X-ray Free Electron Laser
Part-1 Accelerator

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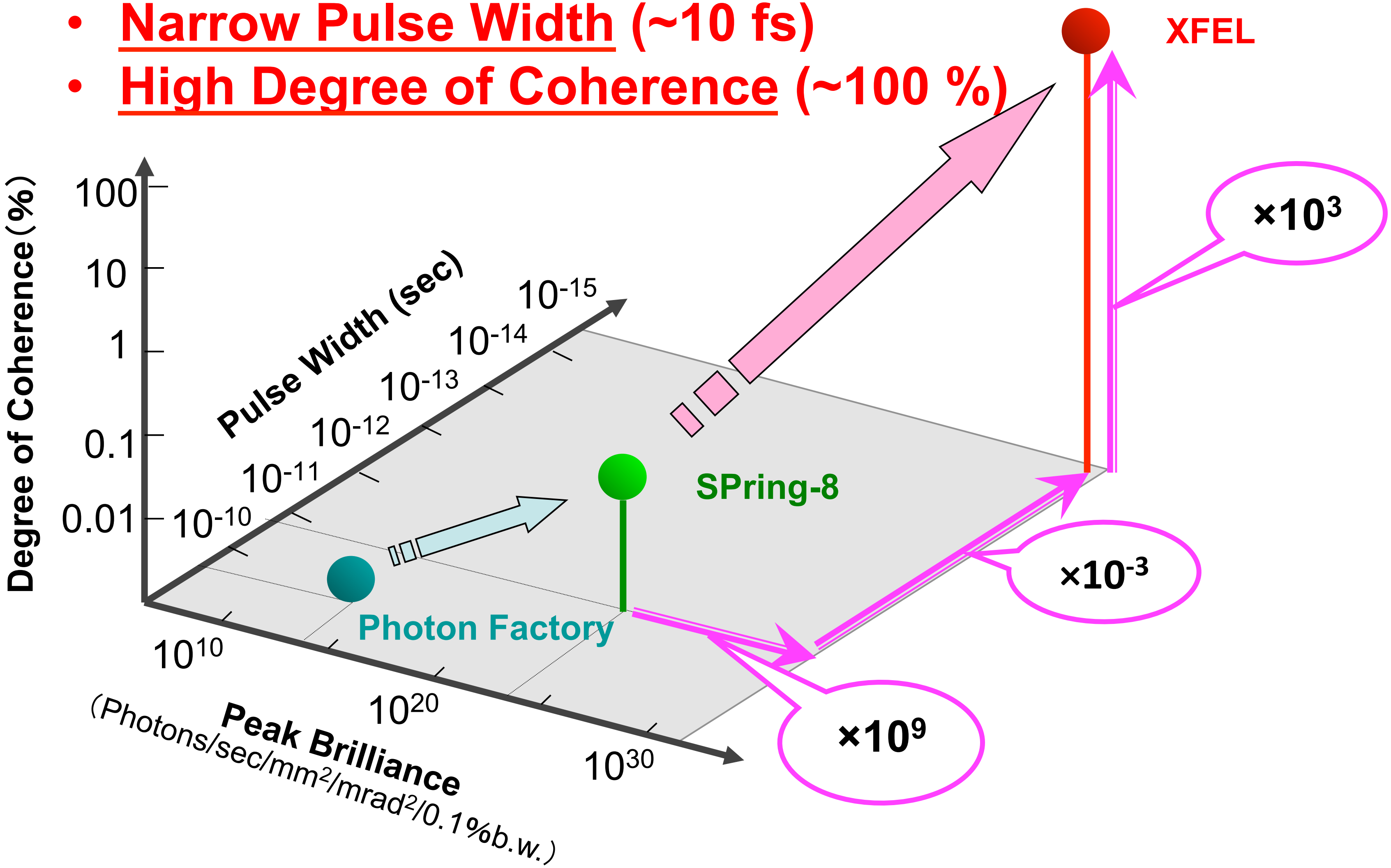
Outline

1. Introduction –What we can observe using XFEL
2. Overview of SASE XFEL
3. Approach to compact XFEL
4. Performance of XFEL

Remarkable Features of XFEL

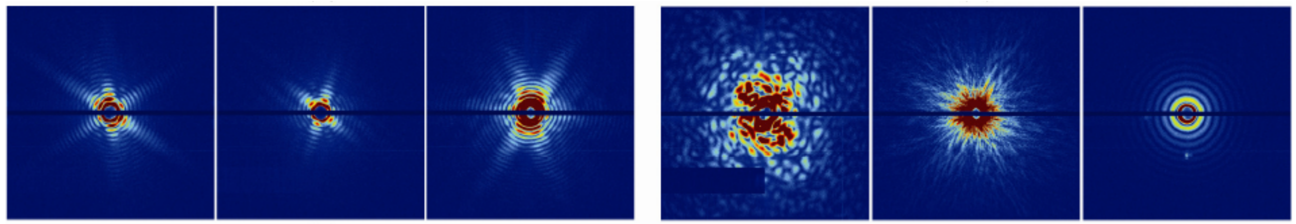
- **High Peak Brilliance** (~10^{33})
- **Narrow Pulse Width** (~10 fs)
- **High Degree of Coherence** (~100 %)



1. What XFEL enables us to observe

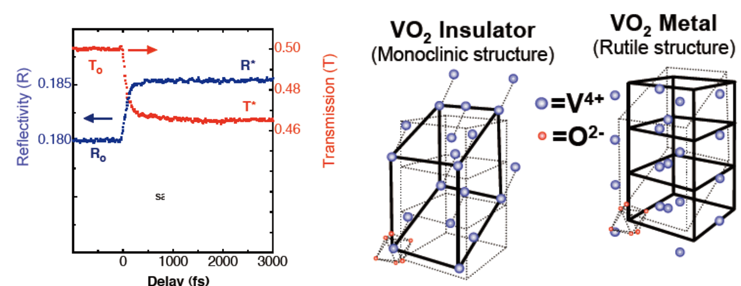
Coherence

Structure analysis on non-crystalline material (e.g., amorphous, single particle)



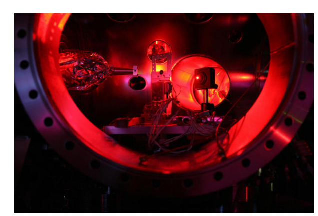
Ultrafast

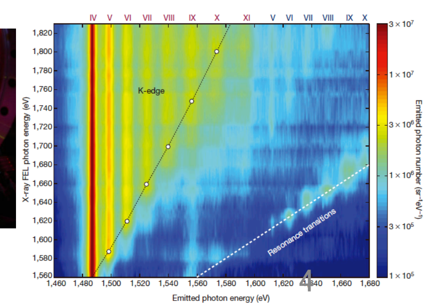
Structure/Electric properties probed with fs temporal resolution (e.g. ultrafast phase transition)



Peak Brilliance

Physics in highly-excited/extreme state under ultra-intense optical field (e.g. high density state)





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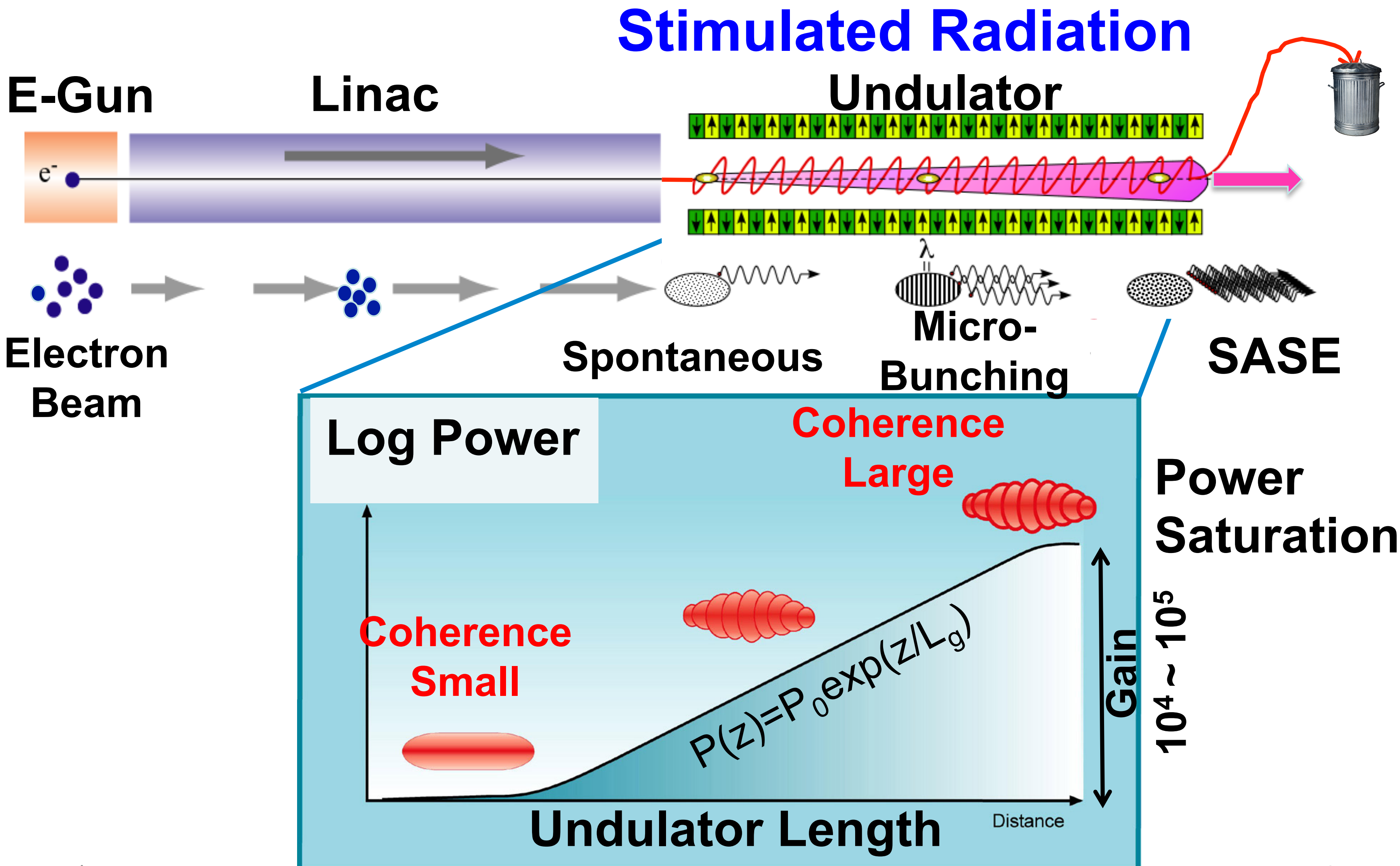
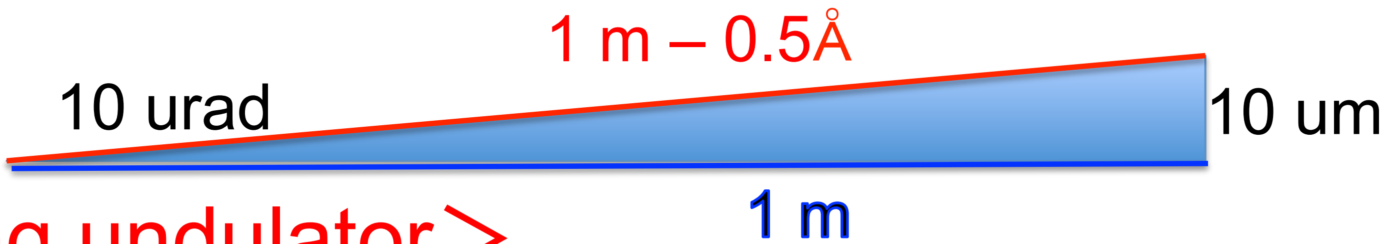
SASE XFEL Scheme



To work optical cavity-free system we need "highly brilliant electron beam" and " long undulator with a large number of periods"

＜Brilliant electron beam＞

High electron density achieving a high gain and low angular divergence keeping density modulation of Å order.



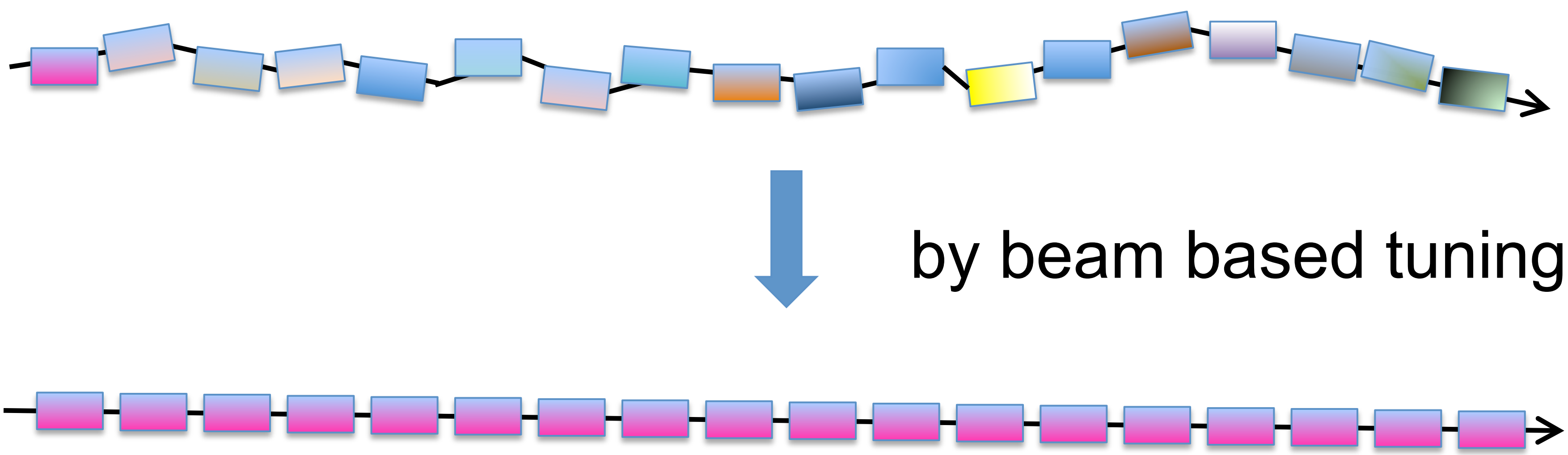
＜Long undulator＞

A larger number of periods realizes a sufficiently high gain by a single pass, which corresponds to that obtained by the optical cavity system.

Long undulator comprising of 18 segments has To behave as a single undulator

For this purpose,

- 18 segments with identical performances (single color)
- Undulator segments alignment (alignment of squares)
- Straight e-beam trajectory (black straight line)



To access short laser wavelength we need “high energy electron beam” , “appropriate period undulators” and large K-value

＜High energy electron beam＞

Undulator radiation wavelength depending on the inverse of gamma square

＜Short period undulators＞

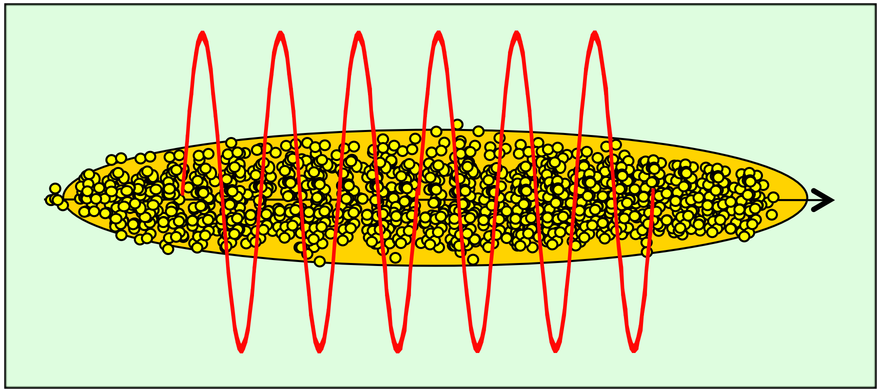
Undulator radiation (laser) wavelength being proportional to the undulator period

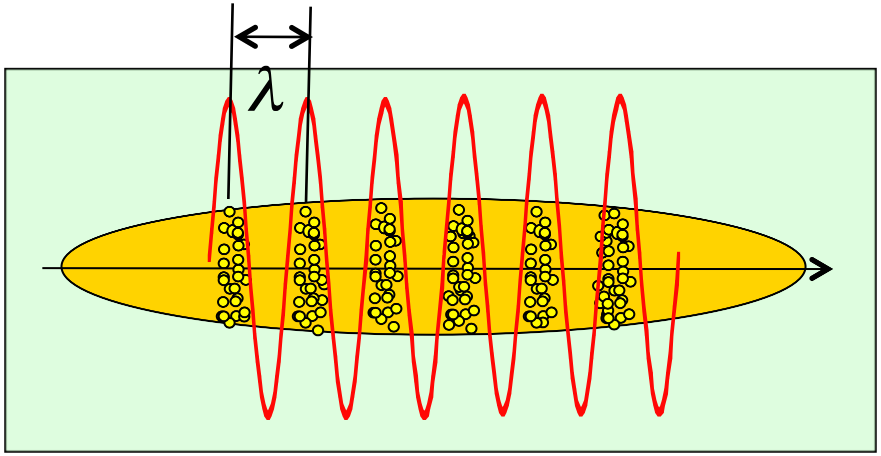
Free electrons as a laser medium

Resonance condition

$$\lambda = \lambda_u - \bar{v}_z T \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right), K = \frac{eB\lambda_u}{2\pi m_0 c\gamma}$$

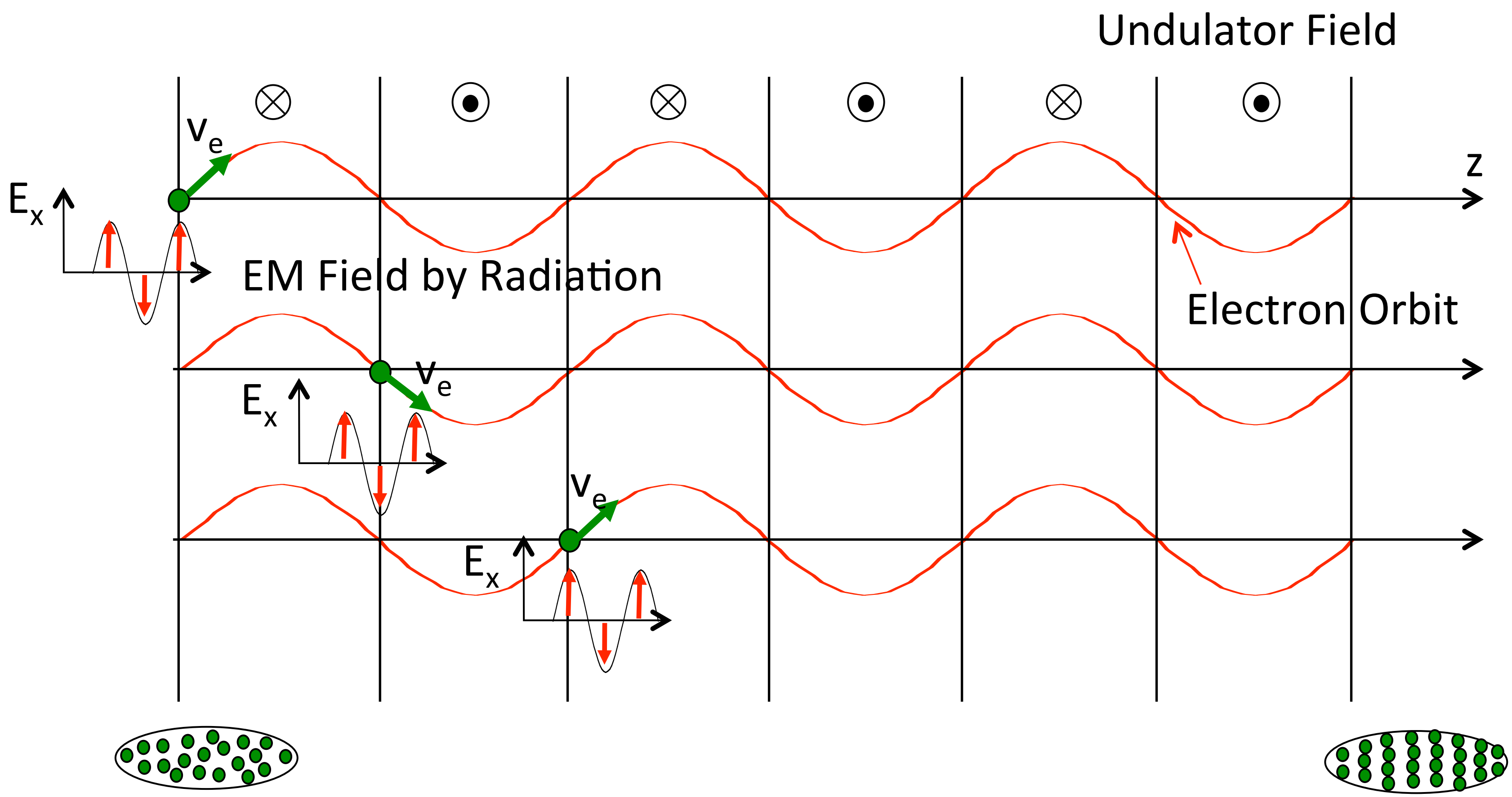
Electron beam is trapped in an electro-magnetic potential and this potential generates energy modulation around the stable fixed point. Then the energy modulation is converted to density modulation through the energy dispersion of the undulator.





Free electrons as a laser medium

Developing density modulation



Free electrons as a laser medium

Instead of stimulated emission, the density modulated electrons with an interval of a resonance wavelength λ , enables laser amplification.

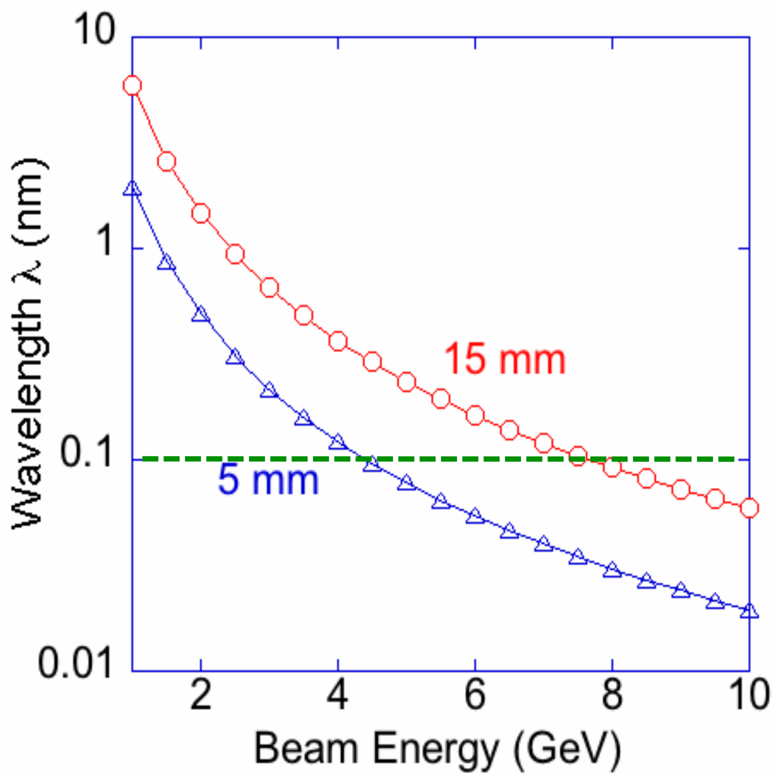
- Independent on energy level in atoms and molecules -

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right), K \cong 1 \sim 2$$

Let's estimate λ assuming

λ_u=15mm, K=2,
γ=3915@2GeV

$\lambda = 1.5\ nm$



Laser Amplification Gain

$$L_{1G} = \frac{\lambda_u}{4\sqrt{3}\pi\rho}, \qquad \rho = \left(\frac{K}{4\gamma}\sqrt{F_1(K)}\frac{\Omega_\rho}{\omega_u}\right)^{\frac{2}{3}}, \qquad \omega_u = \frac{2\pi c}{\lambda_u}, \qquad n_e = \frac{N_e}{\sigma_\ell \sigma_x \sigma_y}.$$

$$F_1(K) = \left(J_0(\xi) - J_1(\xi)\right)^2, \quad \xi = \frac{K^2}{2(1+K^2)}, \qquad \Omega_\rho = \left(\frac{4\pi c^2 r_e n_e}{\gamma}\right)^{\frac{1}{2}},$$

Normalized emittance at a lasing part

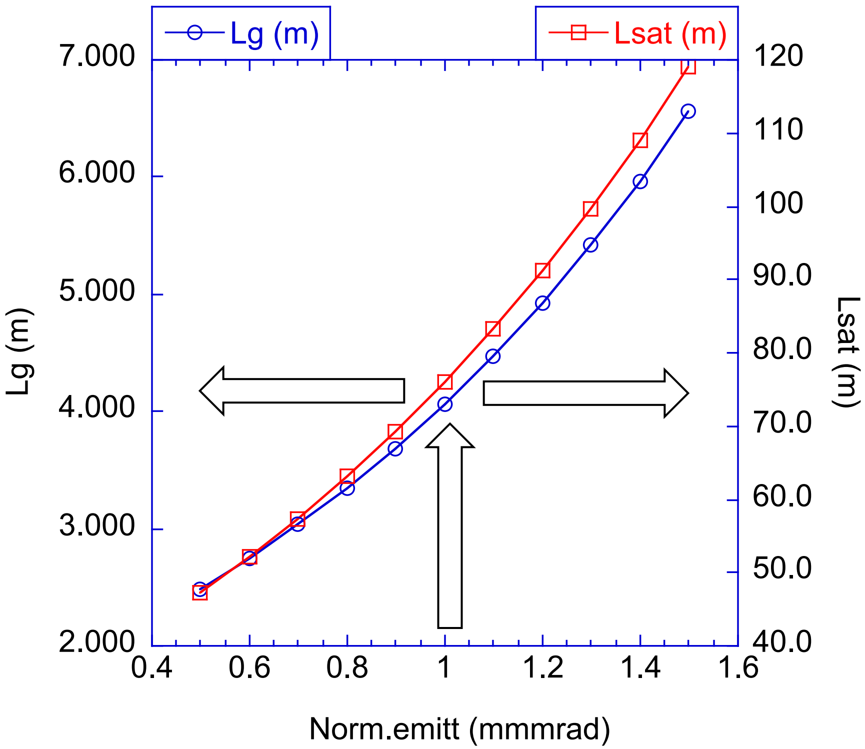
$$L_{1G} \propto \left(\frac{\langle\beta\rangle \varepsilon_{ns}}{I_p}\right)^{1/3}$$

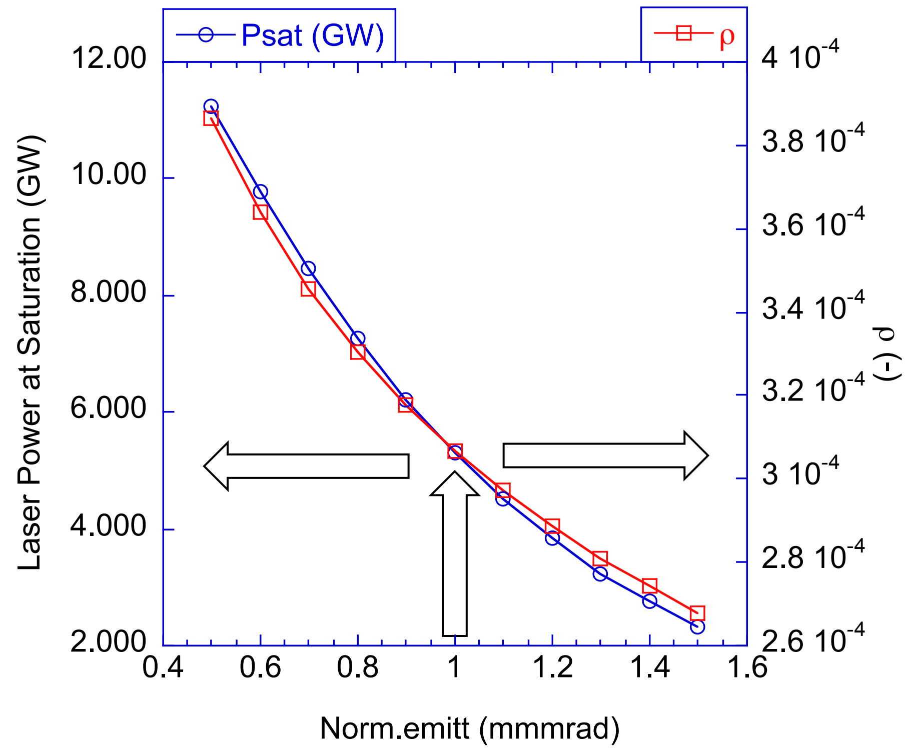
Peak current

For the higher gain, smaller emittance, higher beam current required

Laser Amplification Gain

λ_{SASE}=1Å, K=1.85, λ_u=18 mm, E=8 GeV, I_p=3 kA, $\Delta E/E=4x10^{-5}$, β_{ave}~30m,





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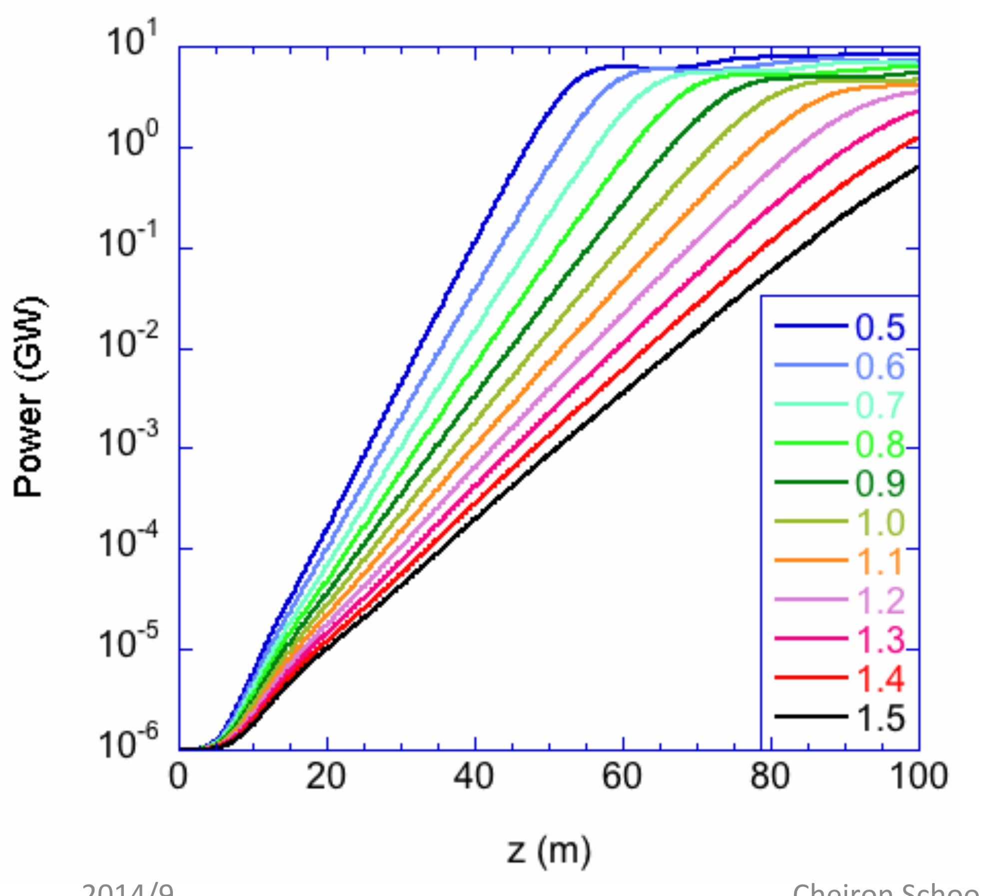

For the higher laser power, accurate overlap between laser field and electron beam along a certain distance, 15 to 25 m

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Future Perspective

Although variety of XFEL applications are expected , one facility can provide only a few BLs.

To widely utilize XFEL, it is essential to make the facility scale compact as much as we can. World's trend goes to this direction as XFEL usefulness becomes gradually clear.

Leading three XFEL

Development Target

SPring-8 Compact SASE Source (SCSS) Concept

Compact , cheaper, but high-performance

versus

Wavelength of undulator radiation,

$$\lambda = \frac{\lambda u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

To generate X-ray with lower beam energy requires a shorter undulator period and smaller K-value

Design Concept of SPring-8 Compact SASE Source (SCSS)

Lower Beam Energy

Size Reduction

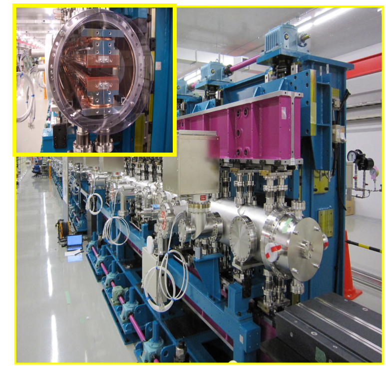
\+

Efficient Acceleration

Further Size Reduction

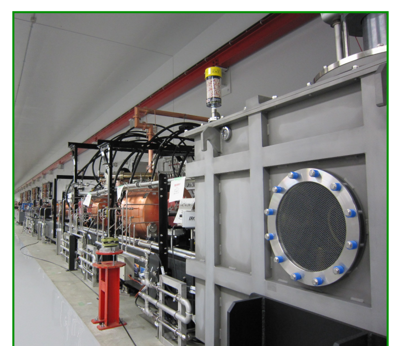
\+ Smaller K

Smaller Normalized Beam Emittance



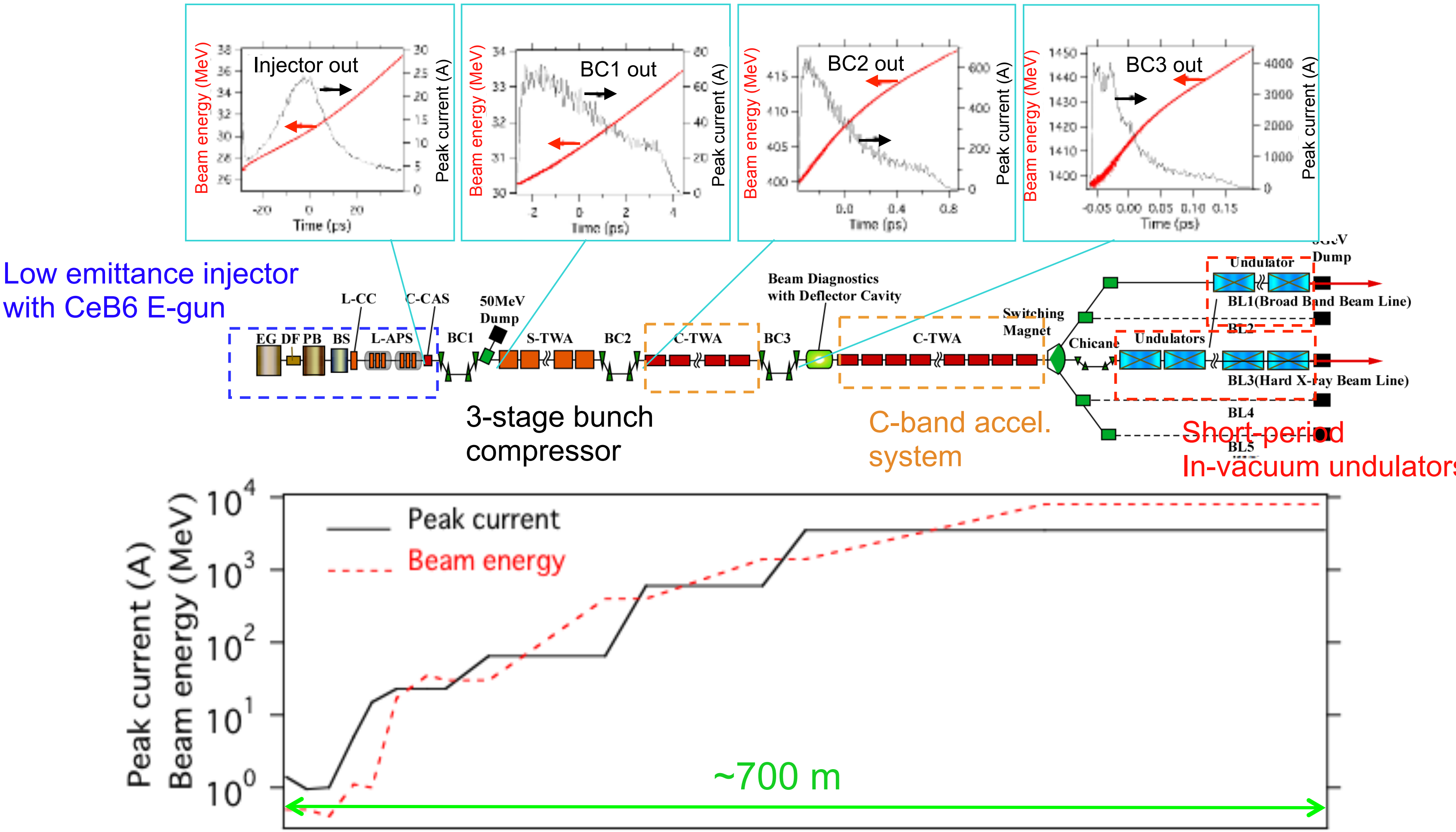
Short period in-vacuum undulator

C-band high gradient acceleration system



Themionic gun based low emittance injector

Compact design for 8-GeV SASE XFEL



Design Performance of XFEL

Comparison with SPring-8 performance

Parameter	XFEL	SPring-8
• Wavelength(fundamental)	>0.06 Å	>0.05 Å
• Pulse Duration	<100 fs	~40 ps
• Repitition	$\leq$ 60 Hz	~40 MHz
• Spatial Coherence	100%	~0.1%
• Peak Power	20~30 GW	100~200 W
• Peak Brilliance	$\sim 10^{34}$	$\sim 10^{24}$
• Averaged Brilliance	$\sim 10^{22}$	$\sim 10^{21}$

Def of Brilliance：phs/sec/mrad^2/mm^2

XFEL/SPring-8 Beamline Technical Design Report Ver. 1.0, June 17 (2008)

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History of SACLA

2006~2010 XFEL construction

2011 Feb. 21 Beam commissioning started

Jun. 7 First lasing at 0.12 nm achieved

Oct. SASE power saturation achieved at 0.12 nm

2012 Mar. 1 User experiments officially started

2013 Apr. 2-Color SASE released to user experiments

Oct. SASE intensity beyond 0.5 mJ/pulse achieved

Nov. First experimental symptom of seeding observed

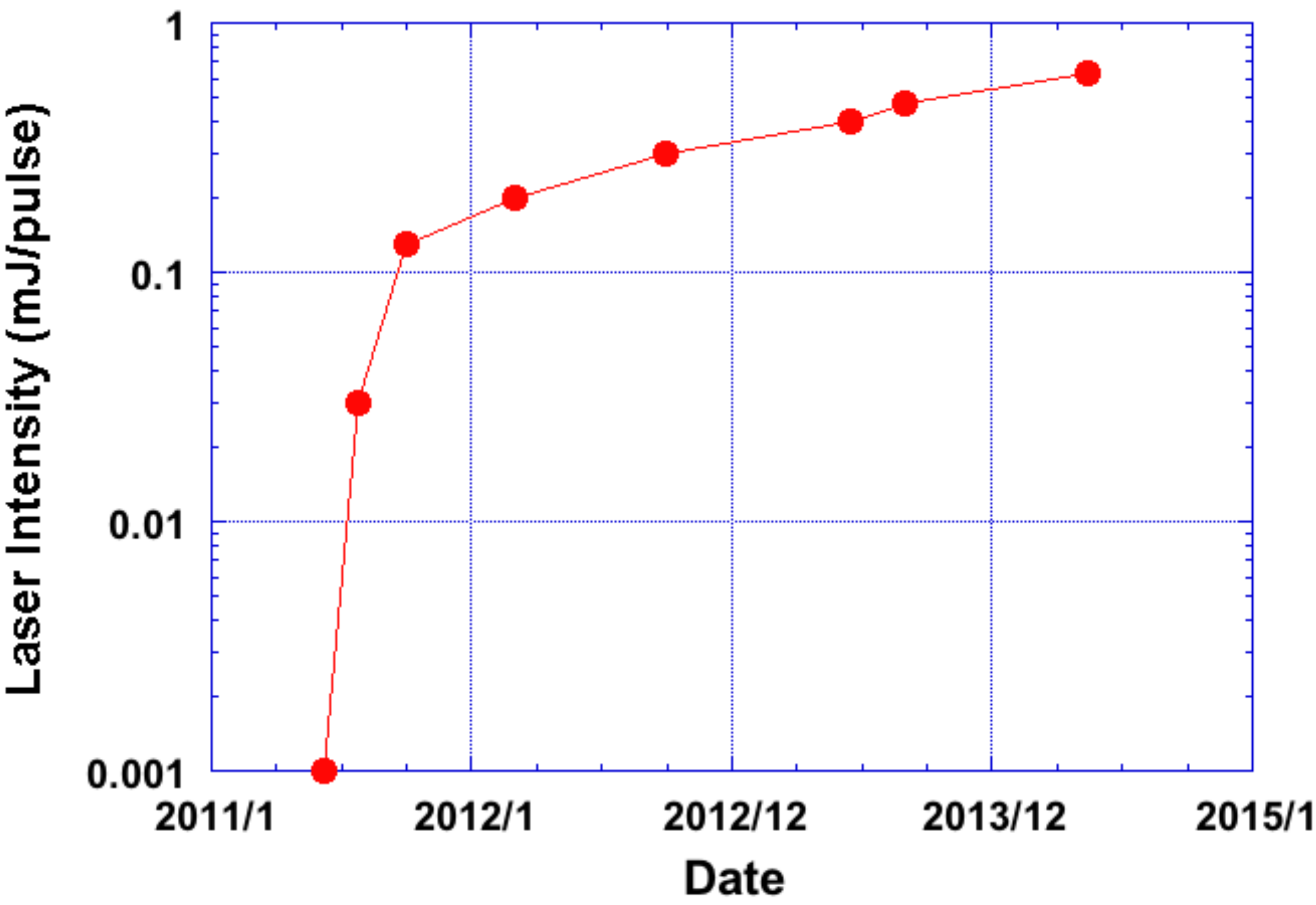
2014 Apr. Circularly-polarized SASE released to user experiments

Summary of Present Performance

Pulse Energy*:	Sub-m J, ~0.6mJ@10keV
Peak Power*:	>60 GW (e-beam, <10 fs in FWHM)
Intensity Fluctuation*:	~10% (σ)
Lasing Wavelength:	0.83 - 2.8 Å (user operation)
Spatial Coherence:	nearly full
Repetition:	30 Hz（Max.60 Hz）
Mean Fault Interval:	30~40 min
Recovery time:	1 min.
Operation mode:	24 hr continuous
Reproducibility:	~70% of the peak

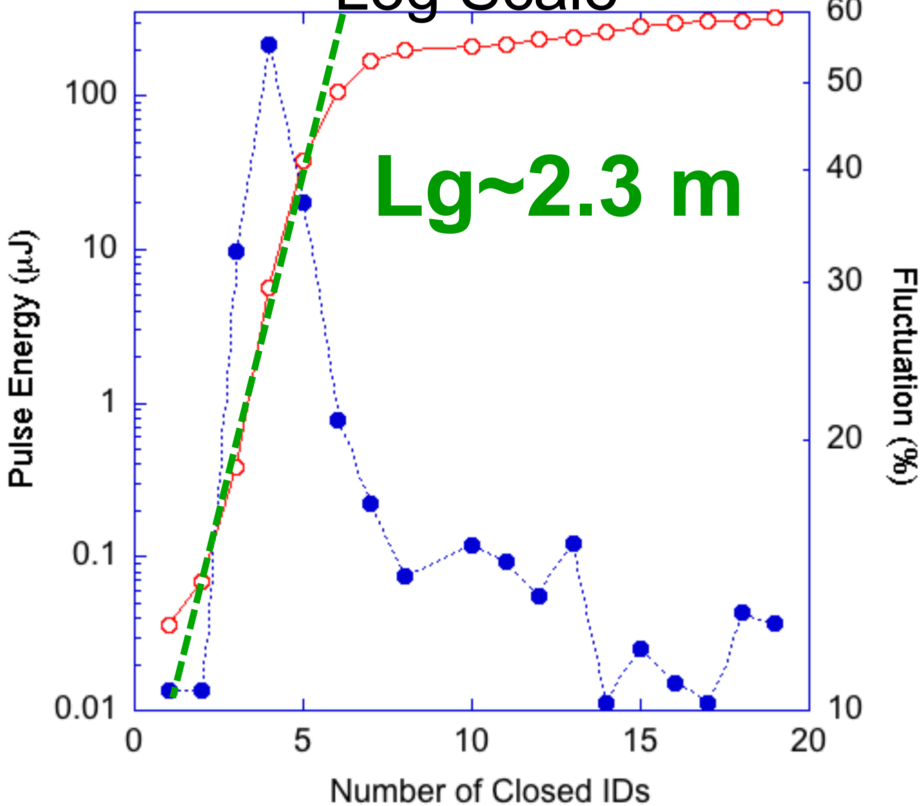
*It depends on the condition

Evolution of SASE Intensity

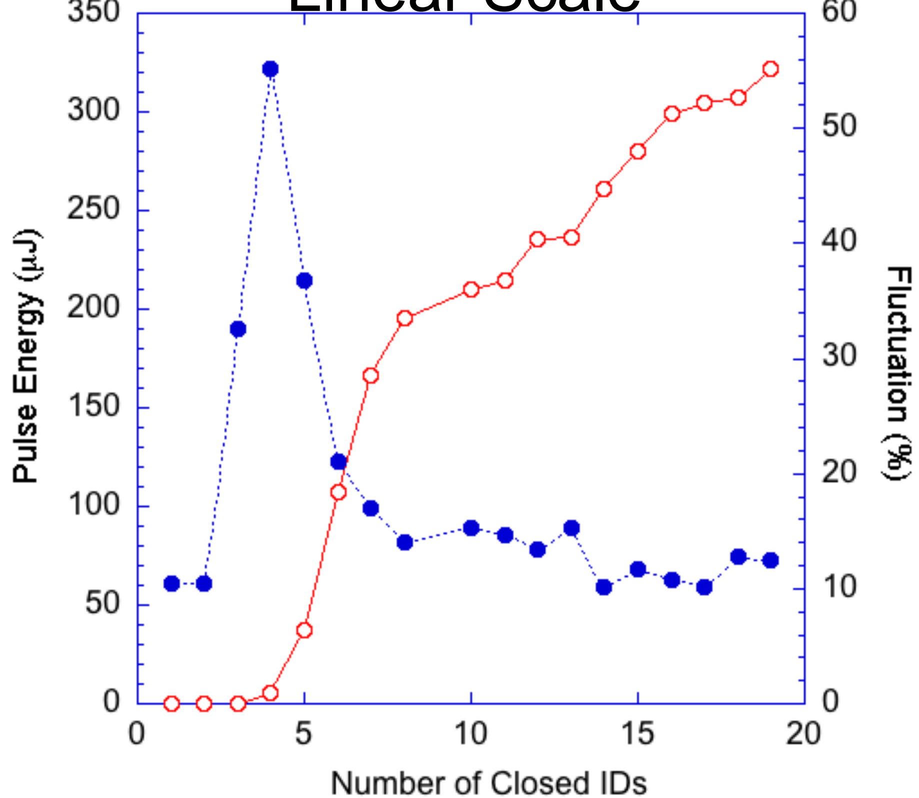


Gain Curve

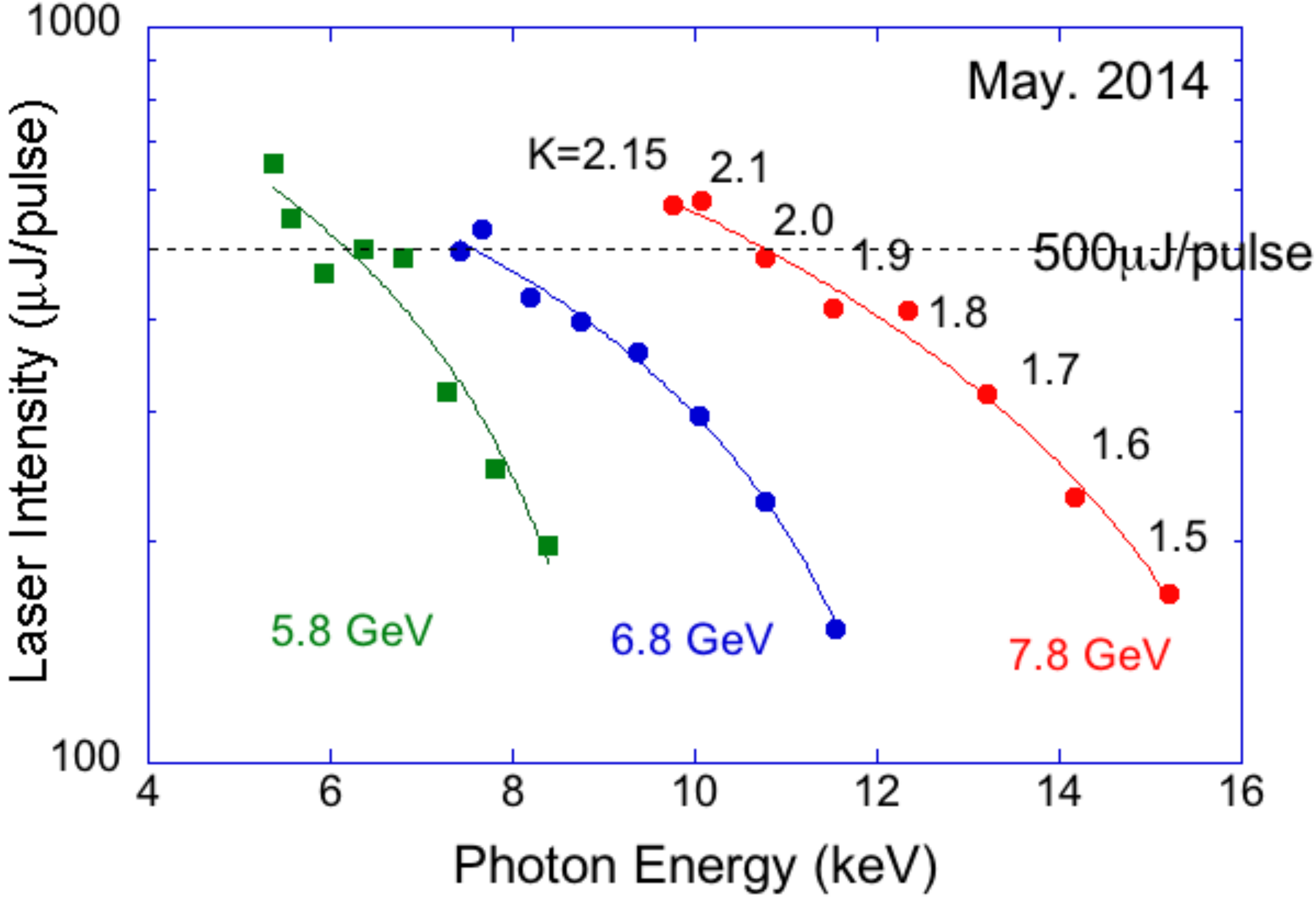
Log Scale



Linear Scale



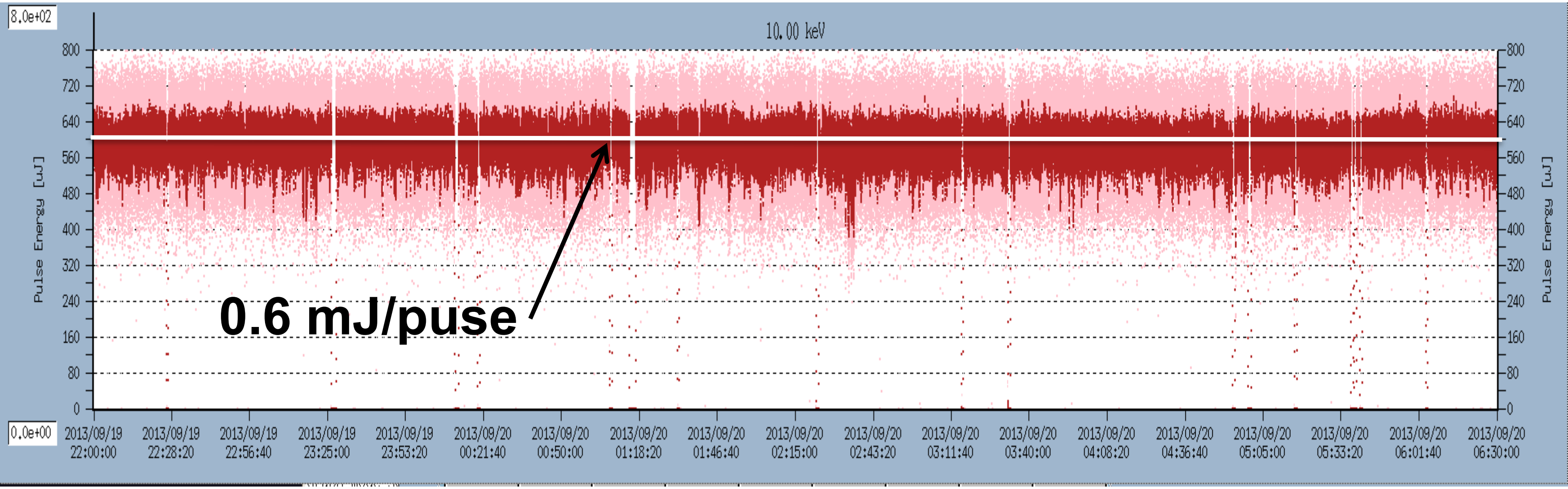
Laser Intensity vs Wavelength(old data)



Laser Stability

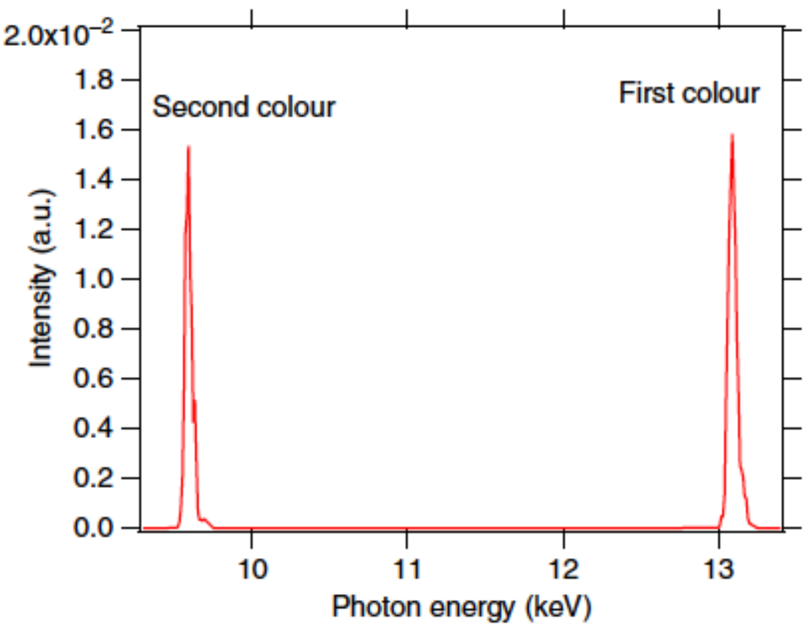
Laser availability in user experimental run is beyond 90%

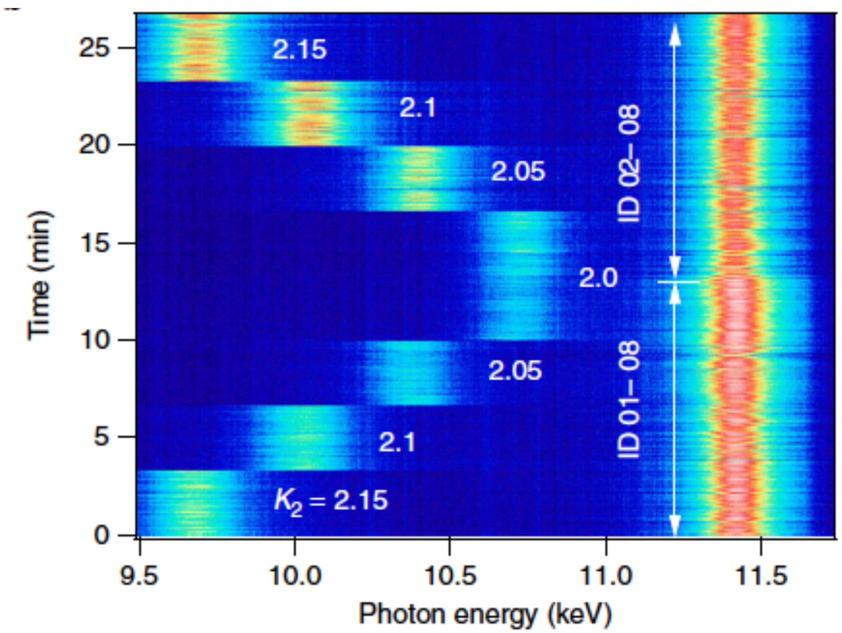
@10 keV   About 8 hr

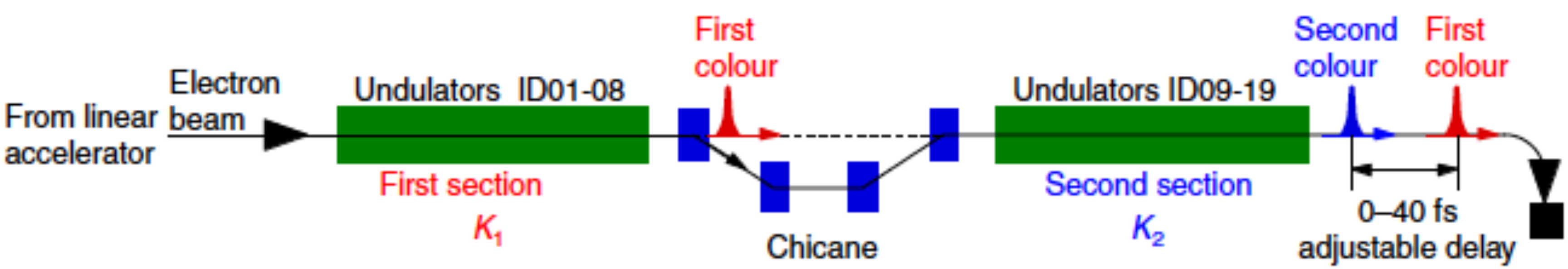


2-Color SASE Routinely Available

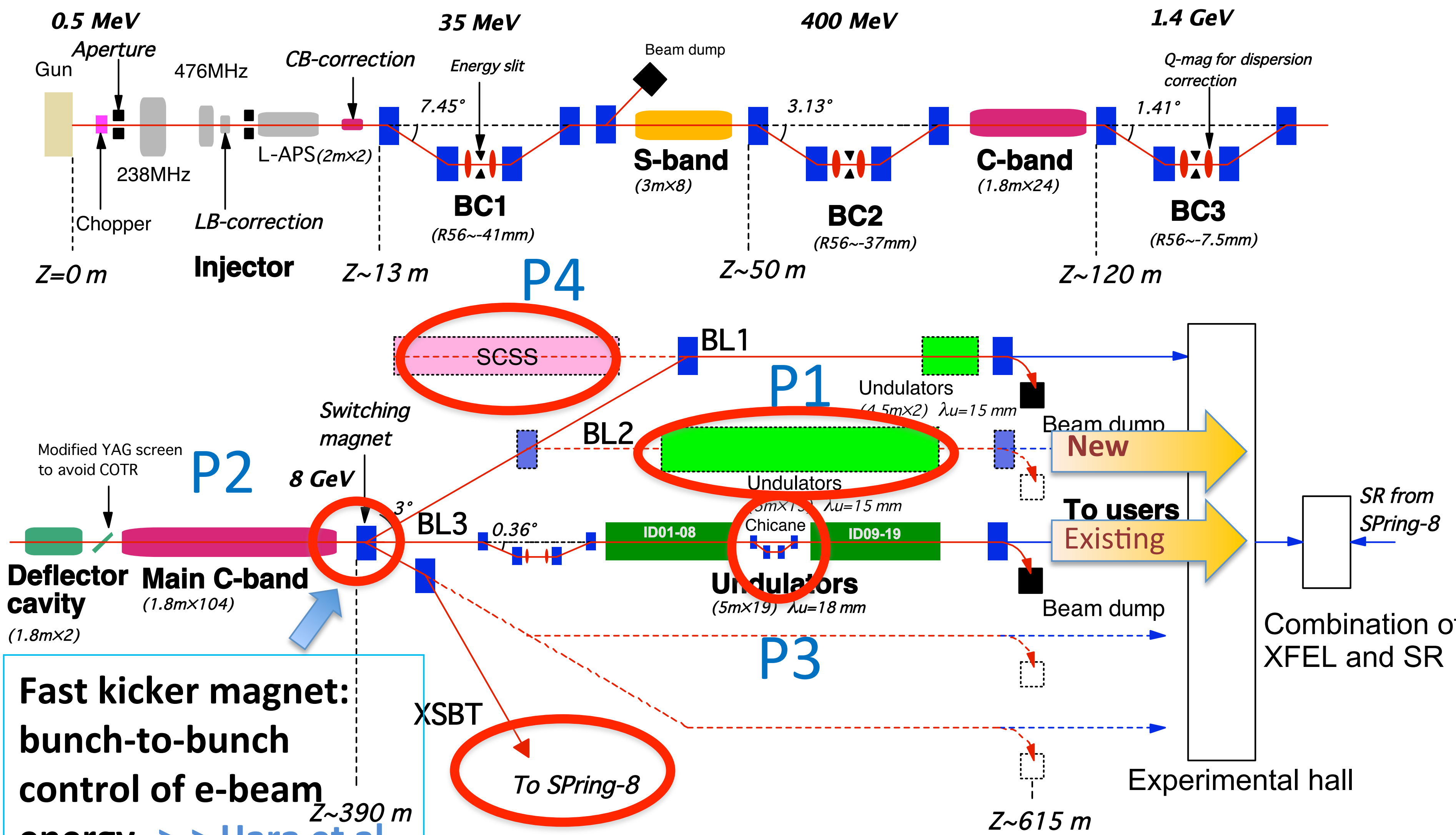
- Wavelength separation of up to 30%
- X-ray wavelength region
- Precise delay control with an attosecond resolution







Outline of System Upgrade



Fast kicker magnet: bunch-to-bunch control of e-beam energy ->-> Hara et al, PRST 16, 080701 2013