intensity stability (24 hours)

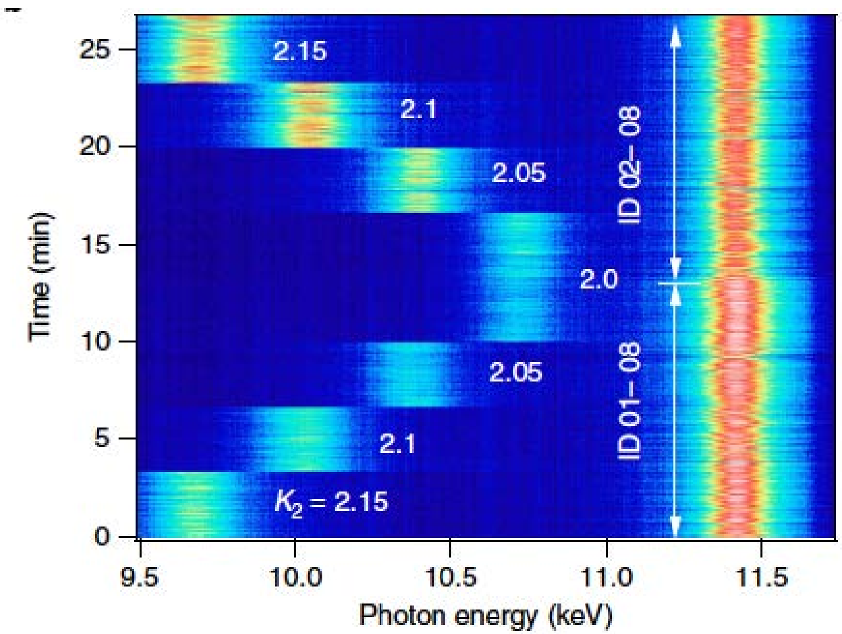
Beam interruption (accelerator fault) due to the microwave arcing and high voltage arcing.

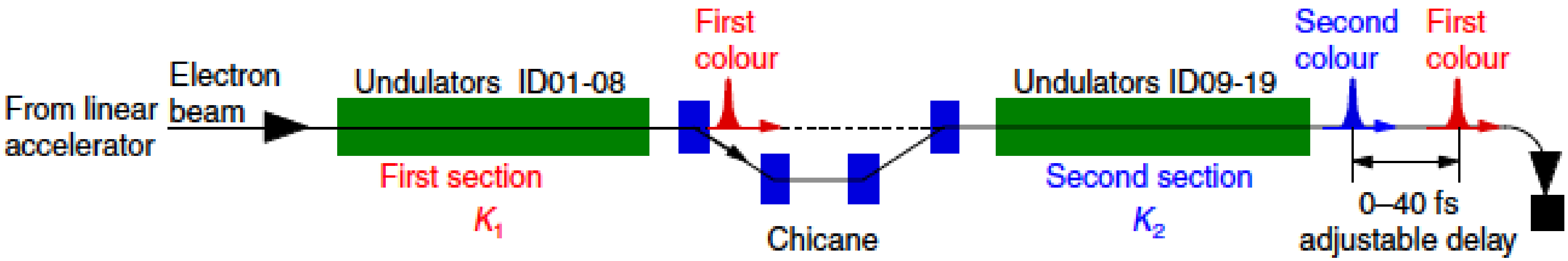
T. Hara, Nature comm. 10.1038, 3919 (2013)

2-Color SASE Routinely Available

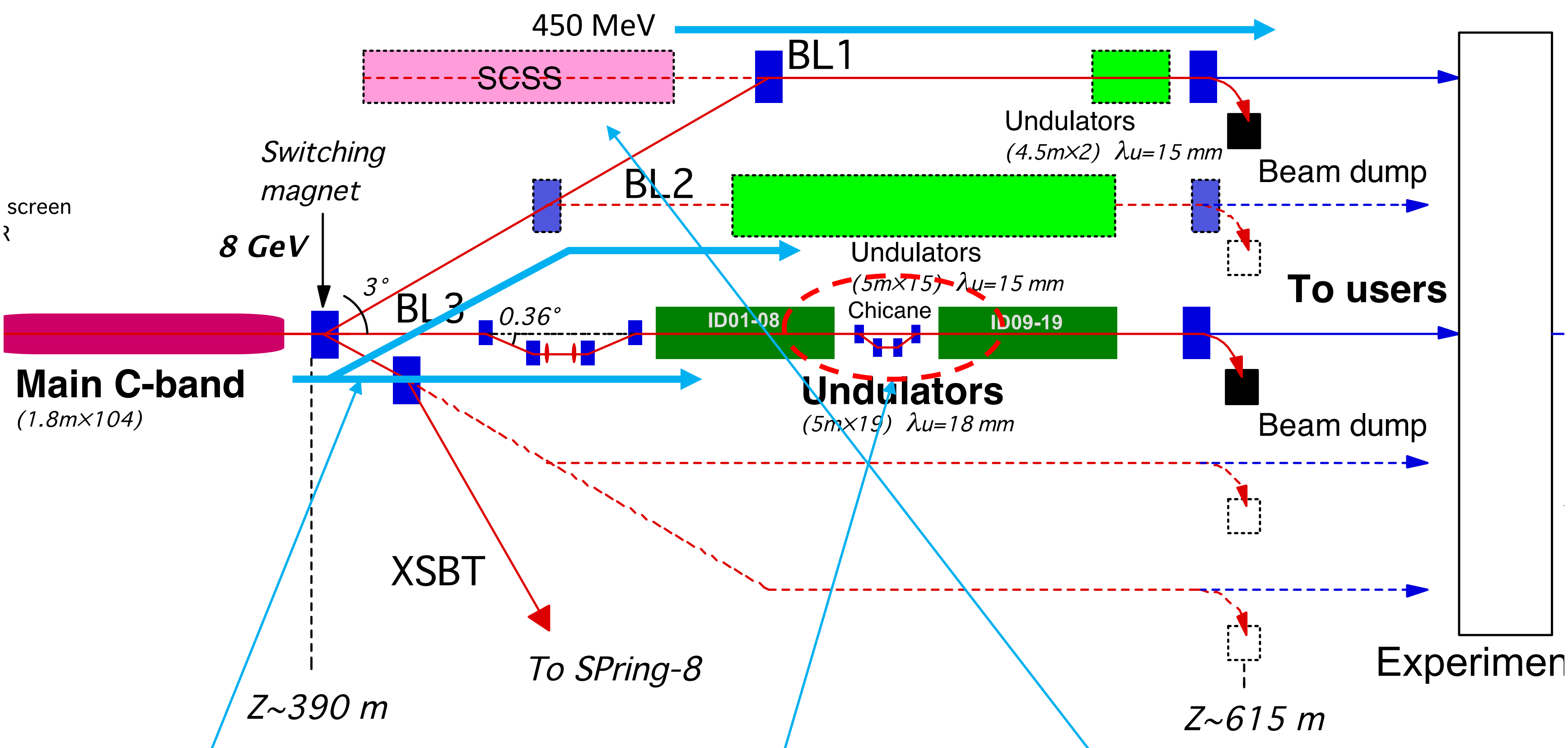
- Wavelength separation of up to 30%
- X-ray wavelength region
- Precise delay control with an attosecond resolution







On-going upgrade plans



More user experiments.
Multi-beamline operation with fast switching magnet.

Monochromatic XFEL
Self-seeding using diamond crystal.

EUV ~ Soft X-ray FEL
Dedicated accelerator has been constructed.

Summary

- X-ray free electron laser (XFEL)
  - Only way to generate laser in X-ray wavelength region.
  - Extremely high brilliant, ultra-short, and spatially full coherent X-ray pulse.
  - Following the two XFEL facilities LCLS and SACLA, several XFEL projects at PAL, PSI, Shanghai, and European-XFEL are under construction.

- SACLA
  - Compact and low construction cost, but high performance XFEL facility.
  - Based on 3 key technologies; a low emittance thermionic gun, high gradient C-band linear accelerators, and short period in-vacuum undulators.
  - Since 2012, SACLA has successfully provided X-ray laser for various user experiments, without any serious troubles.

Thank you