X-ray Free Electron Laser

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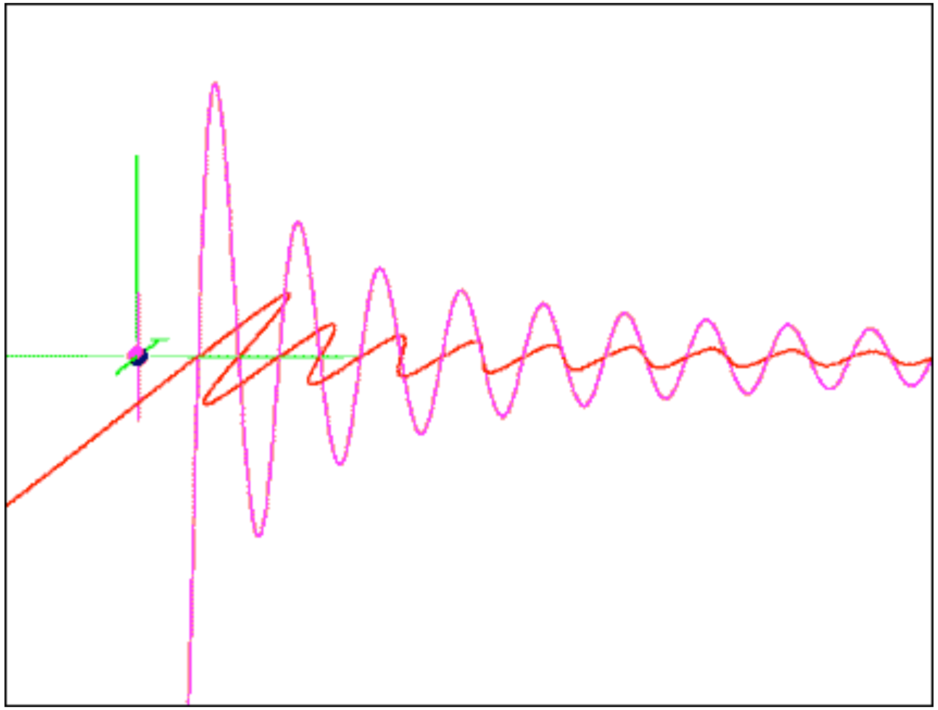
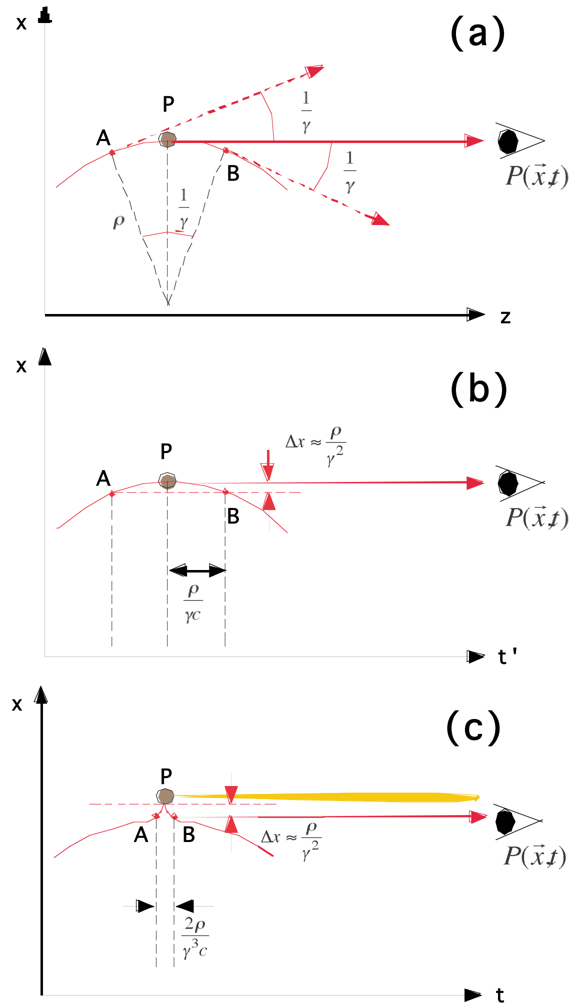
Outline

1. Introduction –What we can and can not observe using SR
2. What XFEL enables us to observe
3. Overview of XFEL
4. Performance of XFEL
5. Words to Young Researchers

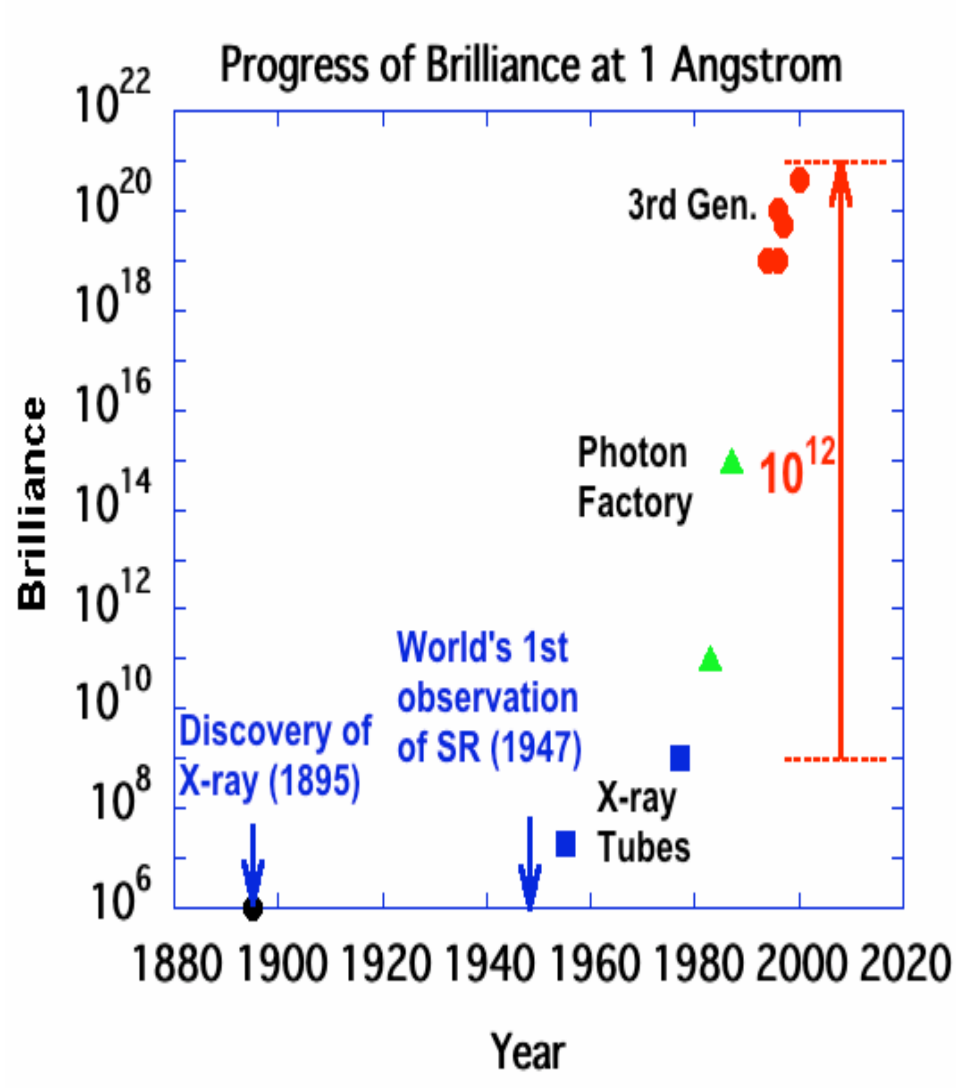
1. Introduction -What we can and can not do using SR-





1.1. Features of SR

1. White / monochromatic
2. High Brilliance
3. Directivity
4. Polarization Control
5. Pulse
6. Quantitativity
7. Wavelength Tunability



1.2. What SR makes visible

Incident X-rays excite electrons in the matter and cause scattering, absorption, diffraction, modulation of transmitted X-ray, photo-electron generation, luminescence, etc.

By analyzing these data, we can find electronic state in the matter, crystal structure, local and global atomic order, magnetism, dynamical distribution of chemical component, etc.

1.3. Variety of SR-Driving Science

- Research object: polymers, organic & inorganic compounds, biopolymers, meteorites and deep earth substance, catalysts, green energy relating material, etc.
- Research target: (1) composition, structure and electric state changes in a reaction process and their responses to external parameter changes, (2) correlation of functionality to electric state and material structure, etc, (3) basic physics.

1.3. Variety of SR-Driving Science con't

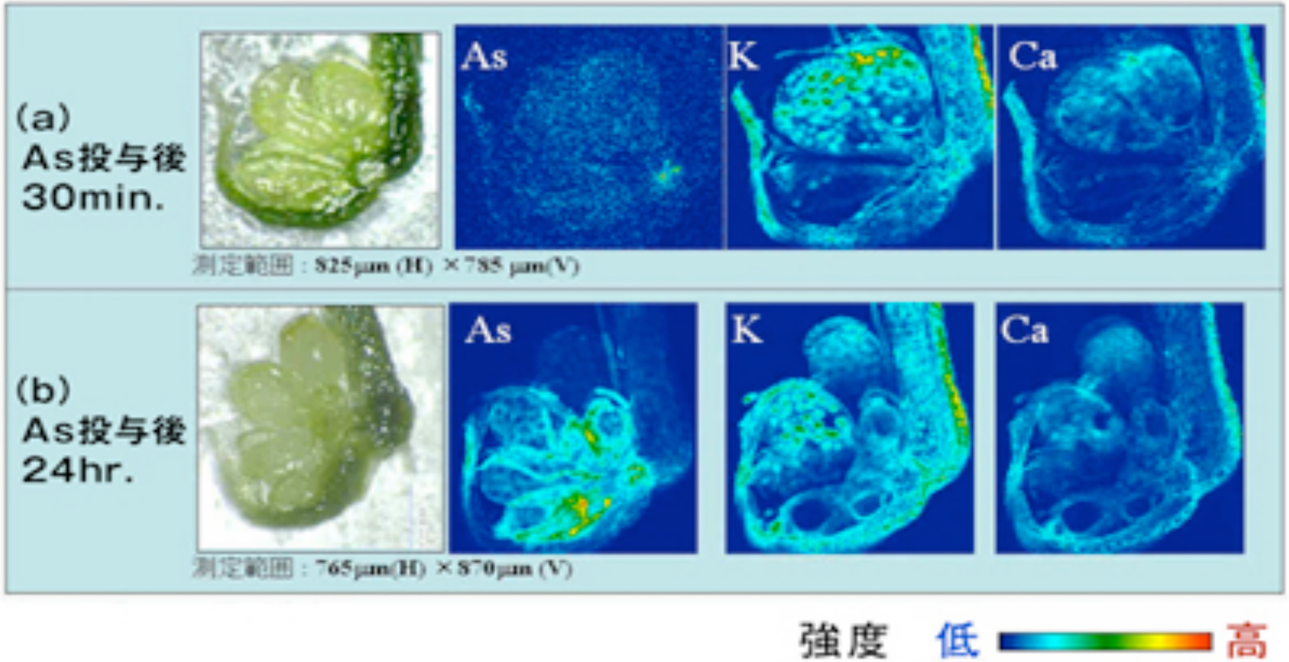


Figure shows two sets of X-ray fluorescence (XRF) 2D imaging data of arsenic, potassium, and calcium in the marginal region of a fern leaf; (a)30 min. after giving arsenic to the fern and (b)12 hr. after giving arsenic to the fern.

1.4. Weak points of SR

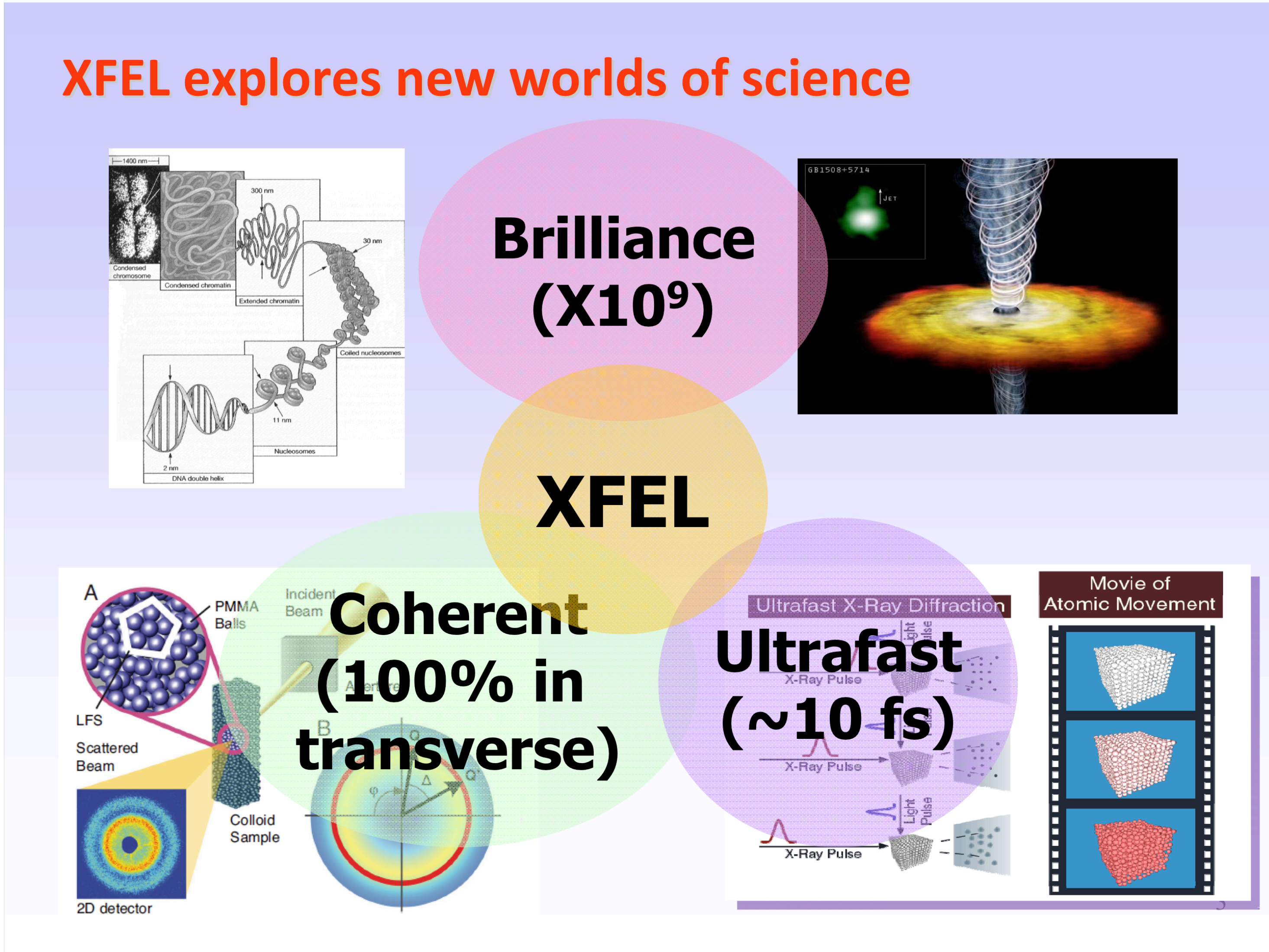
- Chaotic light（light of lamp）
- Long pulse duration（impossible to shorten）
- Weak intensity（difficulty in single-shot measurement）

2. What XFEL enables us to observe

Key words

- Observation of material property change in atomic & femto sec. resolution by a single-shot measurement
- Exploitation & observation of new physics & phenomena by using extremely high electric-field intensity

2.1. Features of XFEL

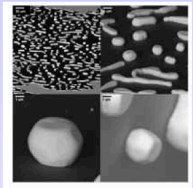
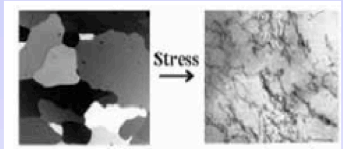


2.2. New Frontier Opened by XFEL

Science with XFEL

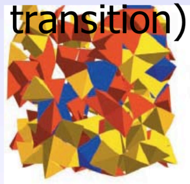
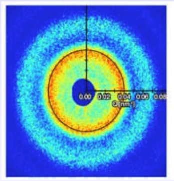
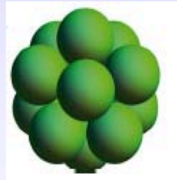
Coherence

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

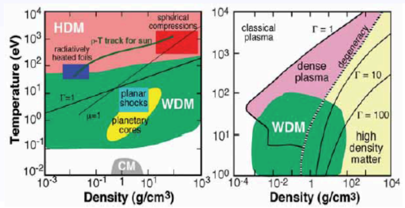
Ultrafast

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

Brilliance

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



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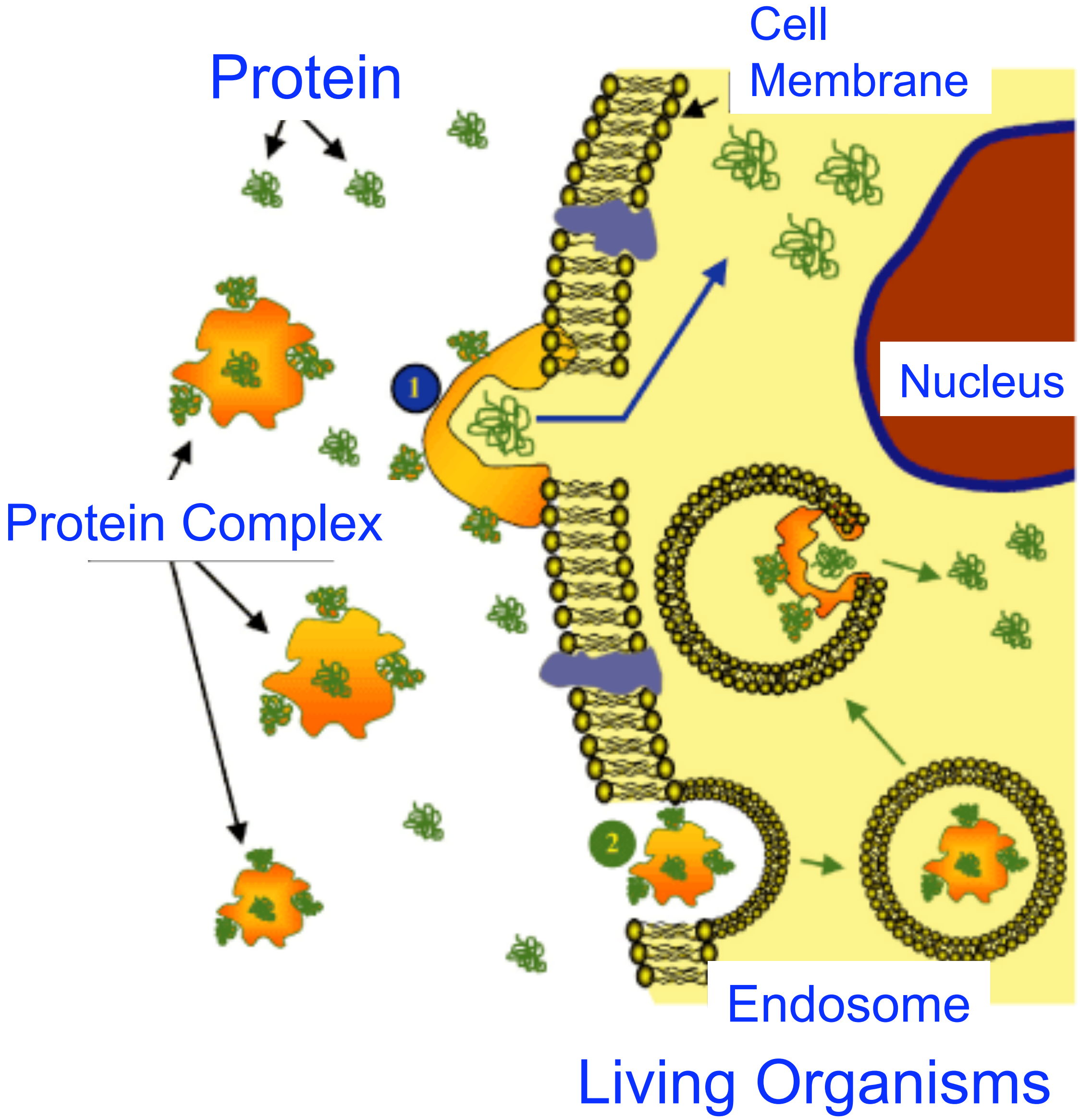
2.2. New Frontier Opened by XFEL con't

Can we see functional expressions in a life phenomenon in real time using XFEL?



3. Overview of XFEL

- Historical Background
- Principle of XFEL
- World’s Trend
- Japanese Strategic Approach

3.1. Long Way to XFEL

1916 A. Einstein proposed principle of stimulated emission of radiation

1958 C. H. Townes invented principle of laser.

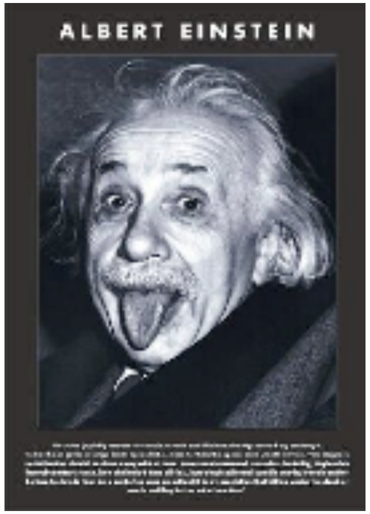
1960 T. H. Maiman developed the world's first Ruby Laser.

1970 I. Maday proposed new laser using free electrons as a laser medium (FEL)

1984 R. Bonifachio and his colleagues proposed"Self Amplified Spontaneous Emission"(SASE) based FEL

2009 SLAC team achieved the world's first SASE XFEL at a wavelength of 1.5 Å

2011 RIKEN/JASRI team realized the world's first compact XFEL at a shortest wavelength of 0.8 Å



Rather new technology !!

3.1. Long Way to XFEL con't

Obstacles against shortening the wavelength

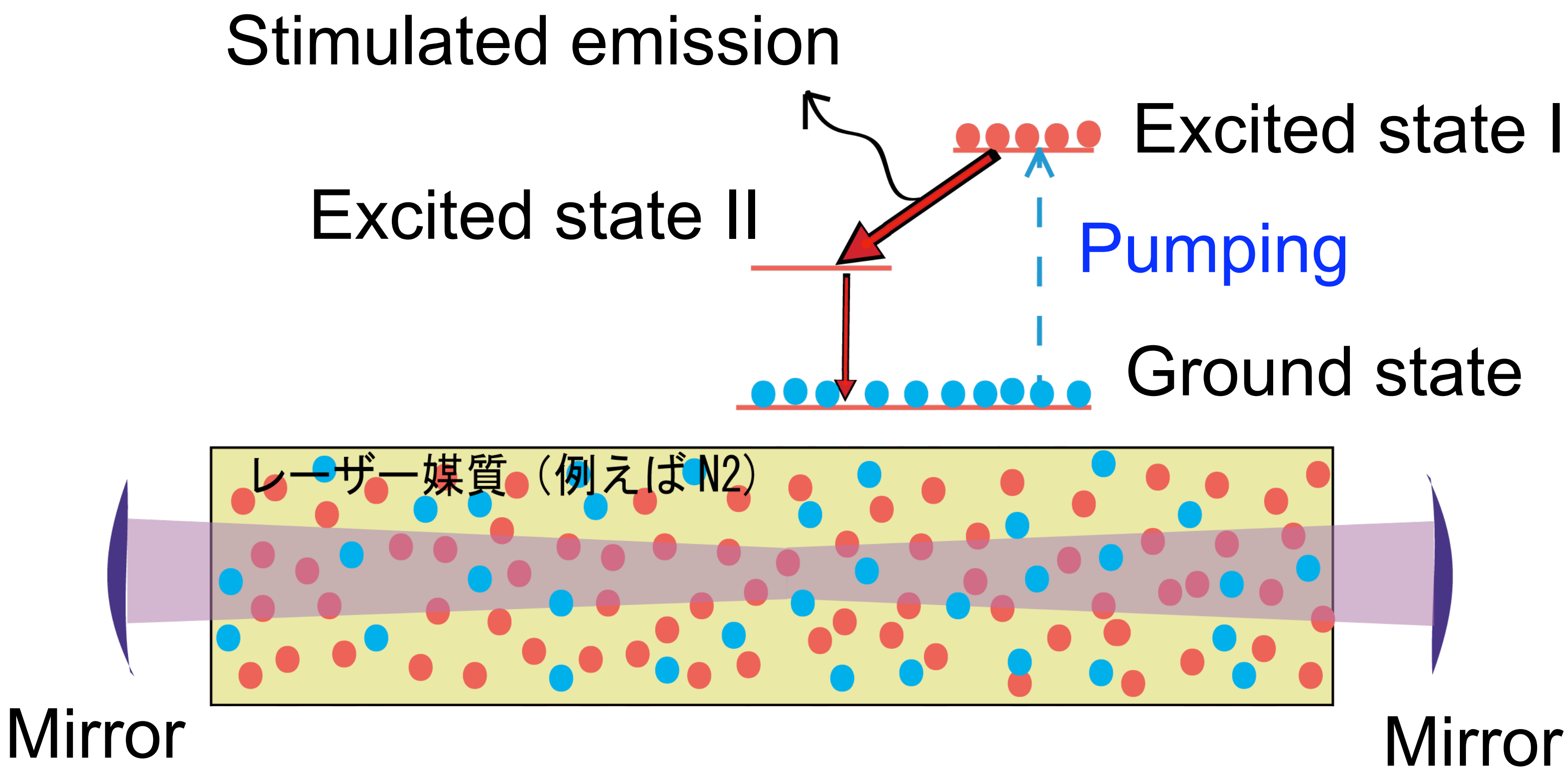
- A energy level corresponding to X-rays is at a deep inside of atoms and quite difficult to control population inversion condition.

- No mirror is available with high reflectivity at a wavelength of X-rays.

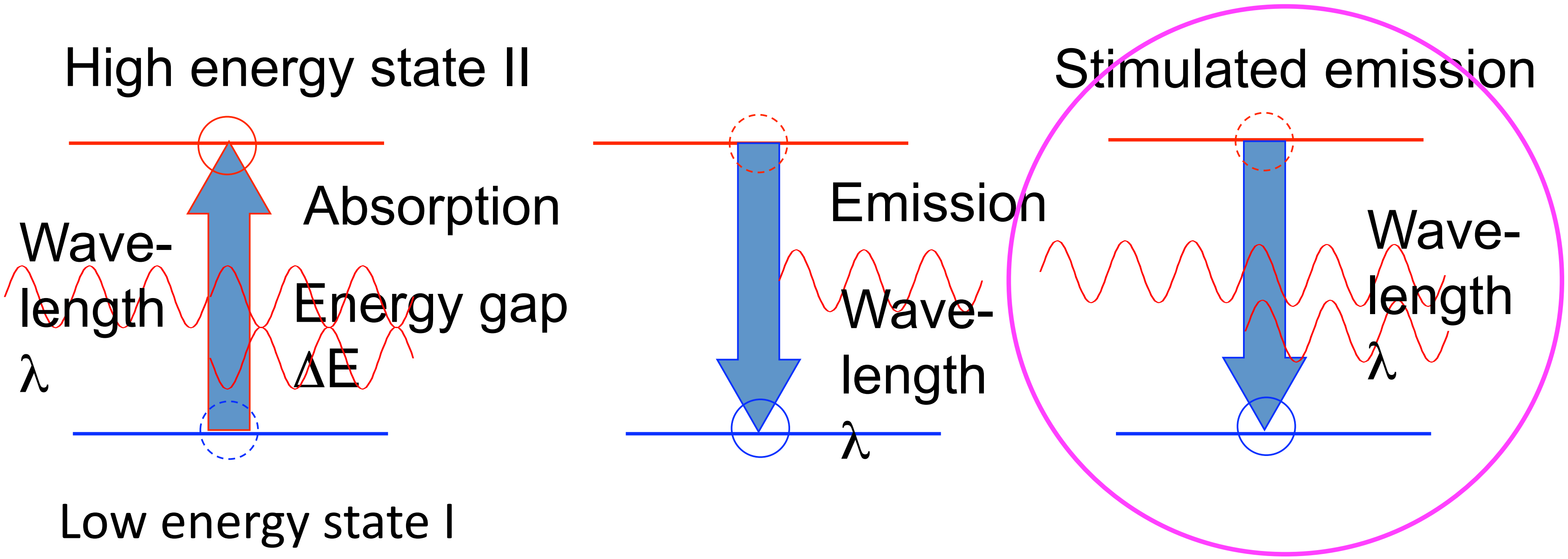
XFEL realization needs overcoming the above two difficulties.

3.2. Principle of FEL

Conventional laser using an optical cavity

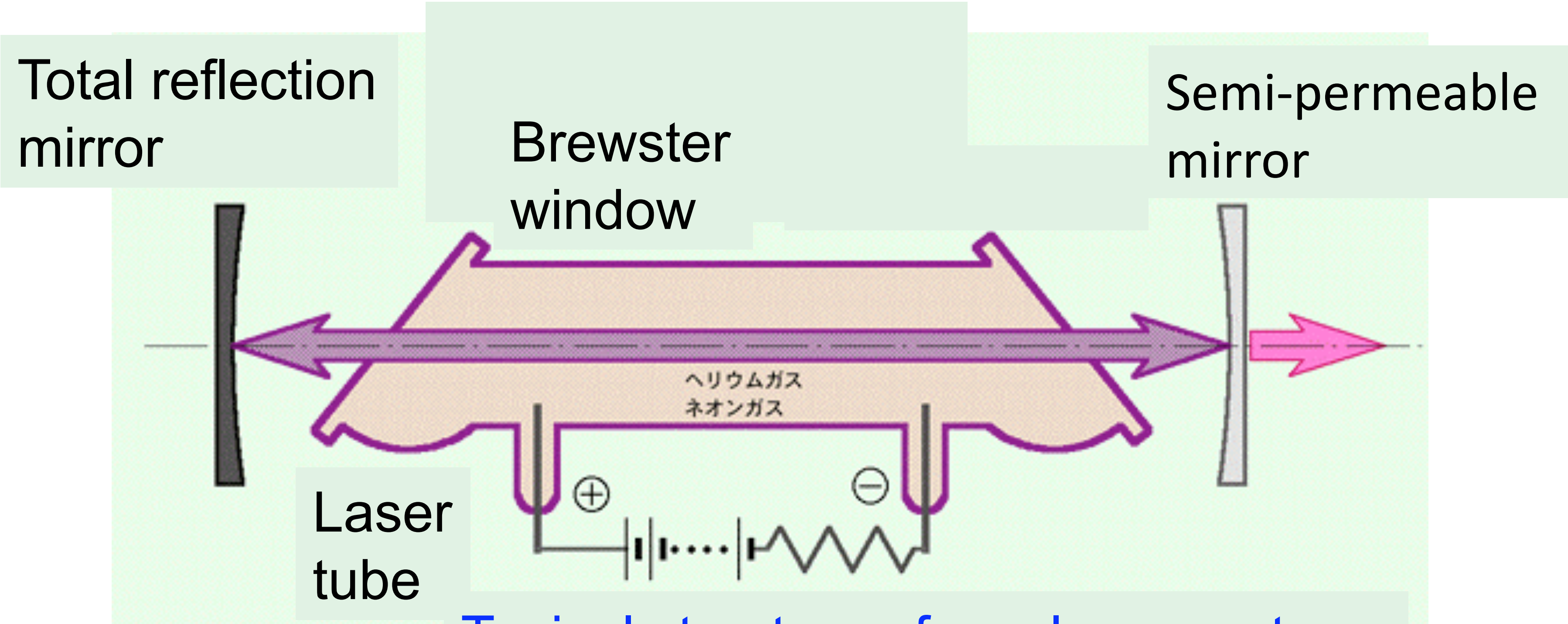


Stimulated emission



Stimulated emission is an inverse process of absorption as shown above.

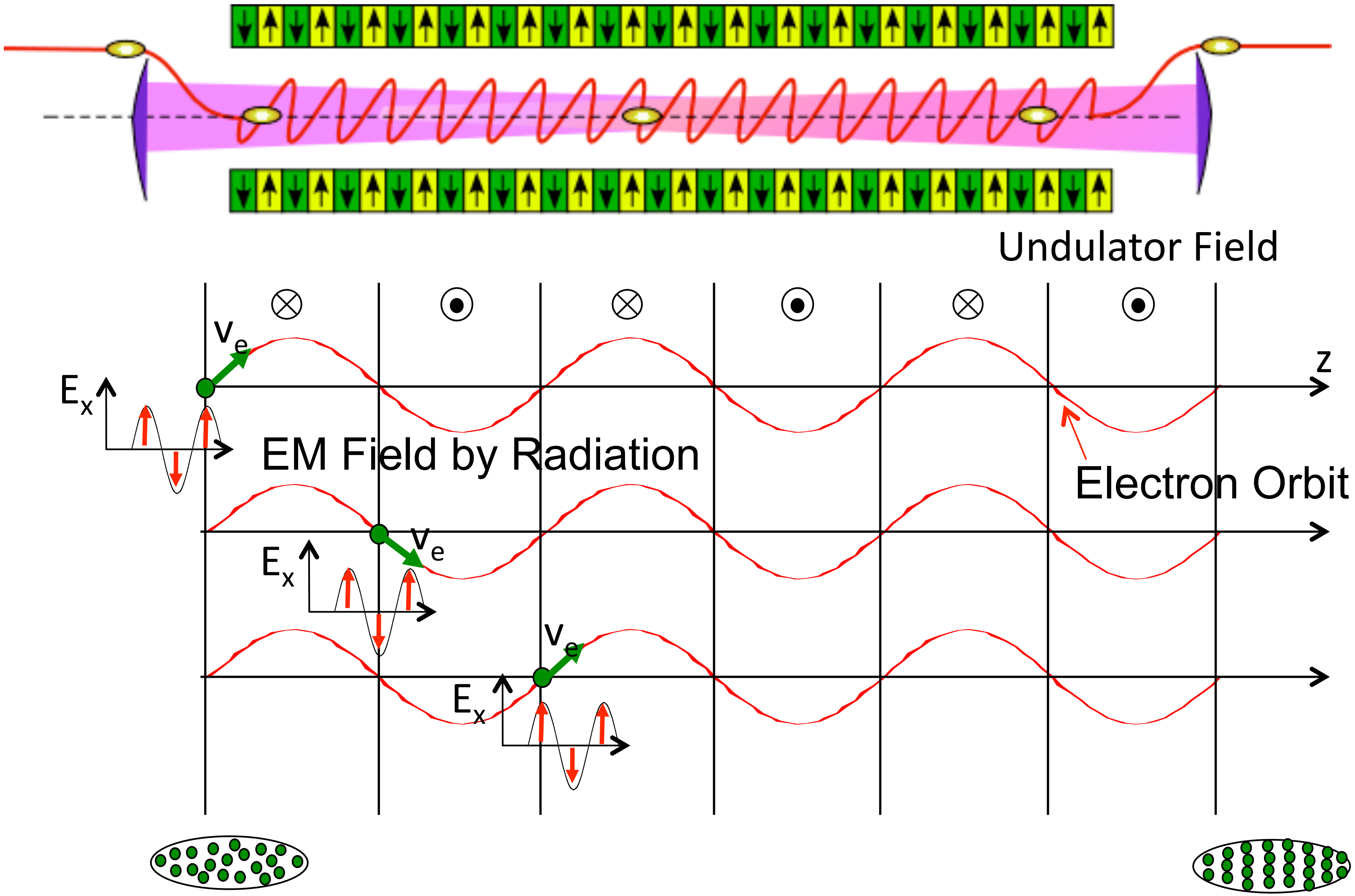
Optical cavity system



Typical structure of gas laser system

Conventional laser amplifies laser power of the selected mode by using stimulated emission from a laser medium during a huge number of round trips in the medium.

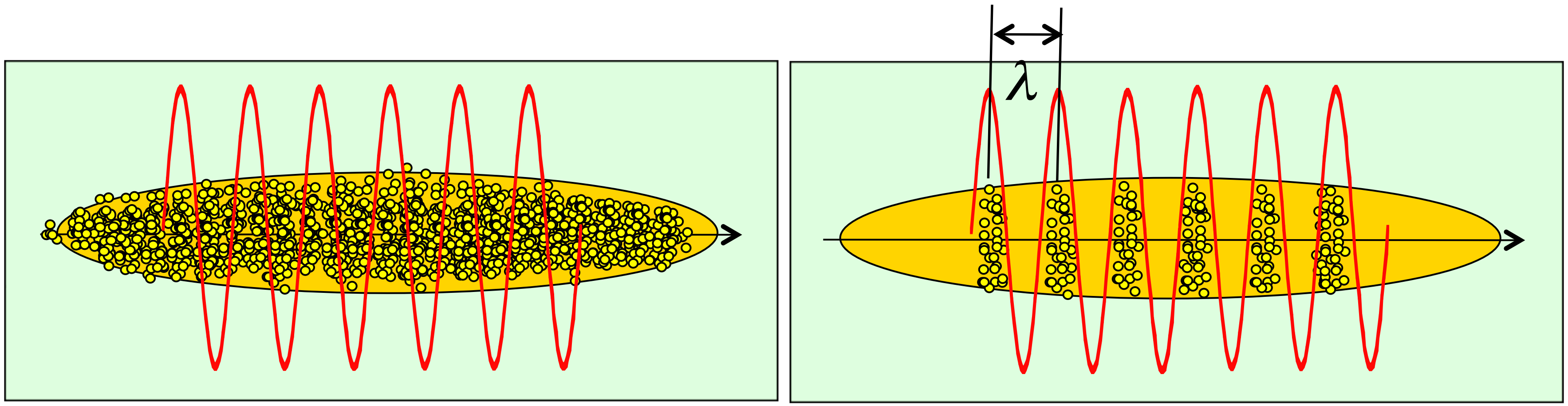
Using free electrons as a laser medium



Using free electrons as a laser medium con't

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.



Using free electrons as a laser medium con't

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

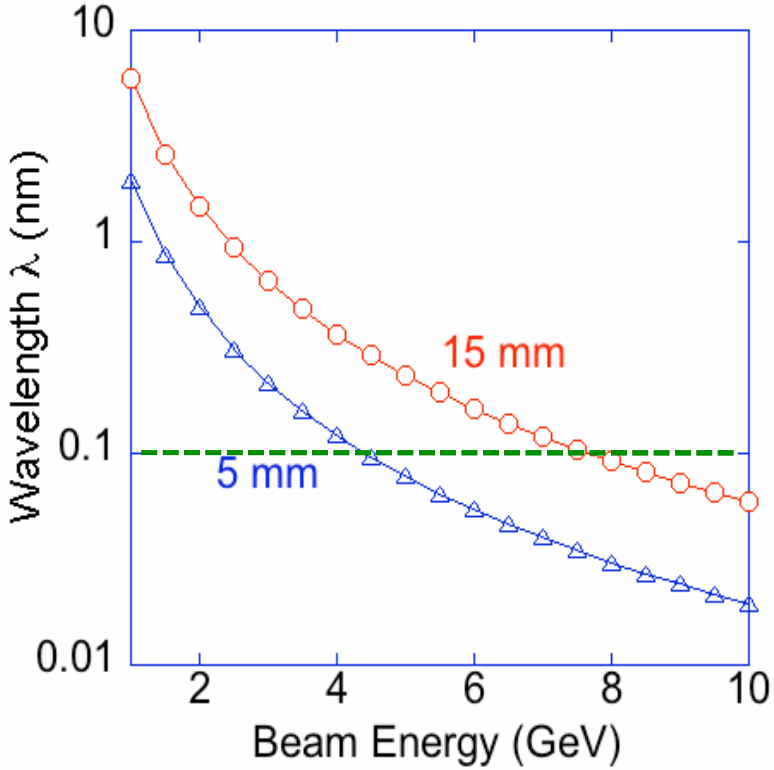
- Independent on energy level in atoms and molecules -

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

Let's estimate λ assuming

λ_u=15mm, K=2,
γ=3915@2GeV

λ = 1.5 nm



Removing optical cavity system

To shorten a laser wavelength down to X-ray wavelengths, optical cavity-free is an essential concept.

Key point

How to realize a sufficiently high gain by a single pass?

Highly brilliant electron beam + long undulator with a large number of periods

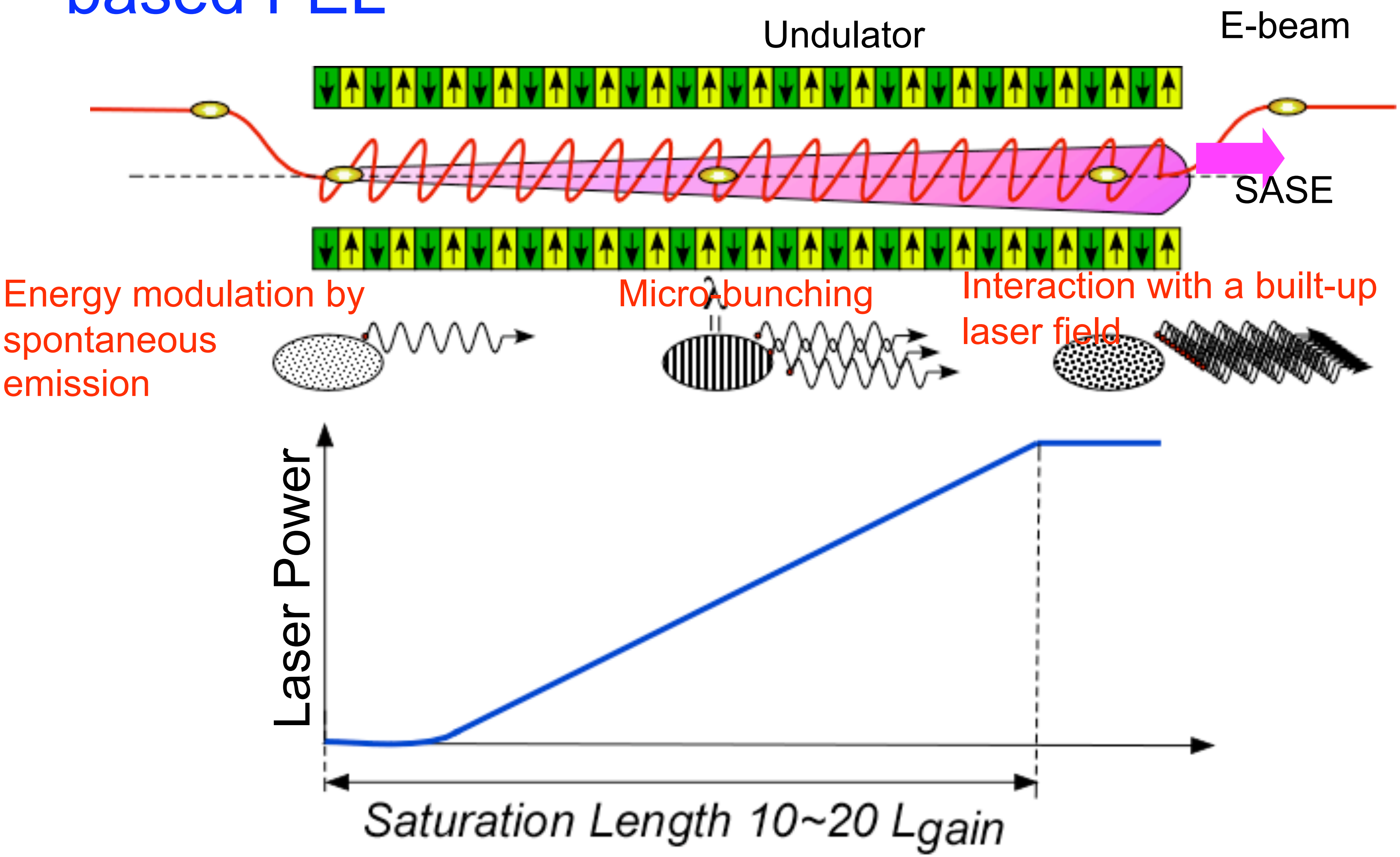
＜Brilliant electron beam＞

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.

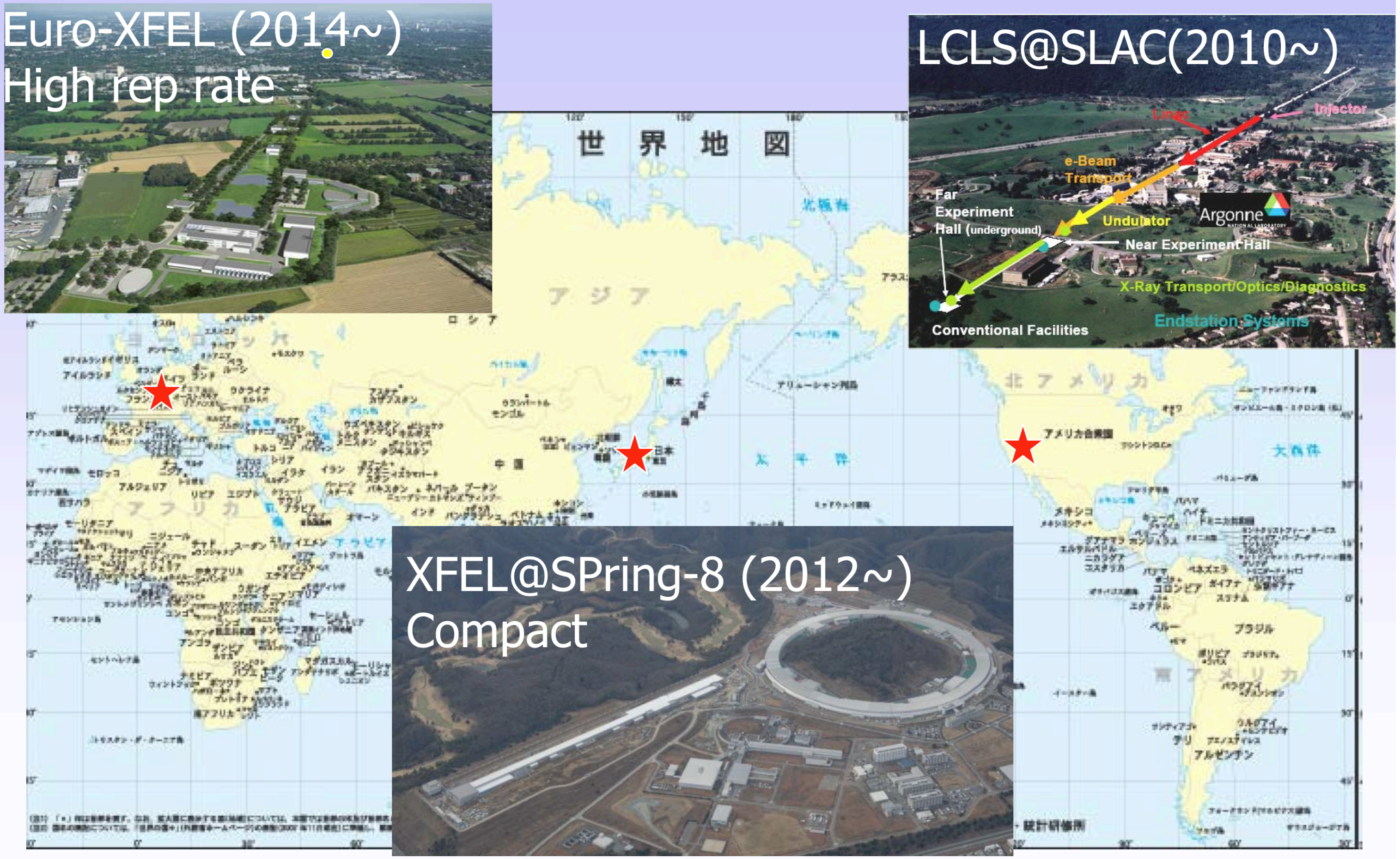
Self-Amplified Spontaneous Emission; SASE based FEL



3.3. World’s Trend

“Big three”

SASE XFELs under operation & construction in 3-sites



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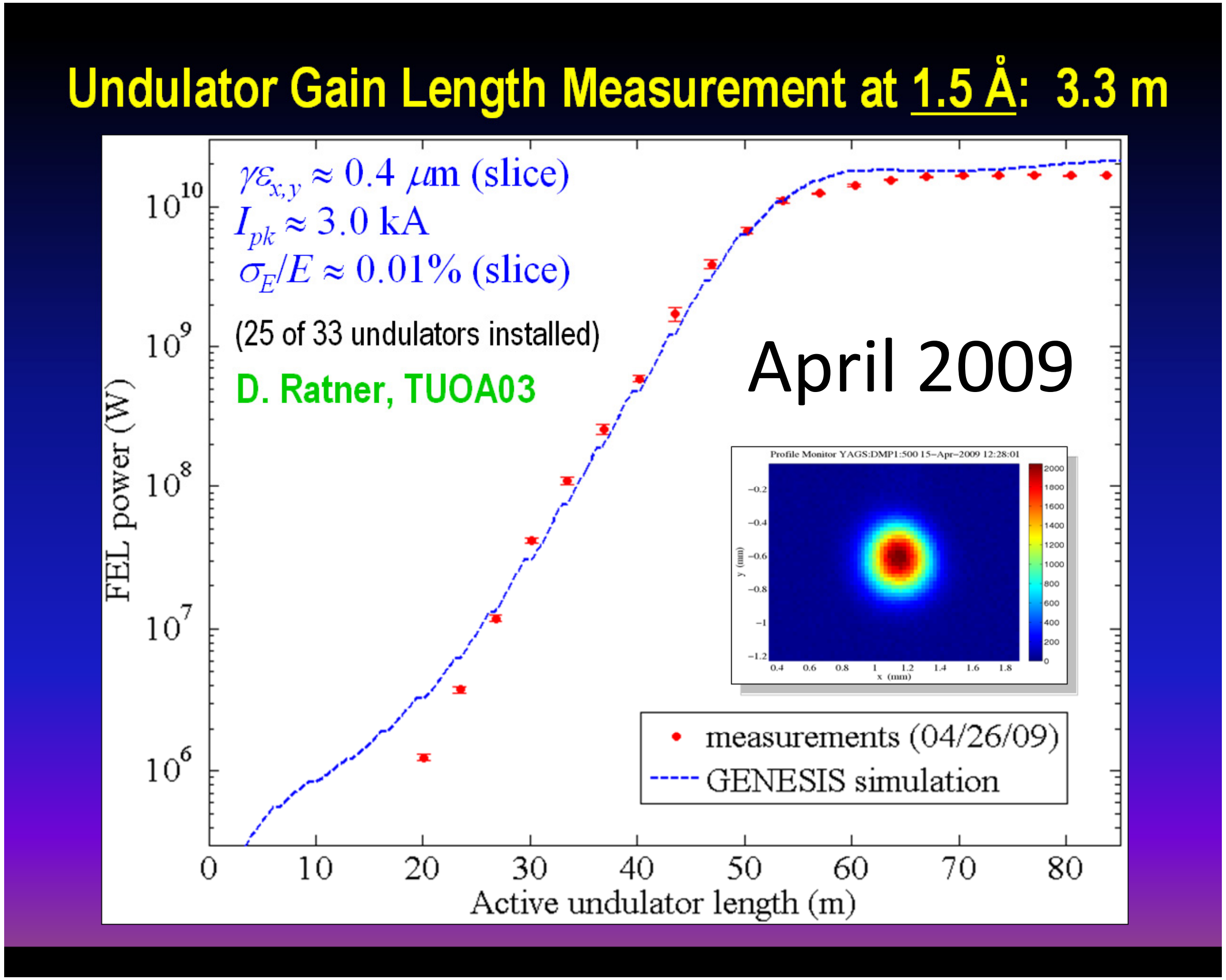
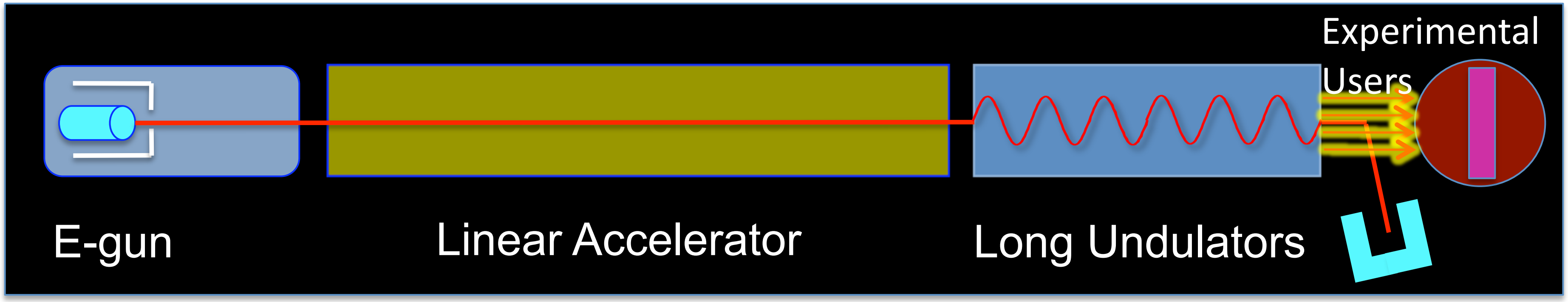
LCLS achieving the world's first power saturaion of SASE-based XFEL at a wavelength of 1.5Å



SASE scheme



From the viewpoint of generating high brilliant electrons,
(1) ring accelerators are unavailable (→ linear accelerators).

(2) High beam energy also has an advantage as follows;

electron beam emittance (phase space volime) $\varepsilon = \varepsilon_n/\beta\gamma$.

SASE scheme con't

From the viewpoint of wavelength shortening,
High beam energy has an advantage as follows;

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

➡ Huge accelerator system longer than a few km!!

3.4. Japanese Approach

Future prediction 1

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.

3.4. Japanese Approach con't

Future prediction 2

SASE is not the goal, because temporal coherence is poor (but, spatial coherence is high).

The goal is X-ray laser having both temporal and spatial coherence.

Development Target

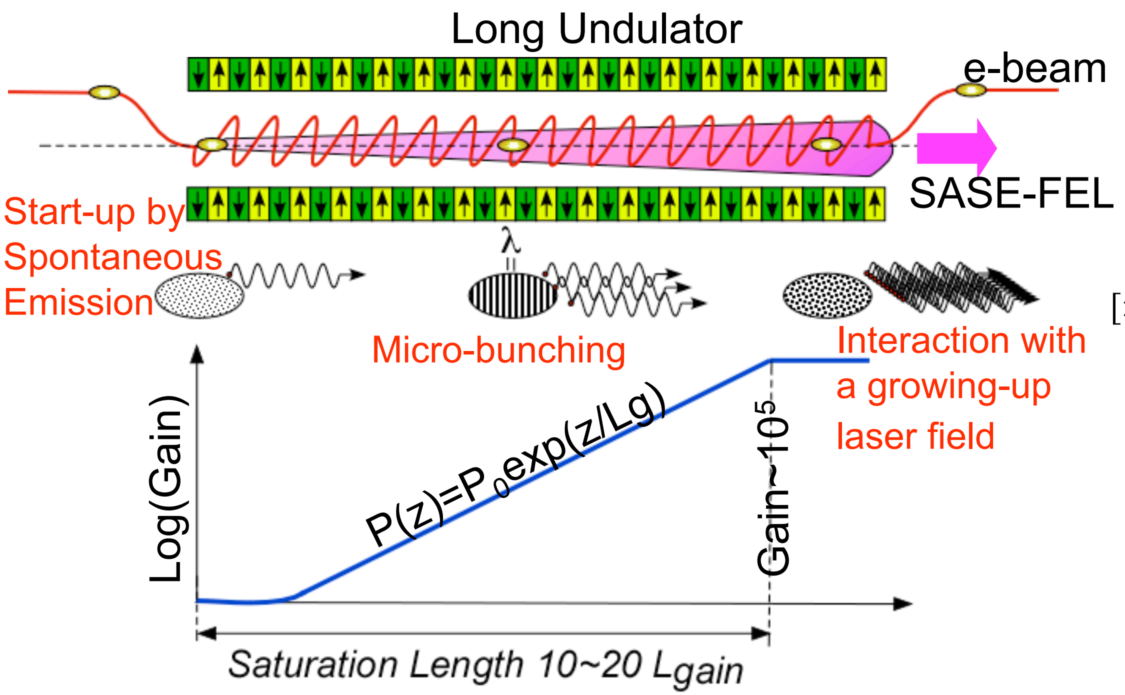
SPring-8 Compact SASE Source (SCSS) Concept

Compact , cheaper, but high-performance

versus

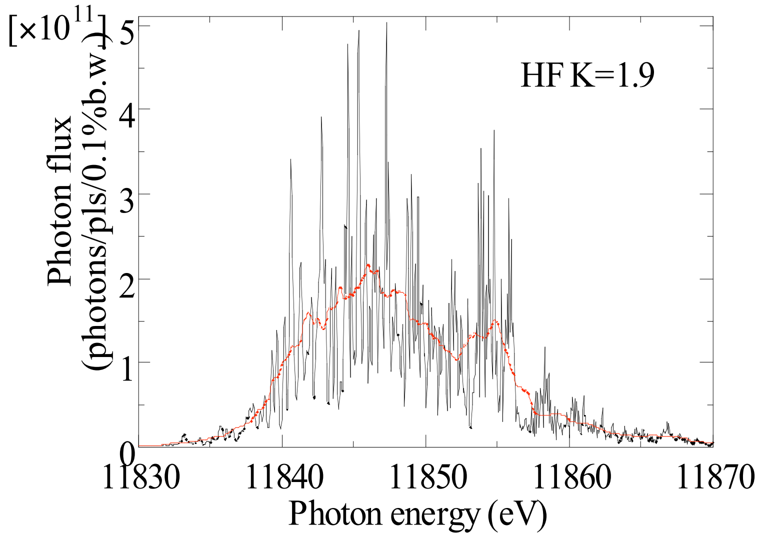
Two-steps approch

Step-1: XFEL by Self-Amplified Spontaneous Emission scheme (SASE-XFEL)



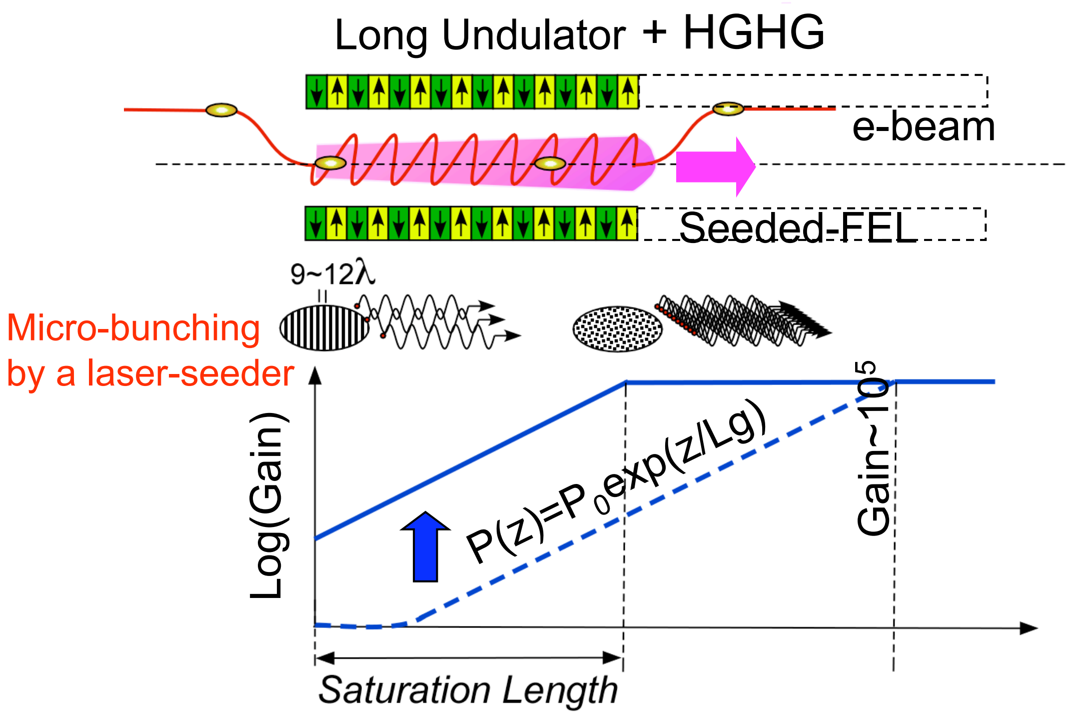
Features

- Poor temporal coherence
- Multi-mode
- Large time jitters
- Less intensity tunability

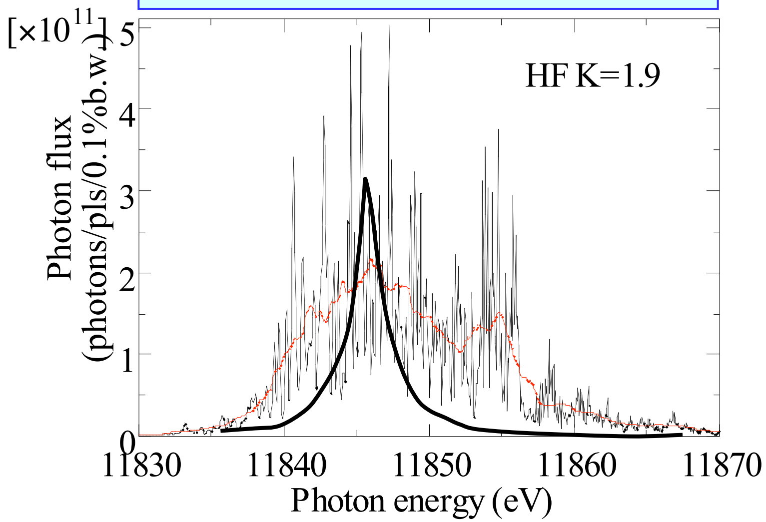


Two-steps approch con't

Step-2: Intensity-tunable XFEL with a single mode (Seeded-XFEL)



Features
SASE Advantage+
- Temporal coherence
- Single mode
- Tunable laser power
- Less power fluctuation



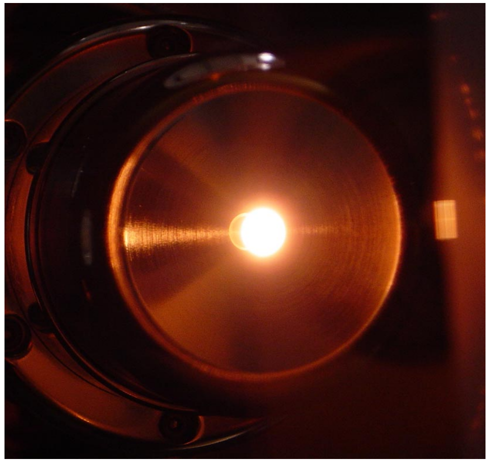
SPring-8 Compact SASE Source (SCSS)

What the SCSS concept is

This concept generates X-ray using a low-energy beam by efficiently accelerating a low-emittance beam with C-band system and passing it through short-period in-vacuum IDs.

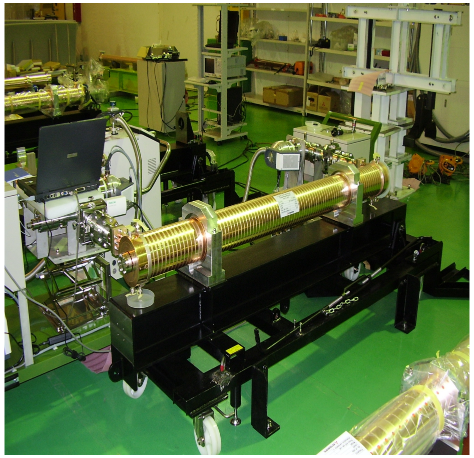
CeB_6 single crystal cathode thermionic gun

$\varepsilon_n \leq 1\pi$mm mrad



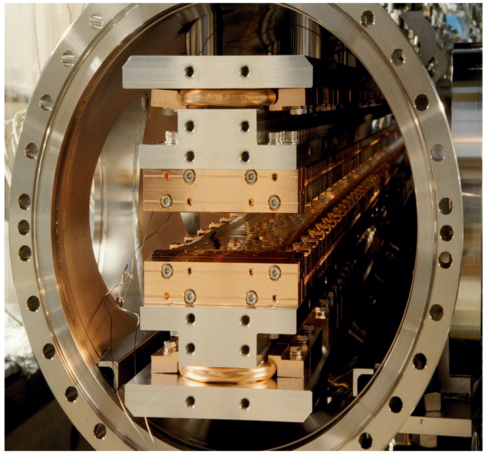
C-band high gradient acceleration system

(>35MV/m)

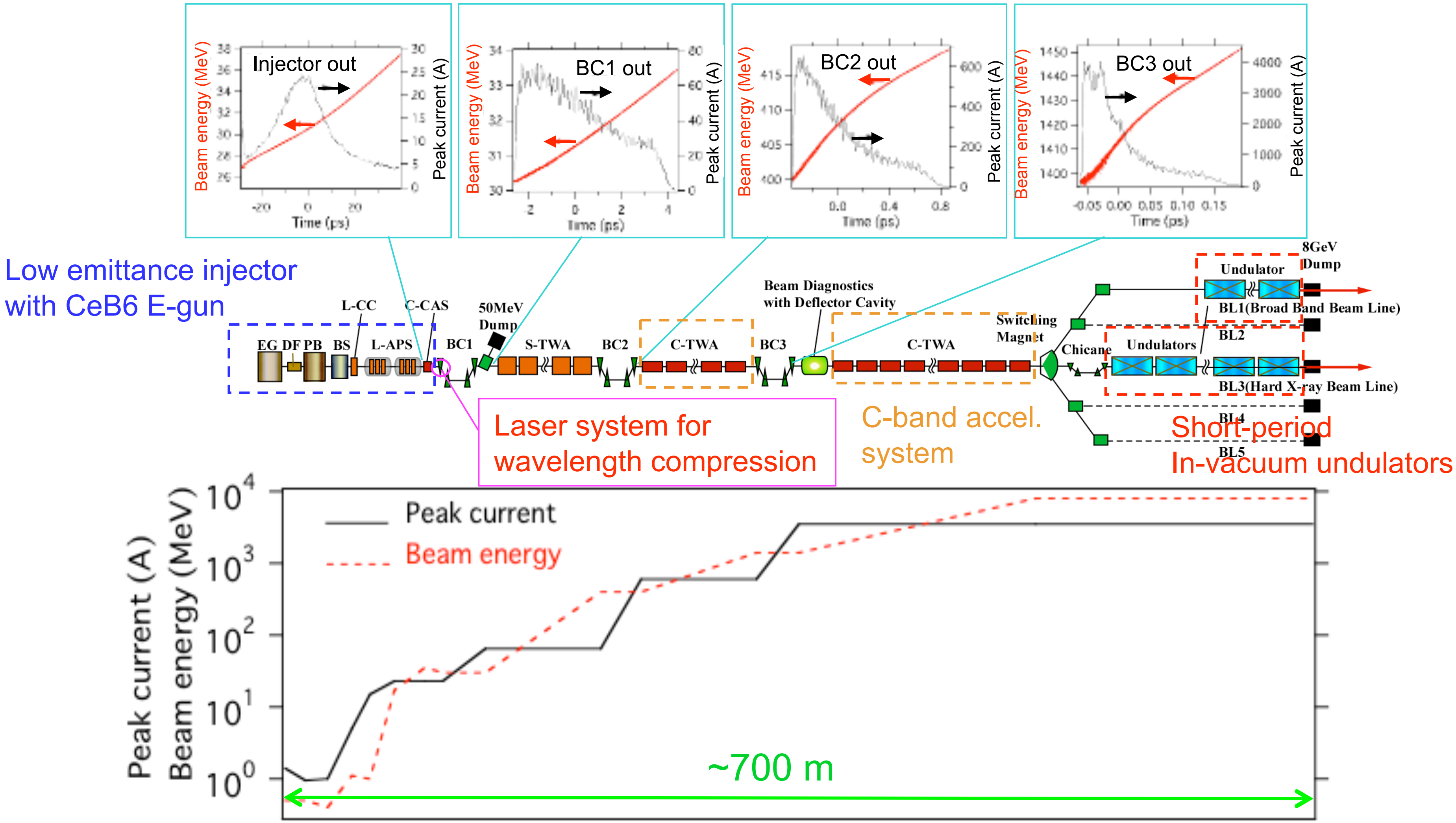


Short-period in-vacuum undulators

(λ_U=18mm, K=2.2)



Compact design for 8-GeV SASE XFEL



4. Performance of XFEL（step-1)

Comparison with SPring-8 performance

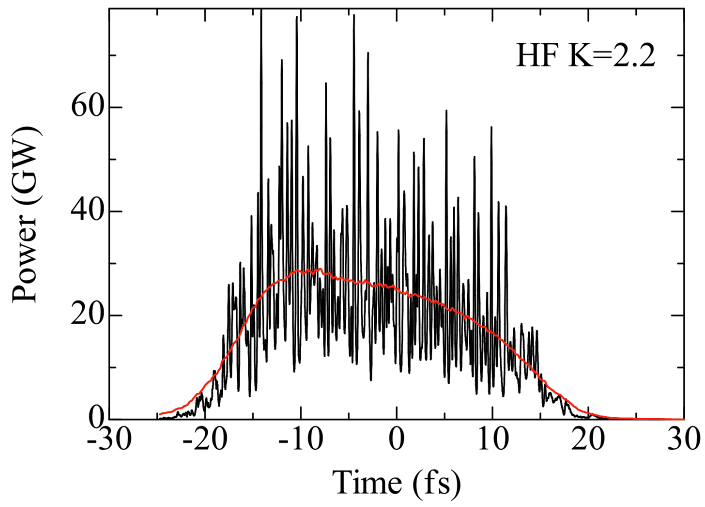
Parameter	XFEL	SPring-8
• Wavelength(fundamental)	>0.06 Å	>0.05 Å
• Pulse Duration	<100 fs	~40 ps
• Repitition	$\leq$ 60 Hz	~40 MHz
• Spatial Coherence	100%	~0.1%
• Peak Power	20~30 GW	100~200 W
• Peak Brilliance	$\sim 10^{34}$	$\sim 10^{24}$
• Averaged Brilliance	$\sim 10^{22}$	$\sim 10^{21}$

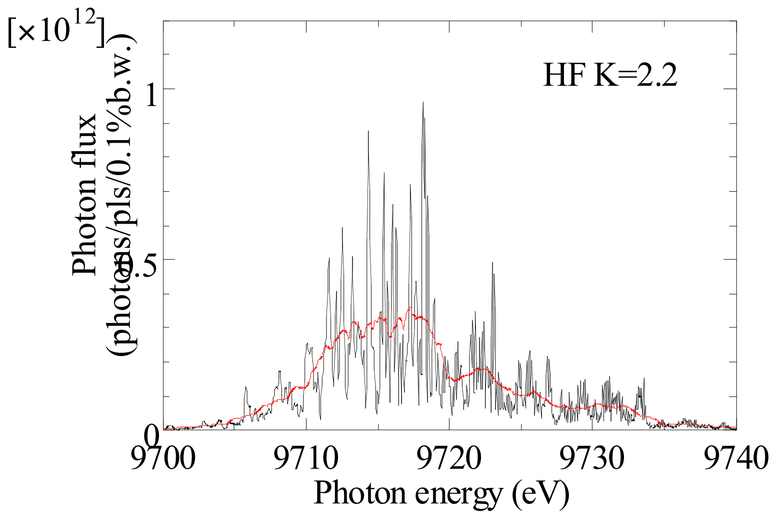
Def of Brilliance：phs/sec/mrad^2/mm^2

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

Typical Performance (1.3Å)

Parameter	XFEL
• B.W.	0.092%
• Pulase Duration	30 fs
• Source Size	33 um
• Angular Spread	0.73urad
• Epulse	0.78 mJ
• Phots/pulse	5E11
• $2^{nd}/1^{st}$	1.3E-4
• $3^{rd}/1^{st}$	2.8E-3





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

5. Words to Young Researchers

Strong E-field

Short Pulse

Variable E-field

Spatial Coherence

Temporal Coherence

Variable Pulse Duration

No authority, everything will start from now on. You are a potential hero (heroine)!

5. Words to Young Researchers con't

Everyone has a chance to becaome a authority in this field. Young guys, be ambitious!

Blue ocean is waiting for your challenge.