MC2: Evolution and Future of Synchrotron Radiation Sources

RIKEN SPring-8 Center

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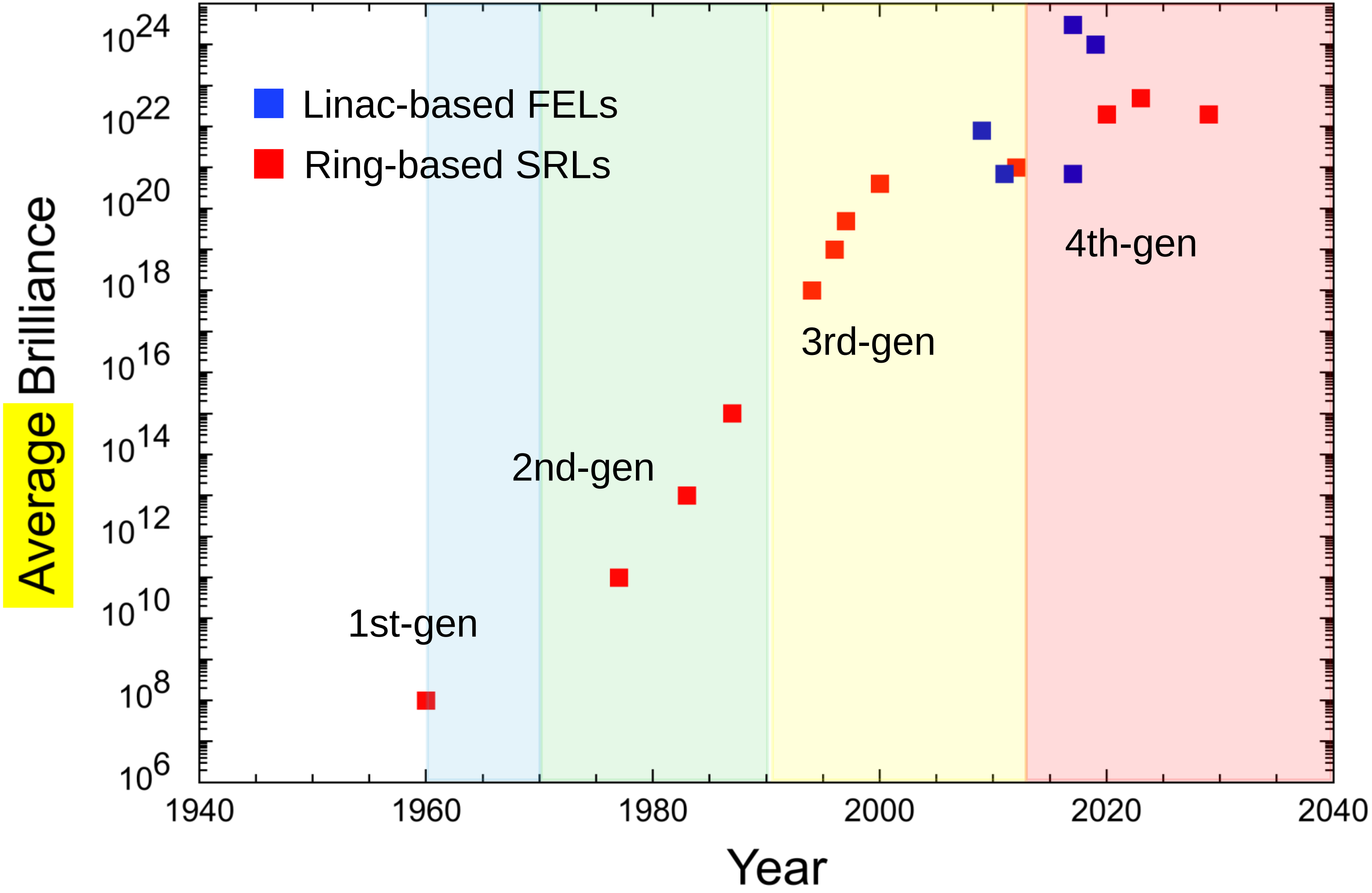
2026/05/16@Deauville

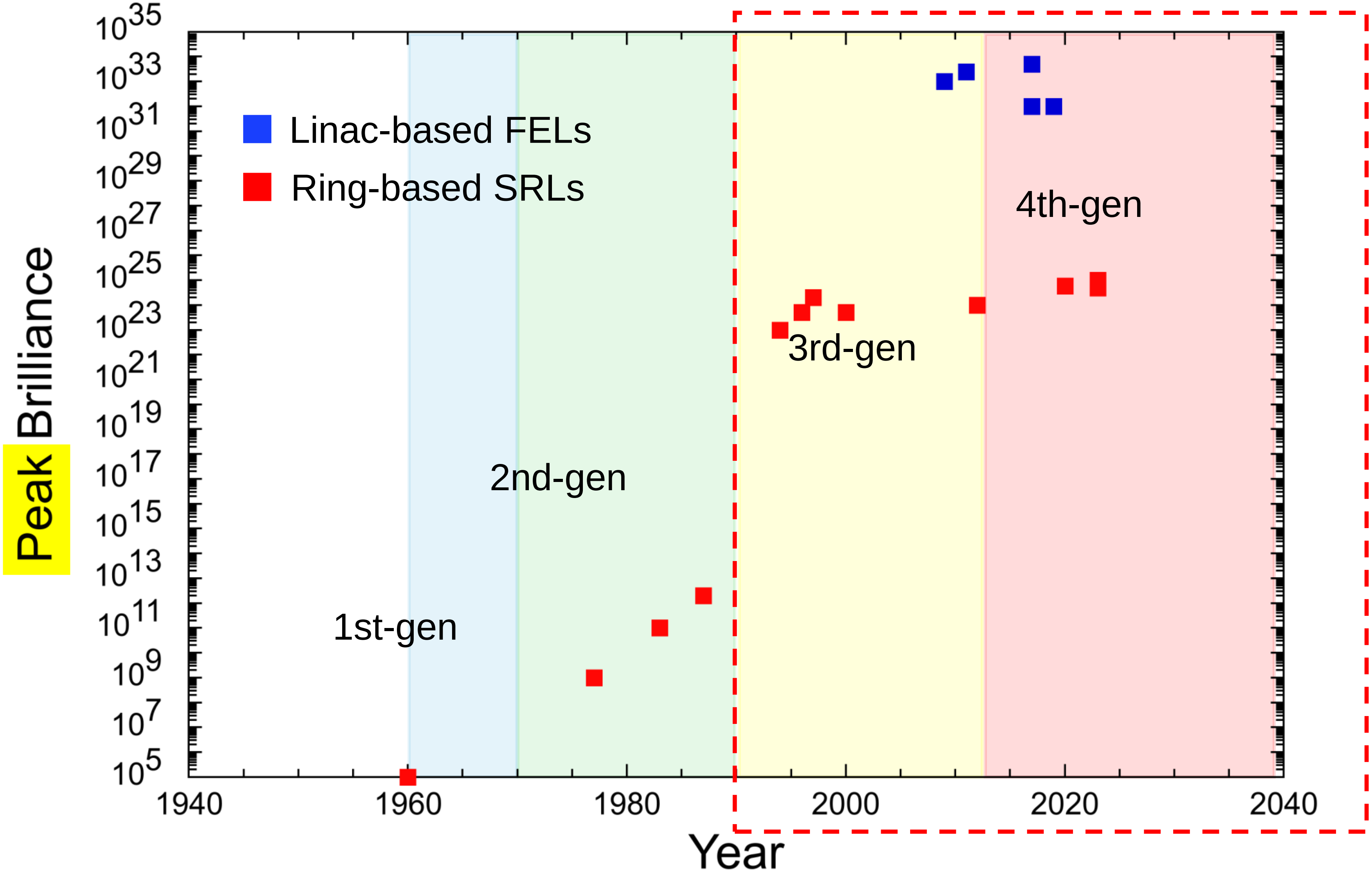
1. History of synchrotron radiation source development
2. Diffraction-limited SR sources
3. Single-pass free-electron lasers
4. Future development direction with a few topics

Brilliance enhancement over the past century



Makina Yabashi and Hitoshi Tanaka, *Nat. Photon.* 11 (2017) 12-14

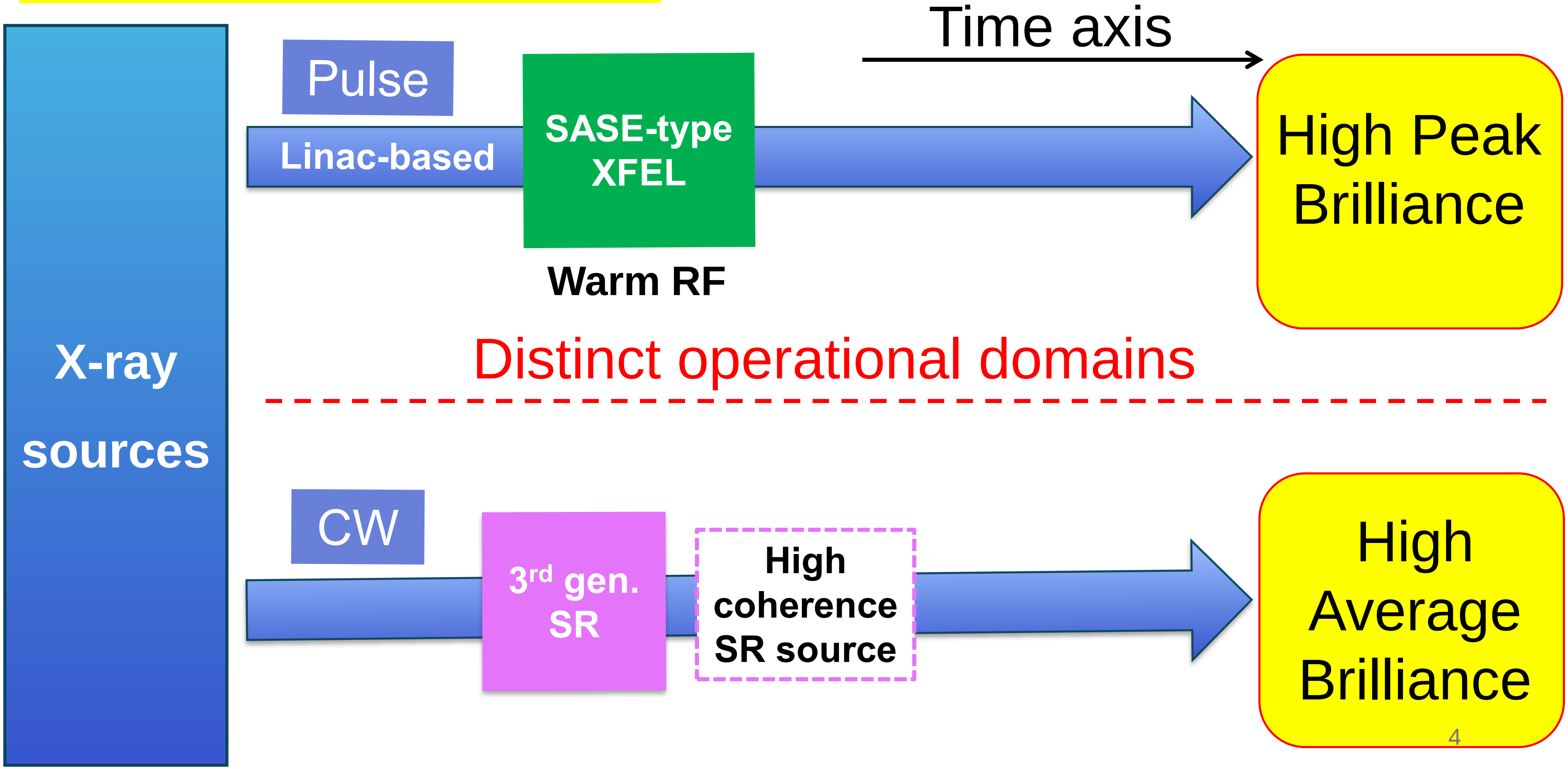
Brilliance enhancement over the past century



Makina Yabashi and Hitoshi Tanaka, *Nat. Photon.* 11 (2017) 12-14

Recent evolution of SR sources

Performance index: Brilliance



X-ray sources

Pulse

Linac-based

SASE-type XFEL

Warm RF

Time axis

High Peak Brilliance

Distinct operational domains

CW

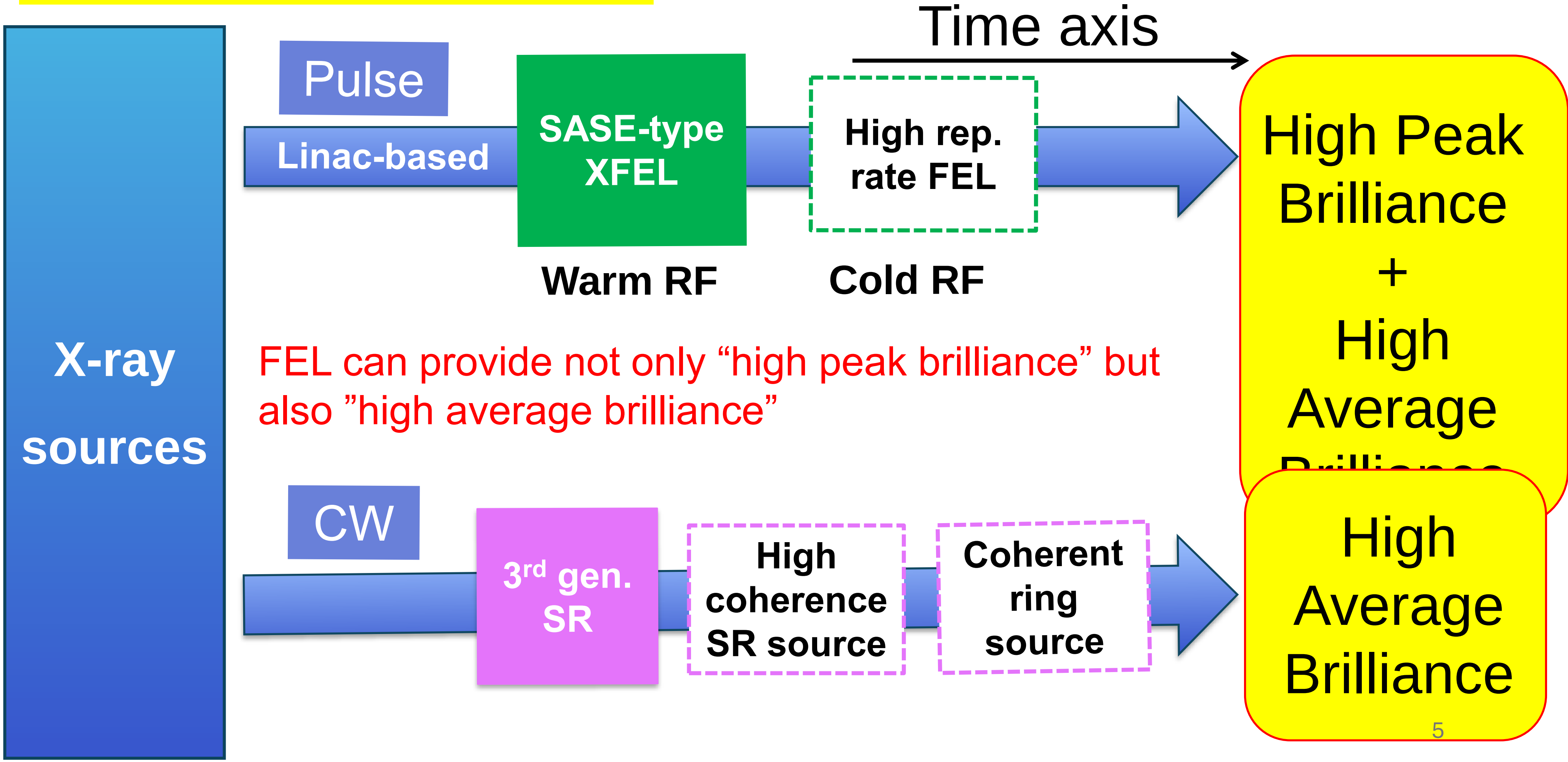
3rd gen. SR

High coherence SR source

High Average Brilliance

Recent evolution of SR sources

Performance index: Brilliance



Time axis

X-ray sources

Pulse

Linac-based

SASE-type XFEL

Warm RF

High rep. rate FEL

Cold RF

High Peak Brilliance + High Average Brilliance

FEL can provide not only “high peak brilliance” but also ”high average brilliance”

CW

3^{rd} gen. SR

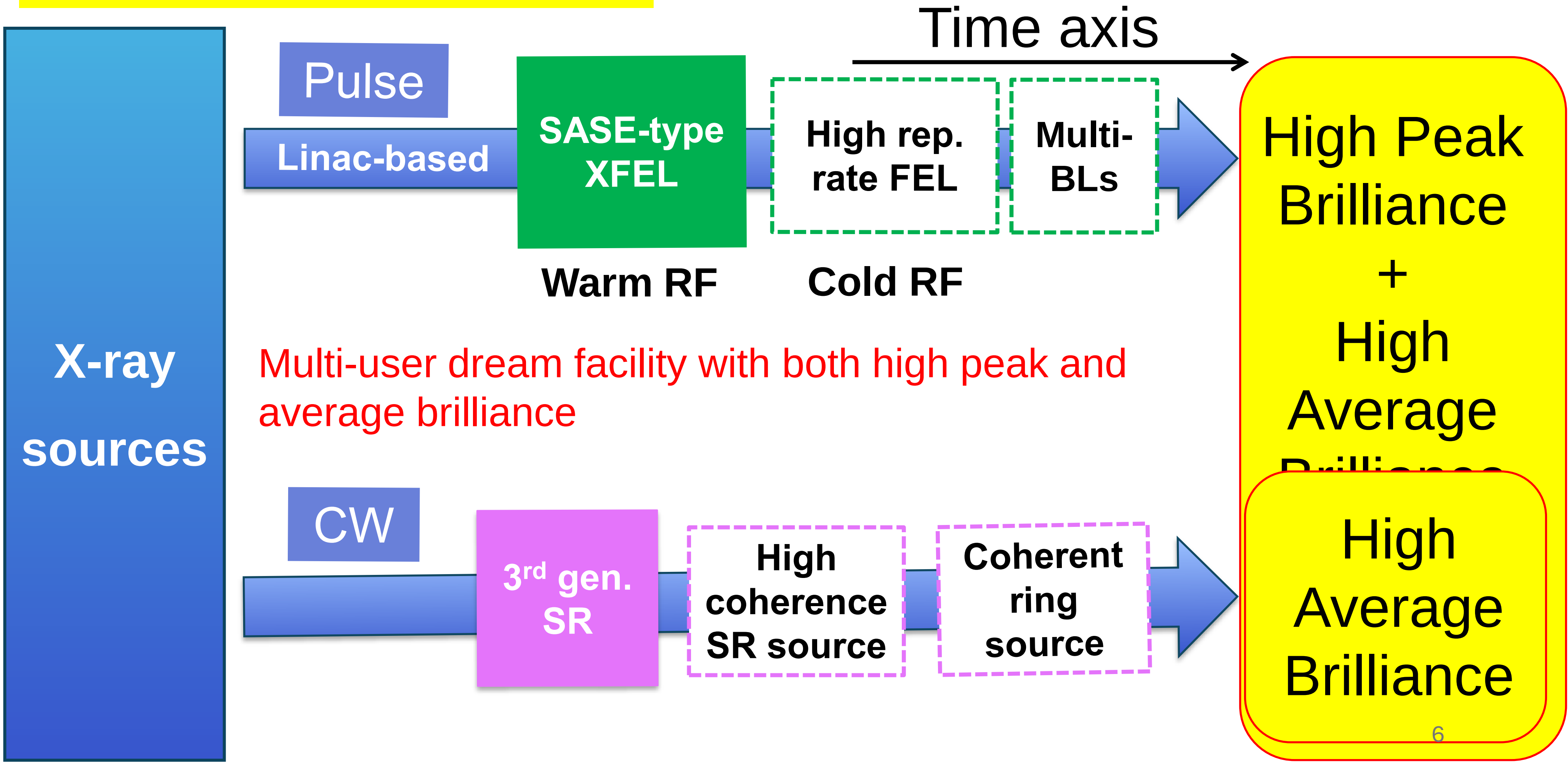
High coherence SR source

Coherent ring source

High Average Brilliance

Recent evolution of SR sources

Performance index: Brilliance



X-ray sources

Time axis

Pulse

Linac-based

SASE-type XFEL

High rep. rate FEL

Multi-BLs

Warm RF

Cold RF

High Peak Brilliance + High Average Brilliance

Multi-user dream facility with both high peak and average brilliance

CW

3^{rd} gen. SR

High coherence SR source

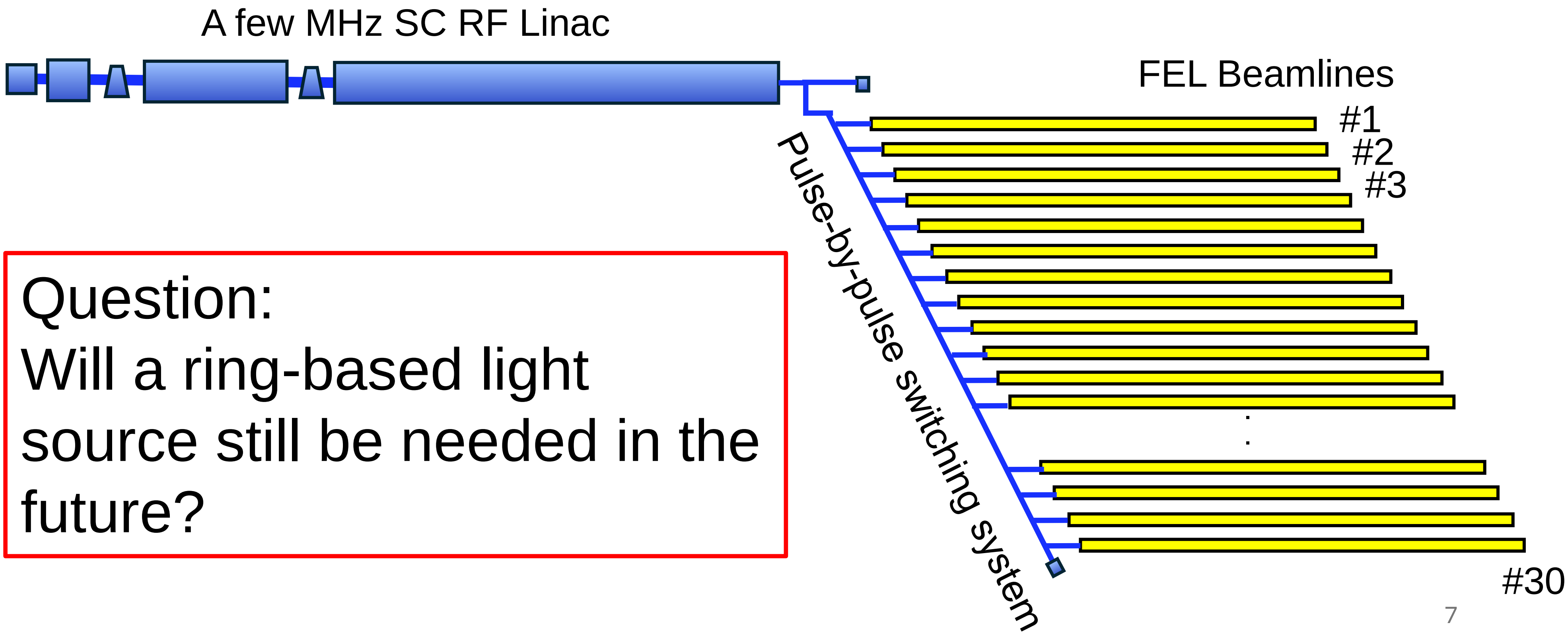
Coherent ring source

High Average Brilliance

Role sharing between FELS and ring-based SRs

Performance index: Brilliance

Image of multi-user dream facility



A few MHz SC RF Linac

FEL Beamlines

#1

#2

#3

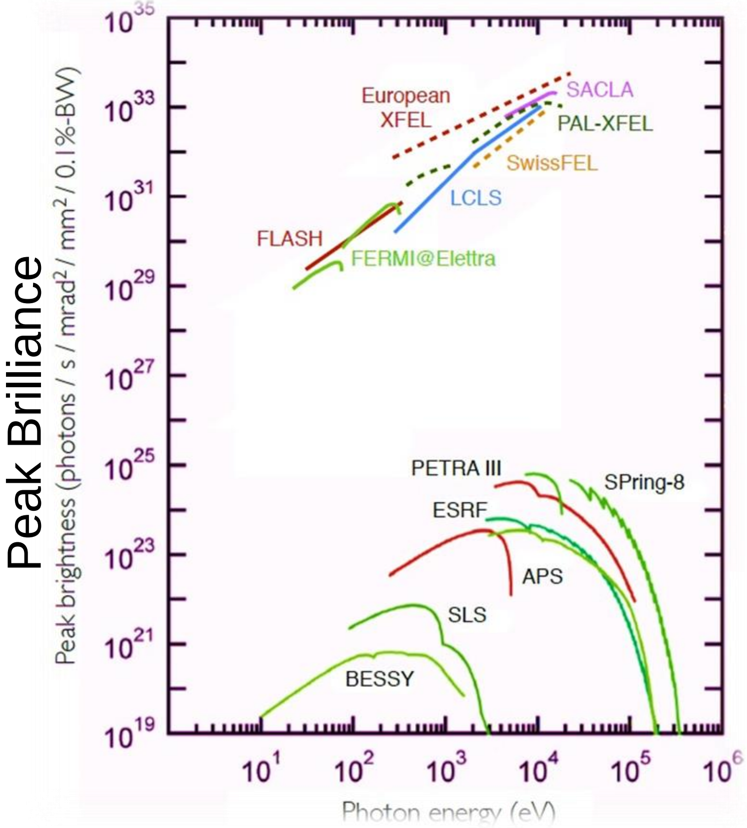
#30

Pulse-by-pulse switching system

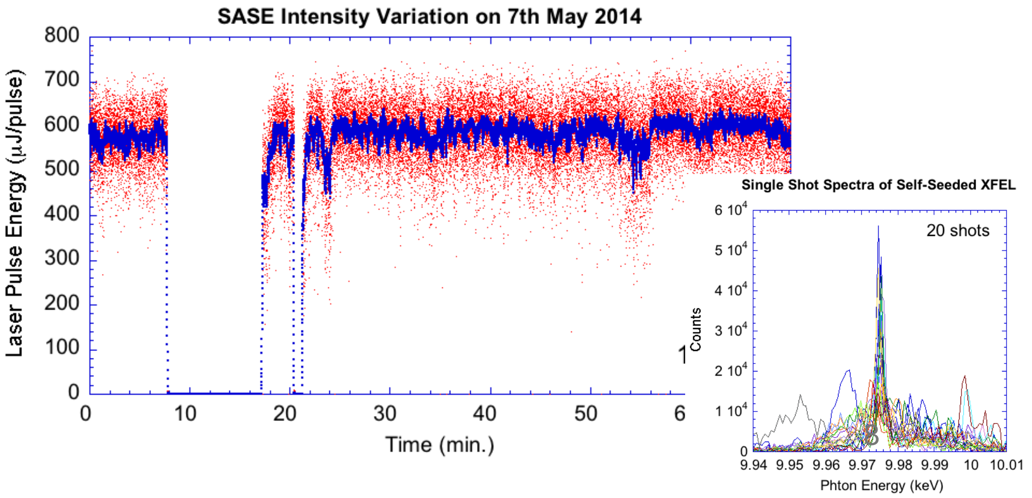
Question:
Will a ring-based light source still be needed in the future?

Role sharing between FELS and ring-based SRs

Performance characteristics of FELs



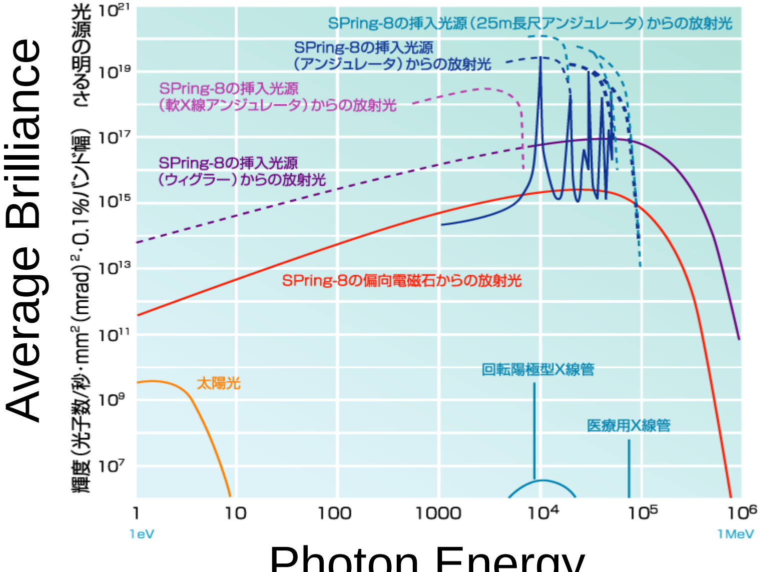
- **Limited photon energy from SX to X**
- **High peak brilliance 10^{29} to10^{34}**
- **High coherence**
- **Short pulse width sub to a few tens fs**
- **Non-negligible shot by shot variations**



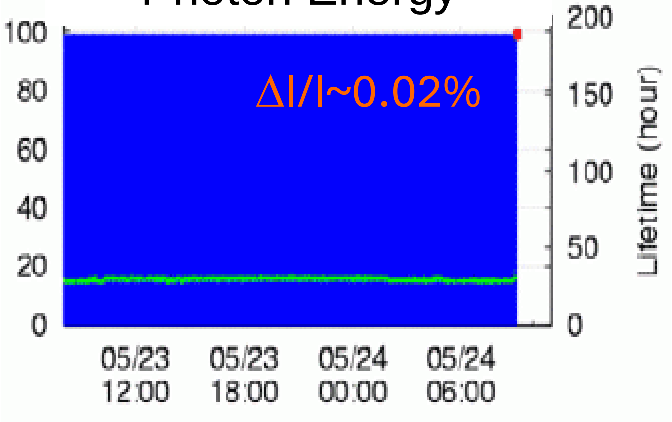
P. Schmuser, M. Dohlus, J. Rossbach, C. Behrens, Springer Tracts in Modern Physics 258 2nd ed., p167.

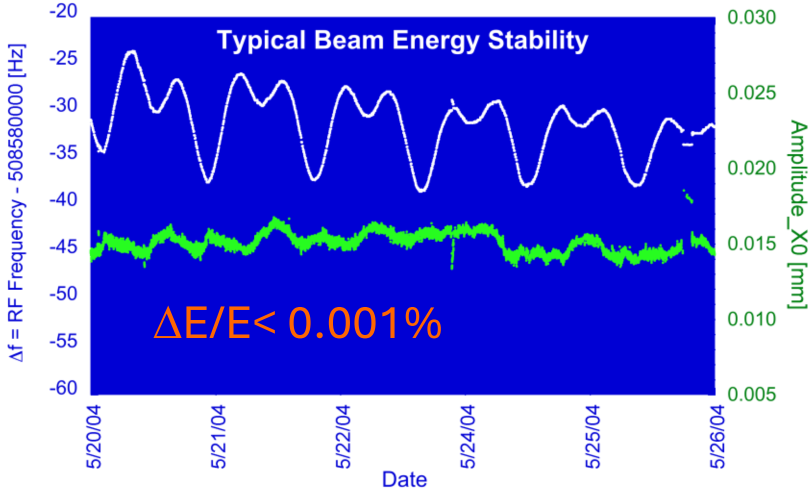
Role sharing between FELS and ring-based SRs

Performance characteristics of ring-based light source



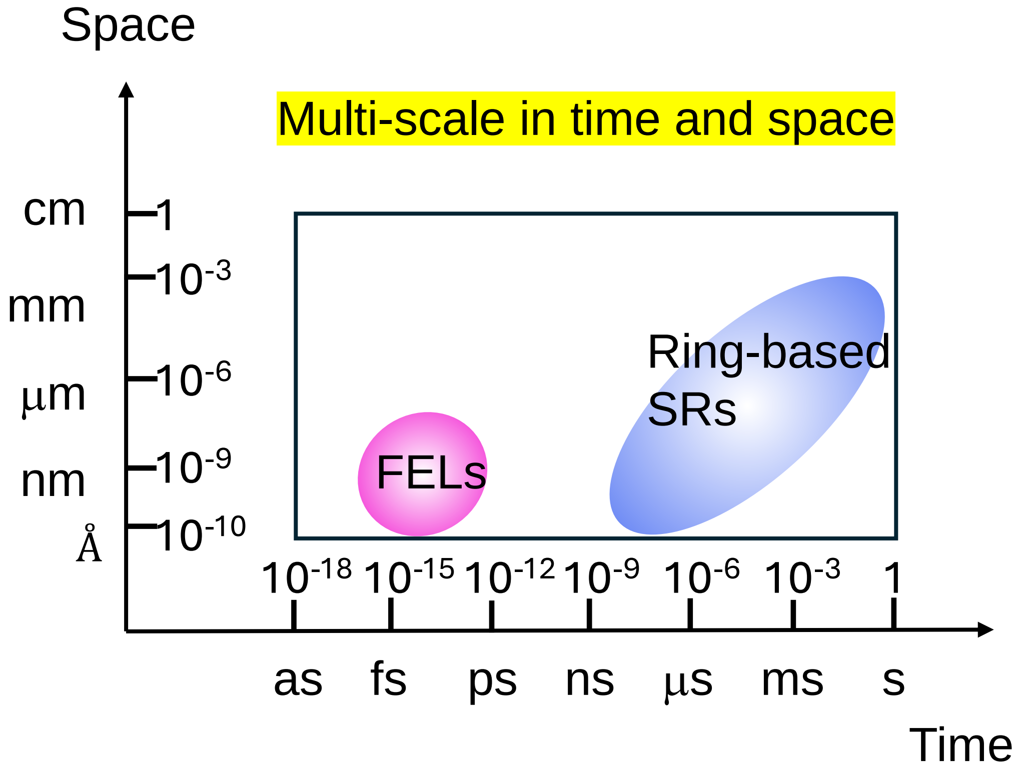
- Photon energy extended to a few 100 keV
- Average brilliance from10^{18} to 10^{21}
- Low Coherence
- Long pulse width a few tens ps
- High stability and reproducibility





Role sharing between FELs and ring-based SRs

Systems to be studied by SRs are complex and multi-scaled in time and space



- High peak brilliance is not a universal solution
- High transverse and longitudinal coherence such as a laser is not essential for all experiments
- Correlation measurements using the same sample are extremely useful in various experiments
- The utilization of higher photon energy becomes increasingly important for various applications

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Diffraction limit

For a given wavelength λ, the product of its size and angular divergence can not be less than λ/4π $(= \varepsilon_{ph})$. In the case of undulator radiation

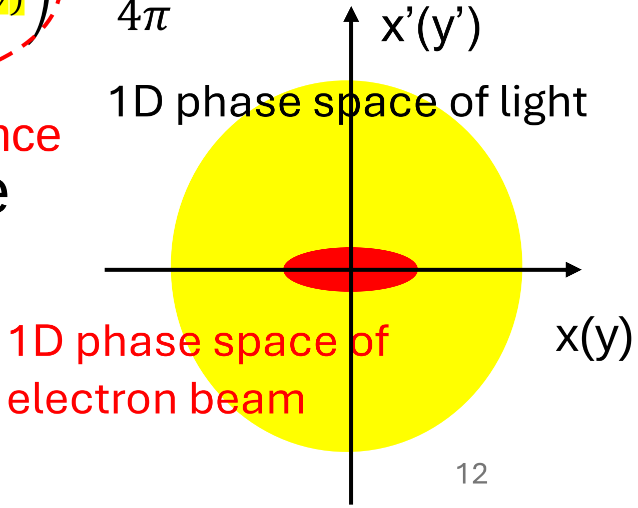
$$Brilliance \equiv \frac{Flux@0.1\%\,BW}{\Sigma_x \Sigma_{\acute{x}} \Sigma_y \Sigma_{\acute{y}}}$$

Σ_i: convolution of contributions from photons and electrons to parameter *i*

Electron

$$\Sigma_{x(y)}\,\Sigma_{\acute{x}(\acute{y})} = \underbrace{\sqrt{\left(\underbrace{\frac{L_u\lambda}{16\pi^2}}_{\text{Photon}} + \beta_{x(y)}\varepsilon_{x(y)}\right)}}_{\text{size}}\;\underbrace{\sqrt{\left(\underbrace{\frac{\lambda}{L_u}}_{\text{Photon}} + \gamma_{x(y)}\varepsilon_{x(y)}\right)}}_{\text{angular divergence}} \approx \frac{\lambda}{4\pi}$$

When the horizontal and vertical phase space volumes of “light source” are nearly λ/4π, this radiation is called diffraction limited and it gives transverse full coherence.



Scaling of natural emittance

$$\varepsilon = C_q \frac{\gamma^2 \left\langle \frac{H(s)}{\rho(s)^3} \right\rangle}{J_x \left\langle \frac{1}{\rho(s)^2} \right\rangle} \propto \frac{\gamma^2 \theta^3}{J_x},$$

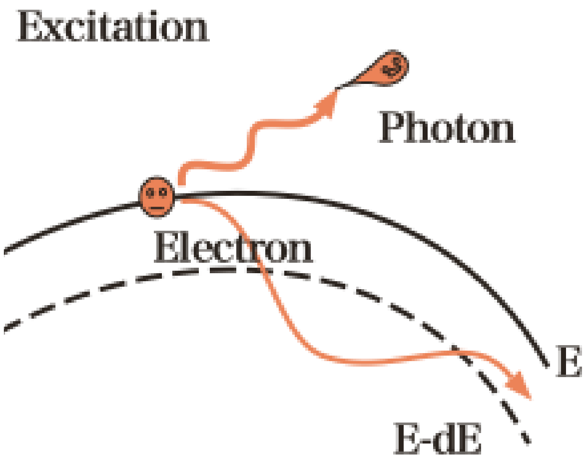
γ: Lorentz factor
θ: Bending angle
ρ: bending radius
H: *H*-function
J_x: Damping partition number

$$H(s) = \frac{1+\alpha_x^2(s)}{\beta_x(s)} \eta_x^2(s) + 2\alpha_x(s)\eta_x(s)\eta_x'(s) + \beta_x(s)\eta_x'^2(s),$$

η_x: Horizontal dispersion
η_x' : Horizontal dispersion angle
β_x : Horizontal beta
α_x : Horizontal alfa

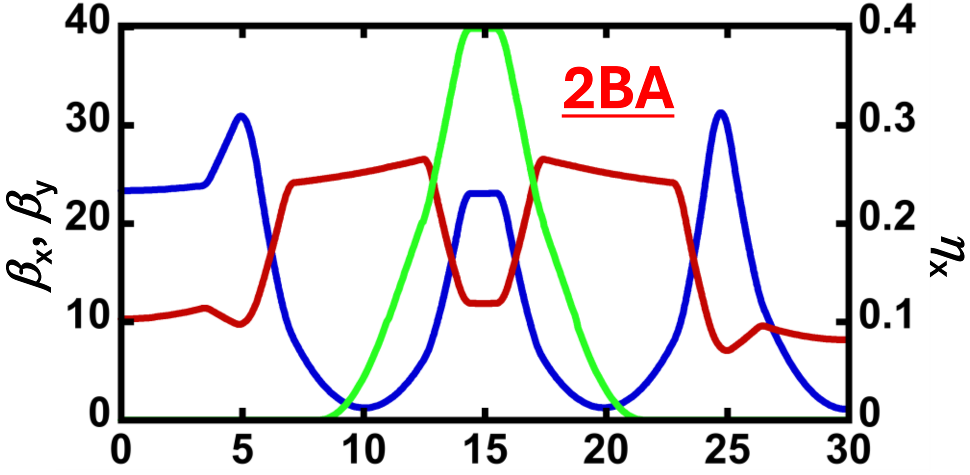
As the number of bending magnets increases, natural emittance decreases inversely proportional the cubic of that number.

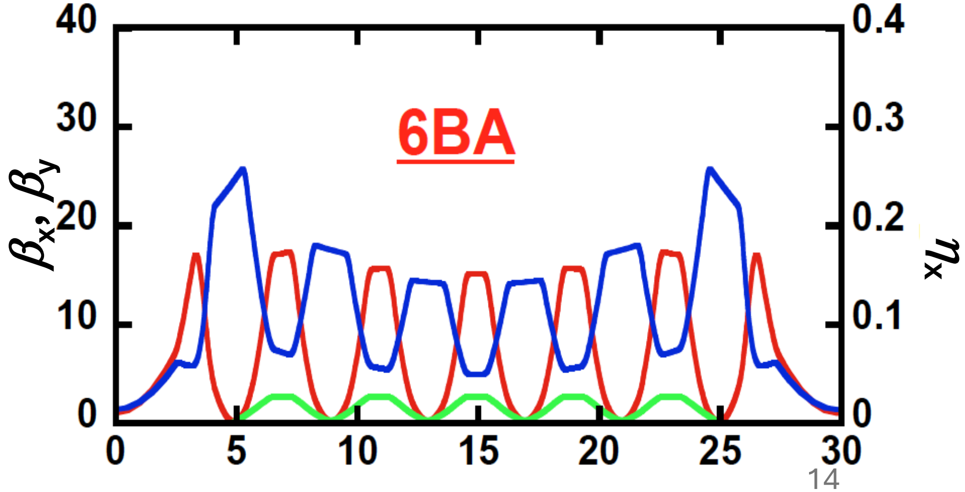
Suppression of radiation excitation to achieve lower emittance



The excited amplitude of a betatron oscillation is determined by the local energy dispersion.

The MBA lattice can effectively suppress the energy dispersion along the ring as shown below.





What breakthroughs made the MBA possible?

The following issues need to be overcome:

1. Narrow space issues
2. Strong nonlinearity from chromaticity correction sextupoles
3. Beam injection scheme applicable for a ring with a small dynamic aperture
4. Stable top-up beam injection compensating a short beam-lifetime and transparent against small emittance stored beam

What breakthroughs made the MBA possible?

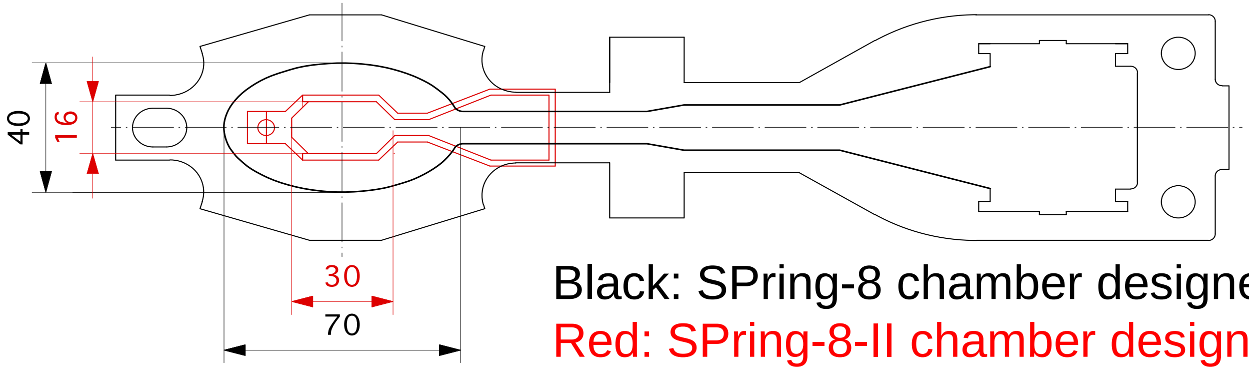
1. Solving narrow spacing issues

Q1: The MBA lattice naturally requires the large number of focusing quadrupoles to focus the beam at each BM horizontally. How can numerous magnets be accommodated within a limited space?

Q2: The shorter focal length and smaller energy dispersion increase the strength of both quadrupole and sextupole magnets. How can extremely strong quadrupole and sextupole fields be achieved?

What breakthroughs made the MBA possible?

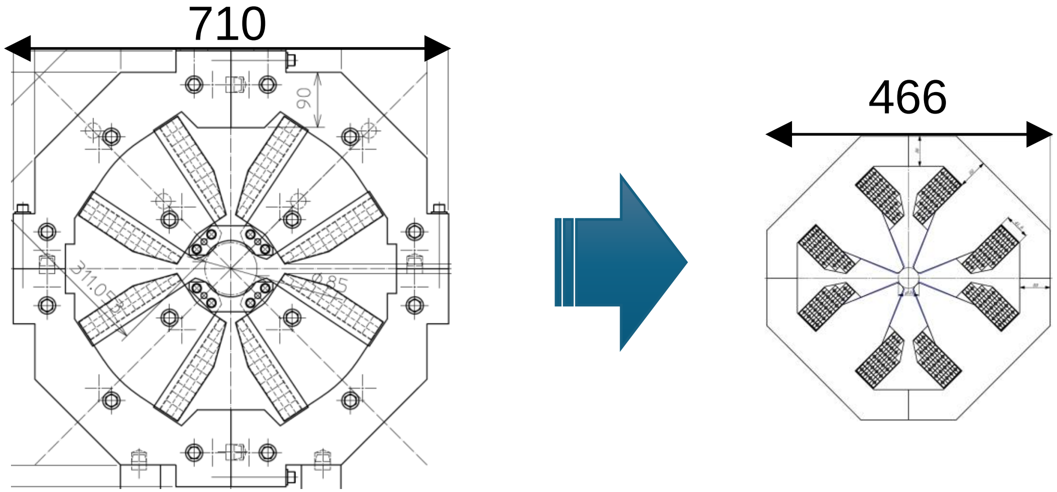
A1/A2: Adoption of the compact vacuum chamber w/wo NEG coating



Black: SPring-8 chamber designed 35 years ago

Red: SPring-8-II chamber designed recently

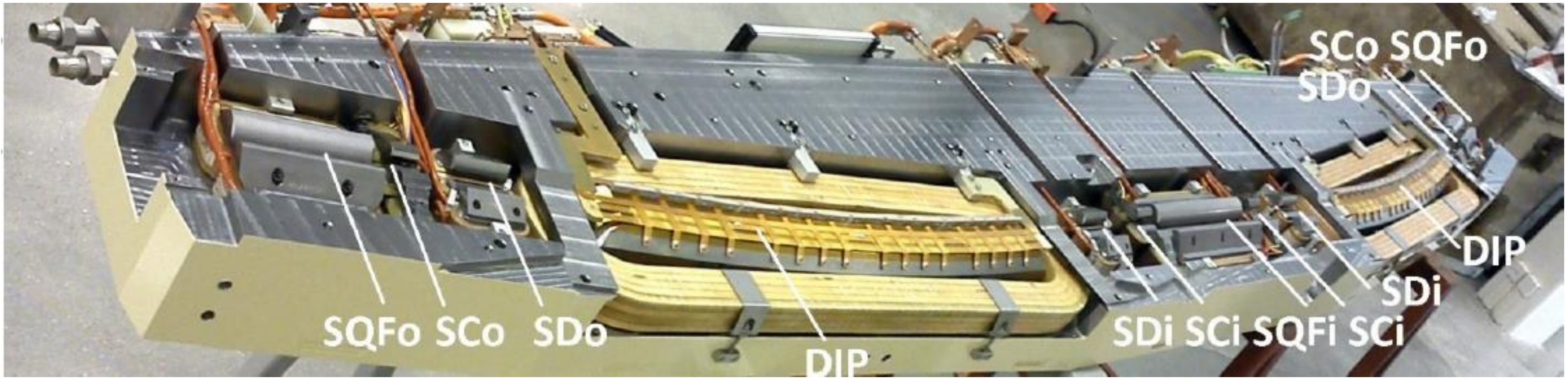
Bore radius
85 mm



Bore radius
34 mm

What breakthroughs made the MBA possible?

A1/A2: Adoption of a single-yoke composite magnet with a spaghetti-type chamber



M. Johansson et. al., *Proc. of NAPAC2016*, Chicago, IL, USA (2016) pp. 1058-1066

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Brief history

The development of a single-pass FEL originated from the TTF (TESRA Test Facility), the test-bed for ILC at DESY and 1.3 GHz superconducting RF system was developed. In 2000, First SASE (Self-Amplified Spontaneous Emission) lasing was observed at 109 nm [1]. TTF demonstrated the SESE scheme operating in the short-wavelength region, thereby establishing the foundation for X-ray FELs subsequently constructed worldwide.

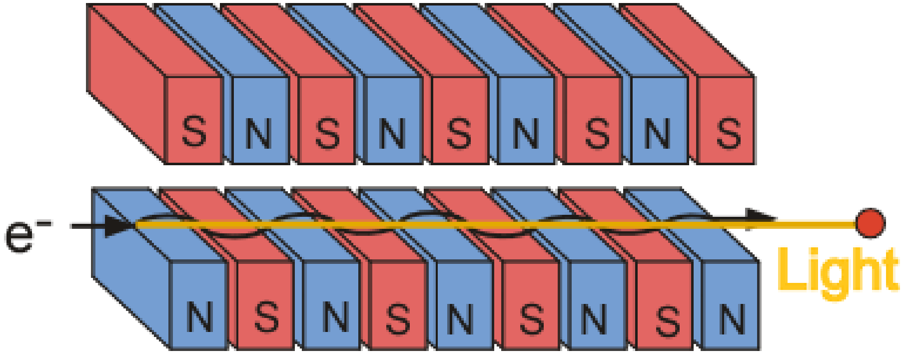
In 2009, LCLS (Linac Coherent Light Source) at SLAC achieved first SASE lasing at 0.12 nm using normal conducting S-band linac (a part of Stanford two-mile linac), out-of-vacuum undulator, RF gun system and so on.

Era of single-pass FEL in short wavelengths was open-up.

[1] J. Andruszkow et. al., *PRL* **85**(18) (2000) 3825-3829
[2] P. Emma et. al., *Nat. Photon.* **4** (2010) 641-547

Resonant Wavelength for Undulator

Self-Amplified Spontaneous Emission



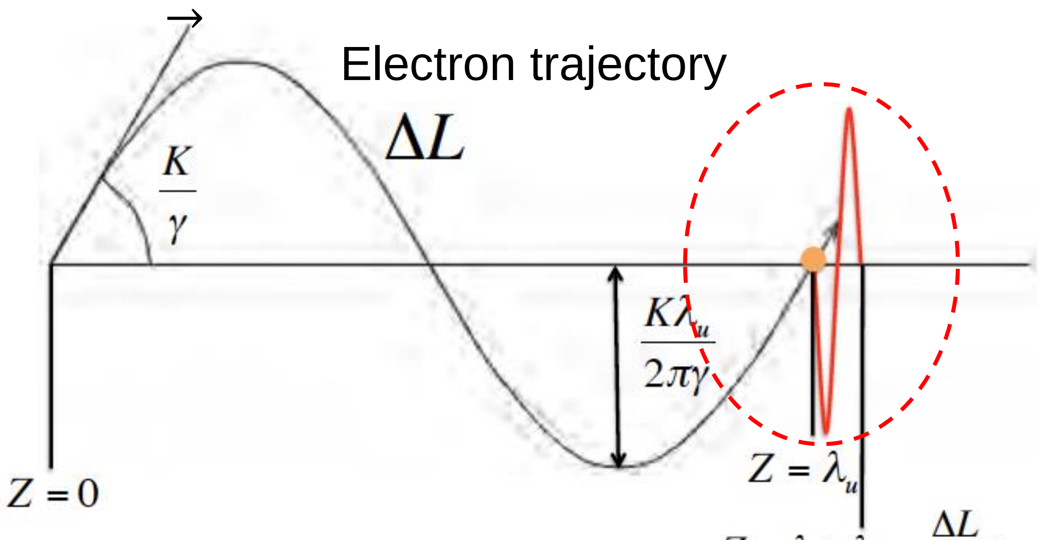
Resonant wavelength o undulator

$$\lambda = \frac{\Delta L}{\beta} - \lambda_u$$

$$\rightarrow$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) + o\left(\frac{1}{\gamma^4}\right)$$

$$K = \frac{eB_u\lambda_u}{2\pi m_e c}$$

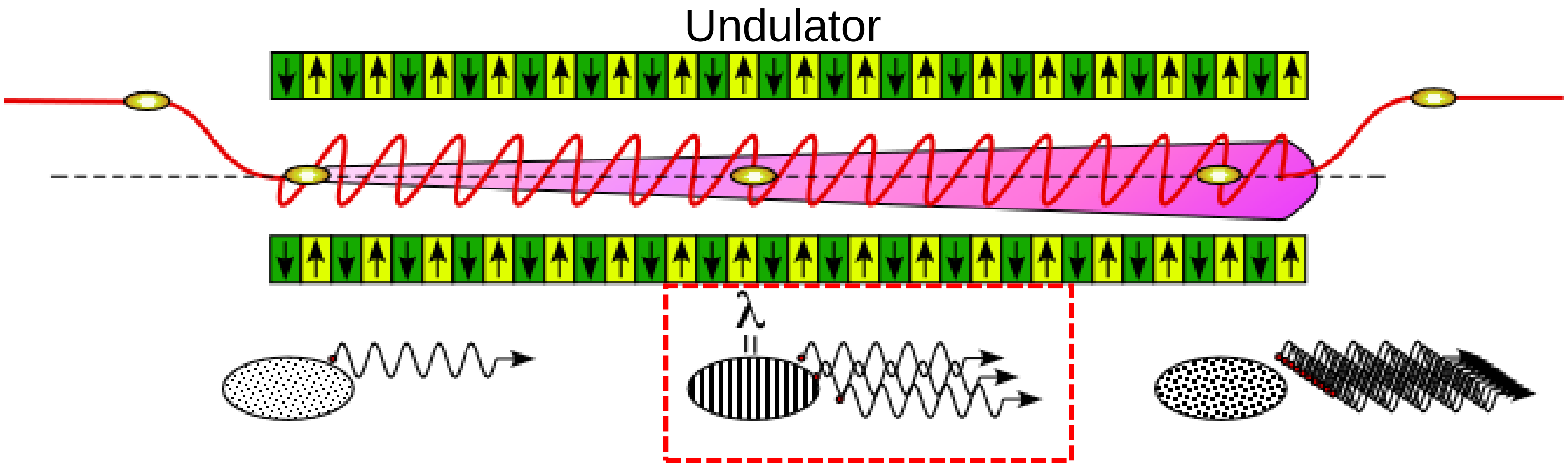


$$Z = \lambda + \lambda_u = \frac{\Delta L}{\beta c} c$$

$$\Delta L = \int_{Z=0}^{Z=\lambda_u} \sqrt{1 + \left[\frac{K\lambda_u}{2\pi\gamma}\sin\left(\frac{2\pi z}{\lambda_u}\right)\right]^2}\, dz \approx \lambda_u\left(1 + \frac{K^2}{4\gamma^2}\right)$$

Energy Modulation with Wavelength Interval

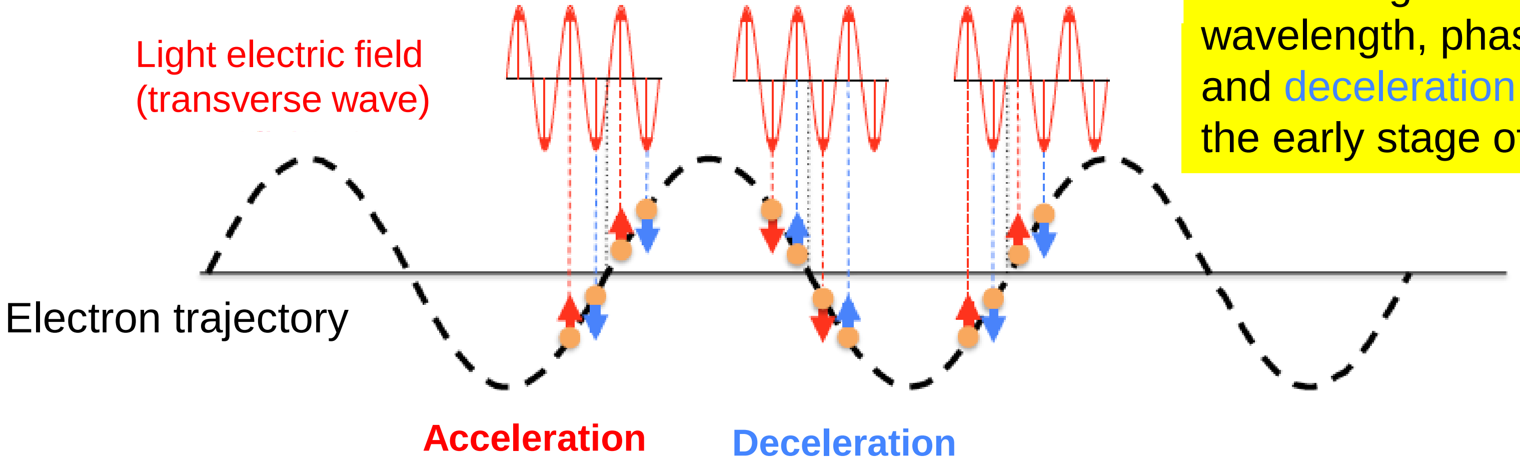
Self-Amplified Spontaneous Emission



Undulator

Light overtakes electrons by one wavelength for every one undulation period

With the light of resonant wavelength, phase of acceleration and deceleration are maintained in the early stage of micro-bunching



Light electric field (transverse wave)

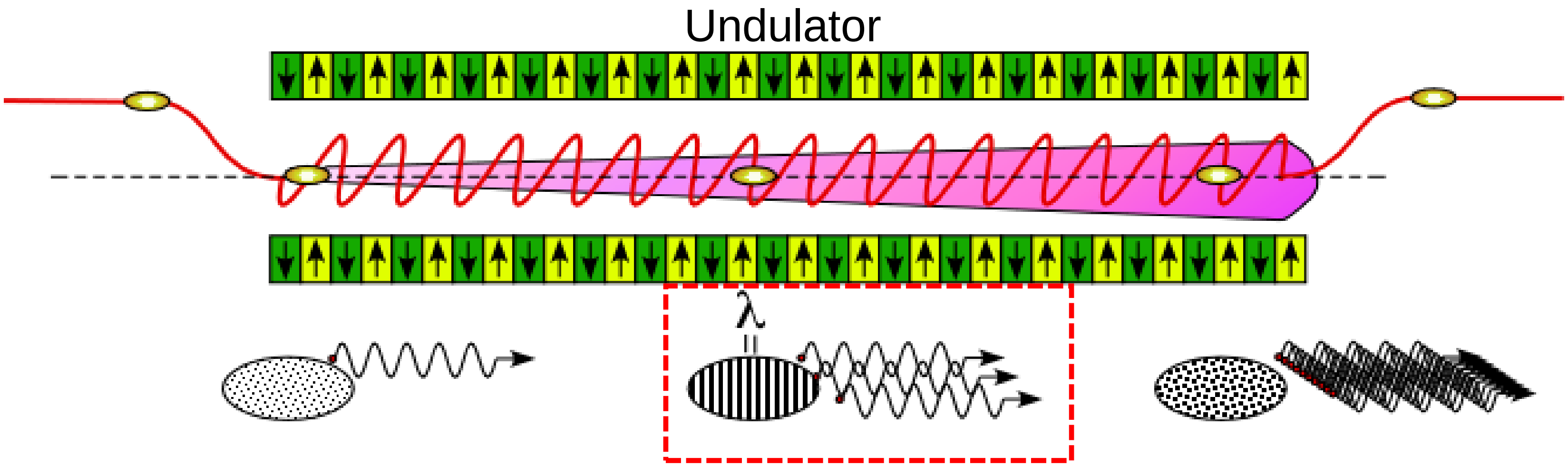
Electron trajectory

Acceleration

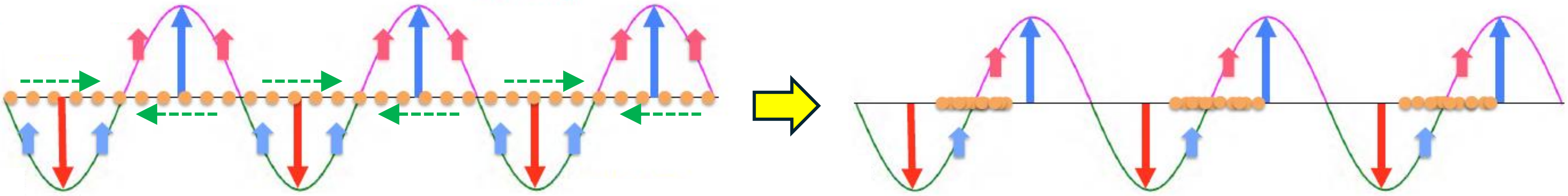
Deceleration

Micro-bunching with Wavelength Interval

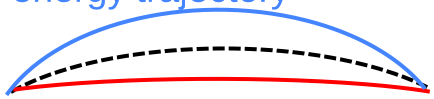
Self-Amplified Spontaneous Emission



Electrons gaining and loosing energy gather towards at the field zero crossing points


Electron deceleration side

Electron acceleration side

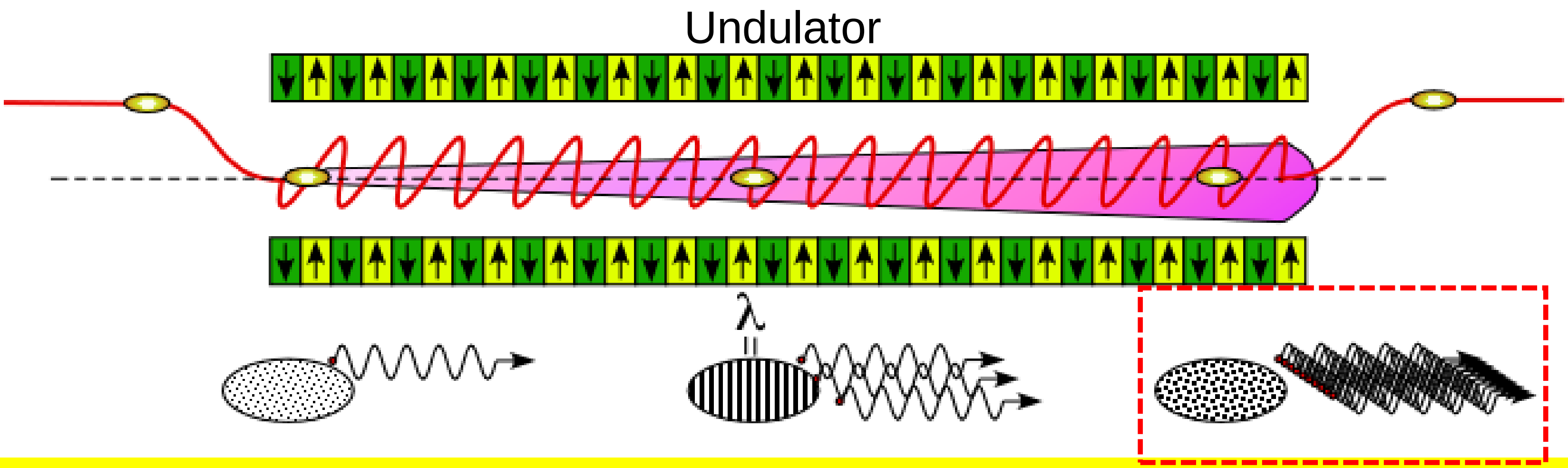

Lower energy trajectory

Design energy trajectory

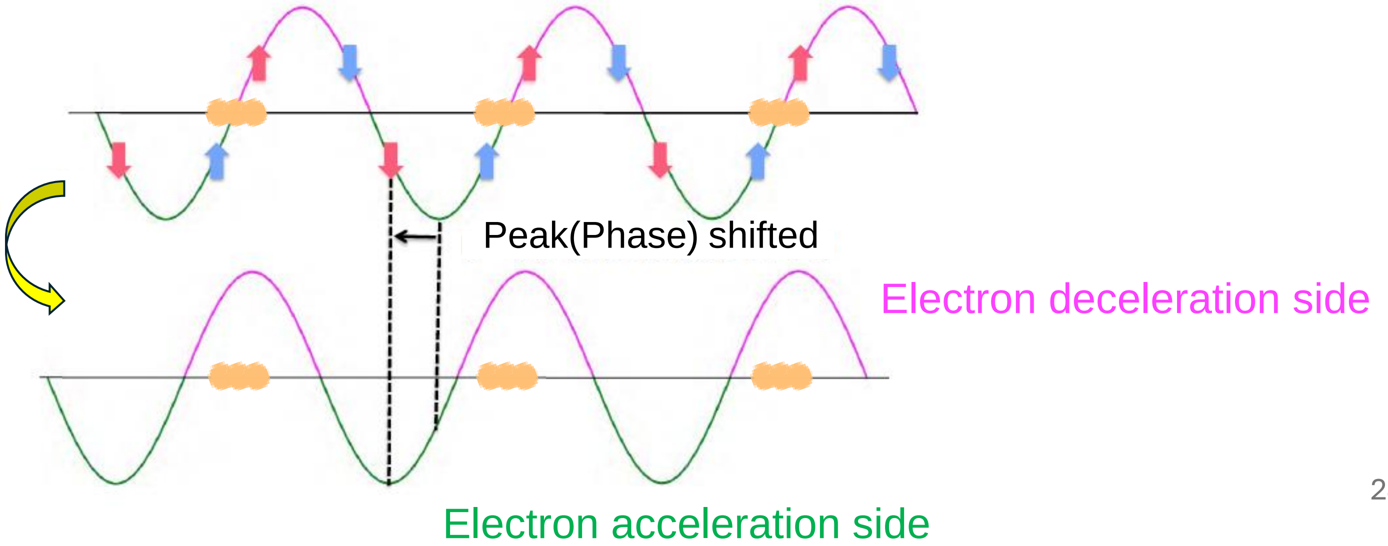
Higher energy trajectory

Phase Shift of Light Electric Field

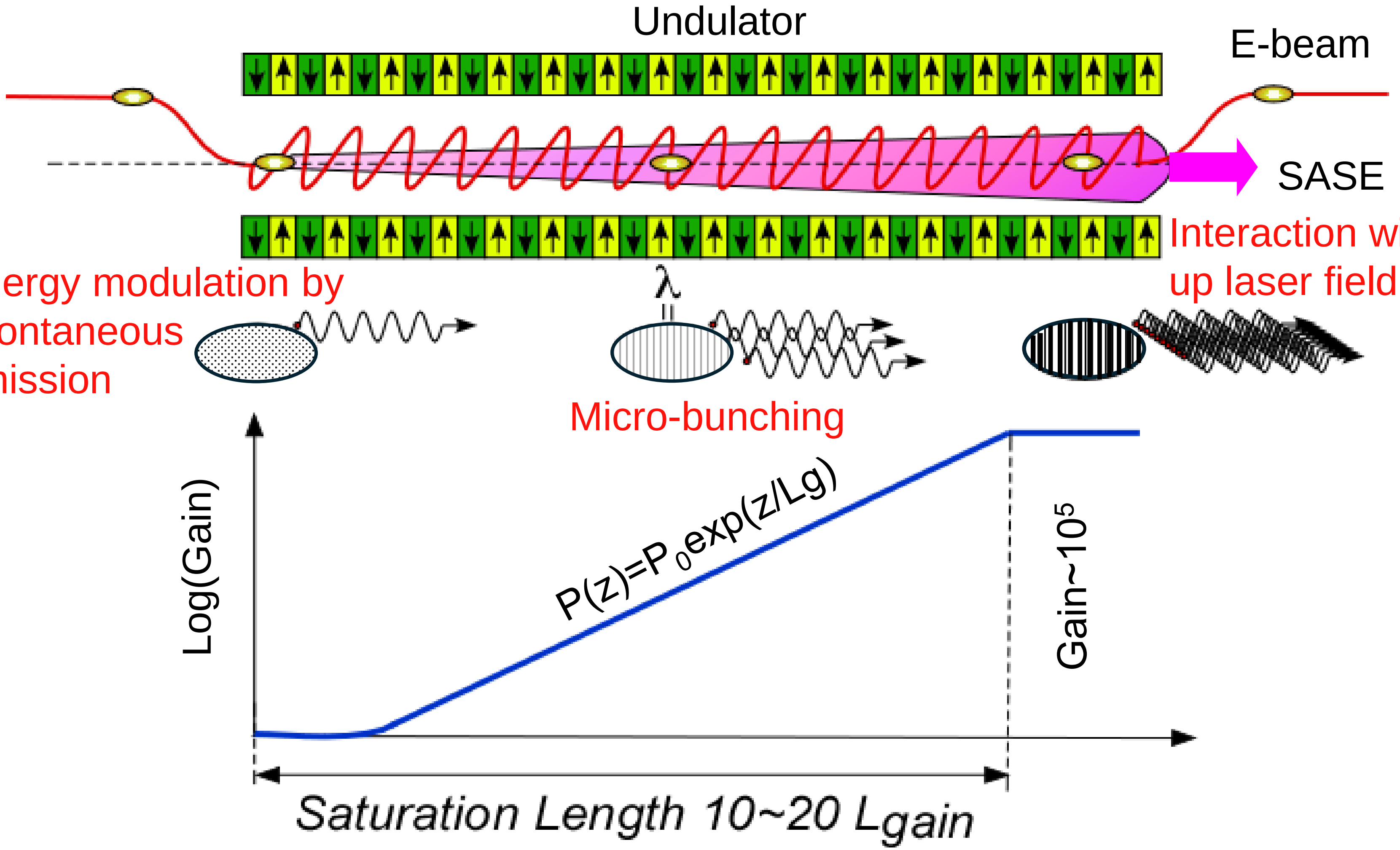
Self-Amplified Spontaneous Emission



Energy exchange with gradually bunching electrons modulates the phase of light electric field



Self-Amplified Spontaneous Emission



Energy modulation by spontaneous emission

Micro-bunching

Interaction with a built-up laser field

1D SASE gain length

The gain length L_G represents the undulator length enhancing the laser power by a factor of *e* (approximately 2.7).

$$P(z) \propto Exp\left(\frac{z}{L_G}\right),$$

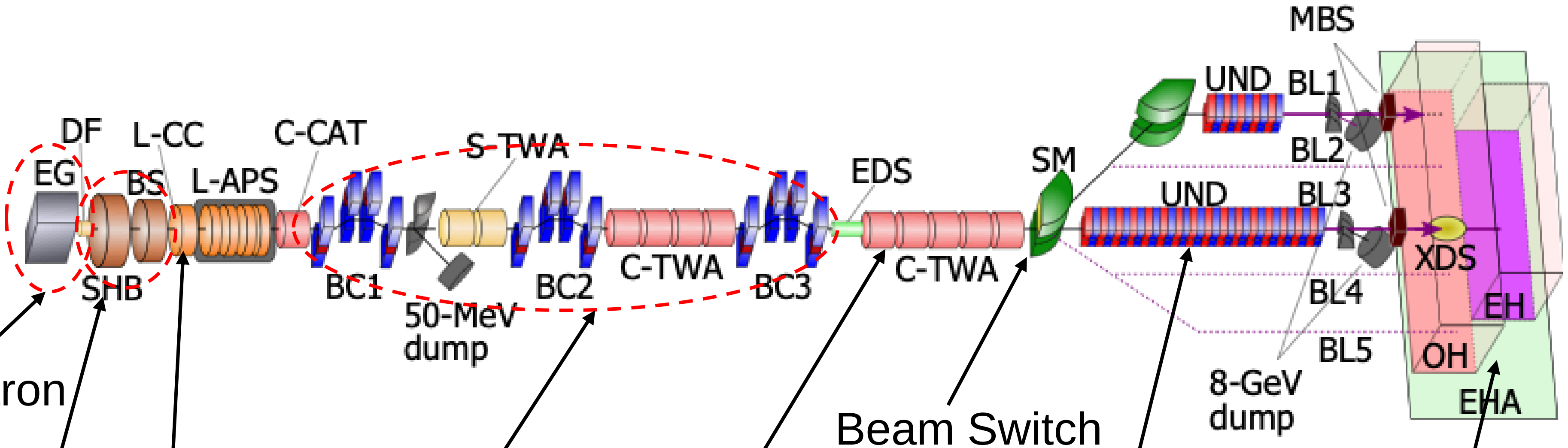
Averaged beta over the undulator

Emittance at the lasing slice

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho} \;, \qquad L_G \propto \rho^{-1} \propto \left(\frac{\sigma_x \sigma_y}{I_p}\right)^{1/3} \approx \left(\frac{\langle\beta\rangle \varepsilon_s}{I_p}\right)^{1/3}$$

Peak current at the lasing slice

Single-pass FEL system



Electron Gun

Buncher

Chirp Lineariser

Multi-stage Bunch Compressor

Main Acceleration System

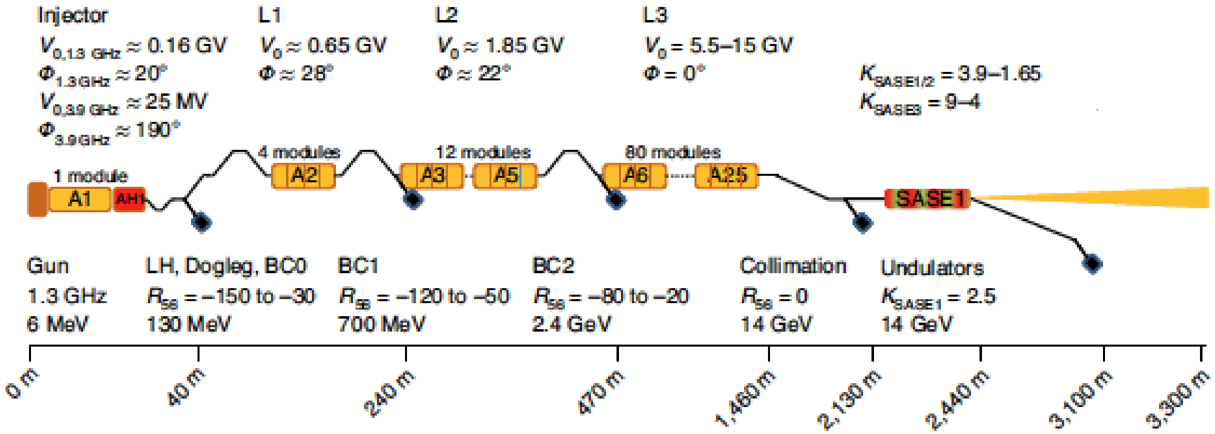
Beam Switch Yard

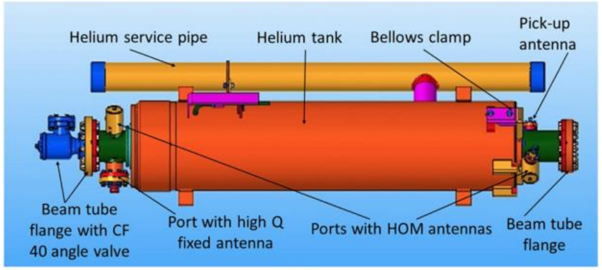
Undulator Beamline

Experimental Hutch

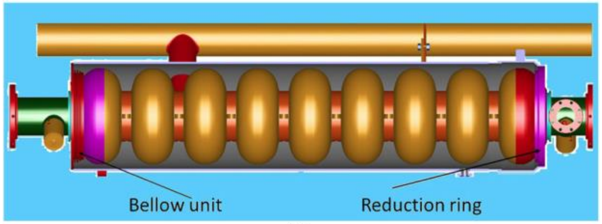
T. Ishikawa et. al., *Nat. Photon.* **6** (2012) 540-544

High repetition rate XFEL based on superconducting linac (mainstream)





(a)



(b)

W. Decking et. al., *Nat. Photon.* **14** (2020) 391-397

SPring-8 Compact SASE Source (SCSS)

Lower Beam Energy

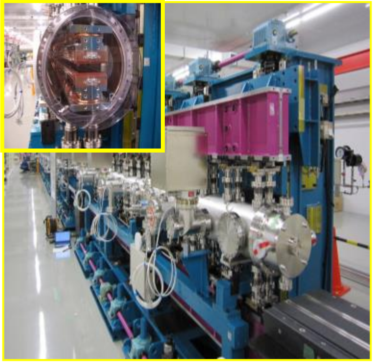
Size Reduction

Efficient Acceleration

Further Size Reduction

Smaller Normalized Beam Emittance

T. Ishikawa et. al., *Nat. Photon.* **6** (2012) 540-544



Short period in-vacuum undulator

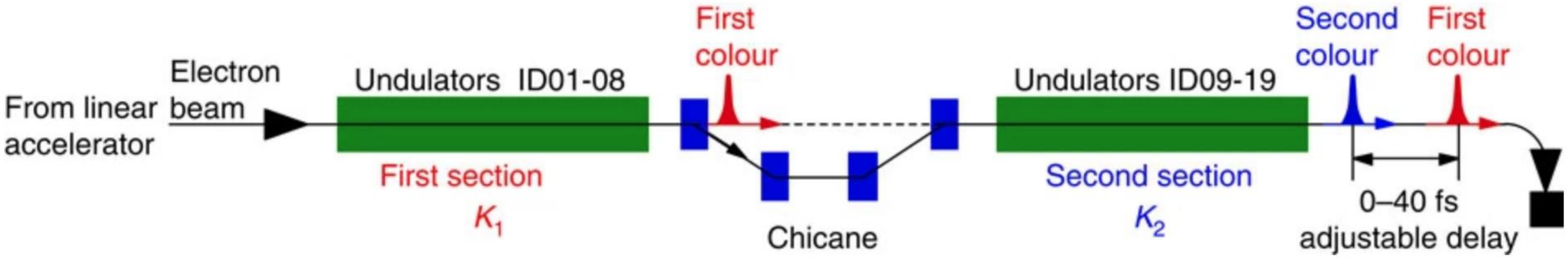
C-band high gradient acceleration system

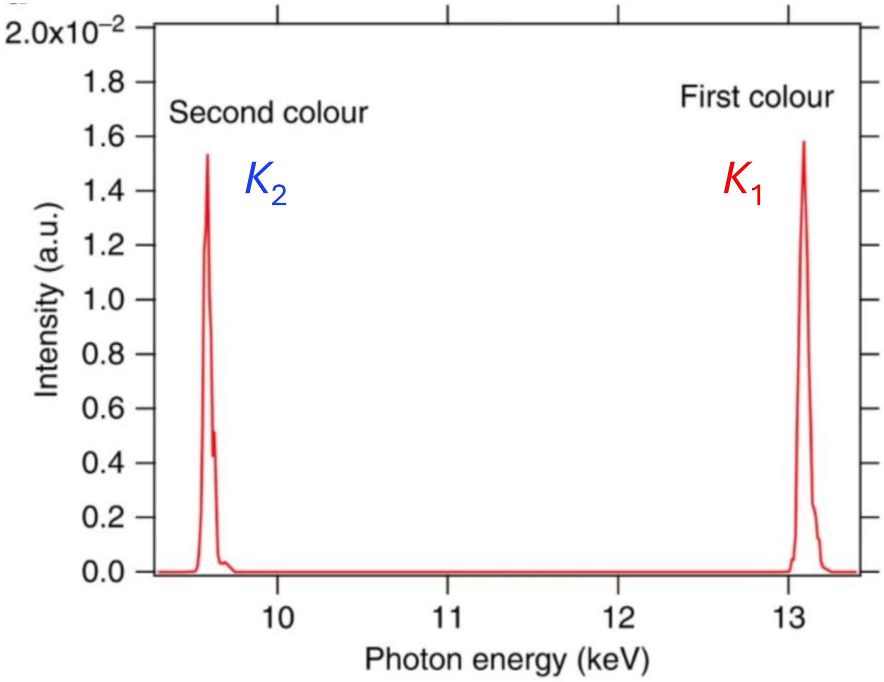
Thermionic gun based low emittance injector

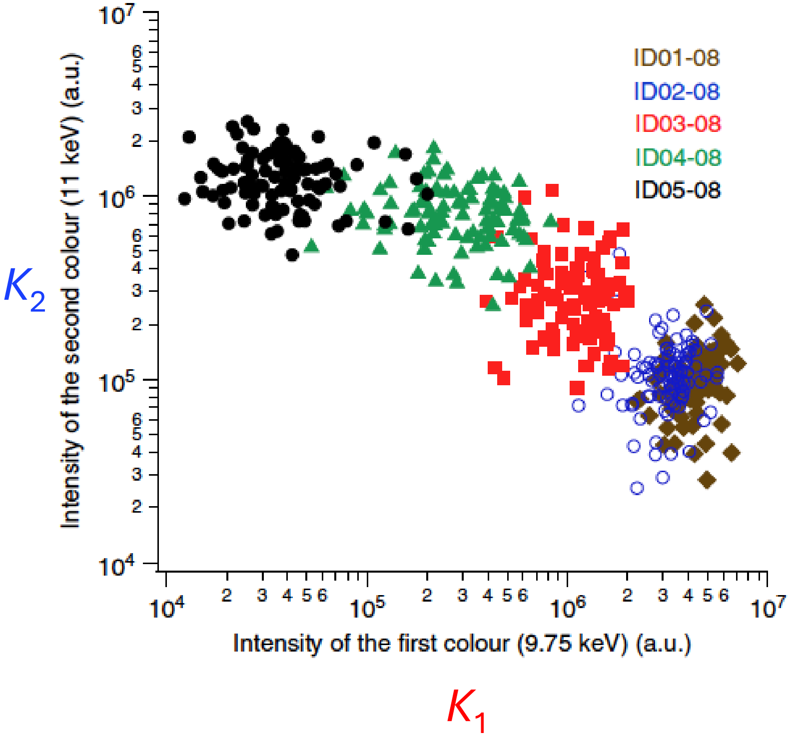
Variety of XFELs

1. Two-color FEL
2. Self-seeded FEL
3. Circular-/liner-polarized FEL
4. Extremely short-pulsed FEL

Two-color XFEL with wide tunability

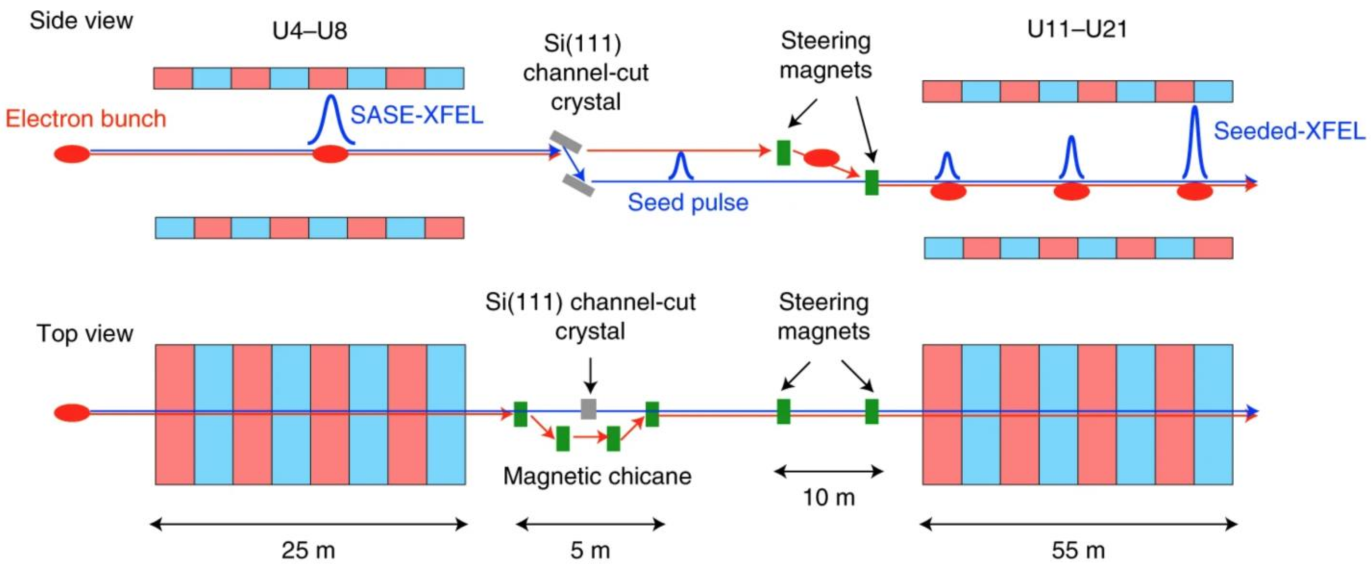


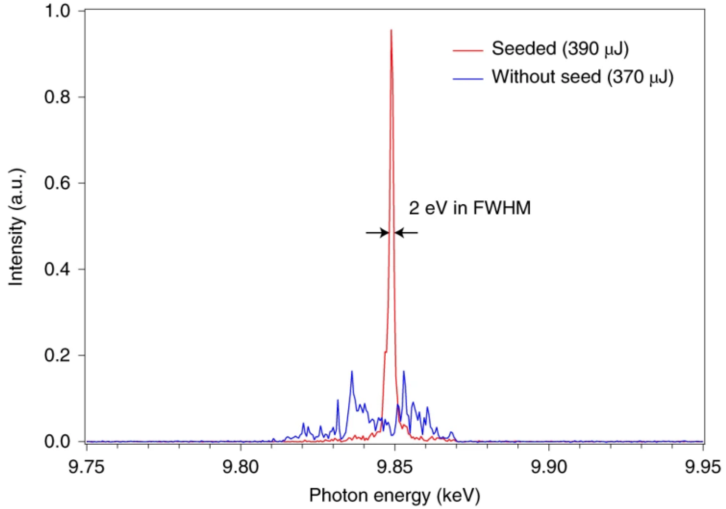


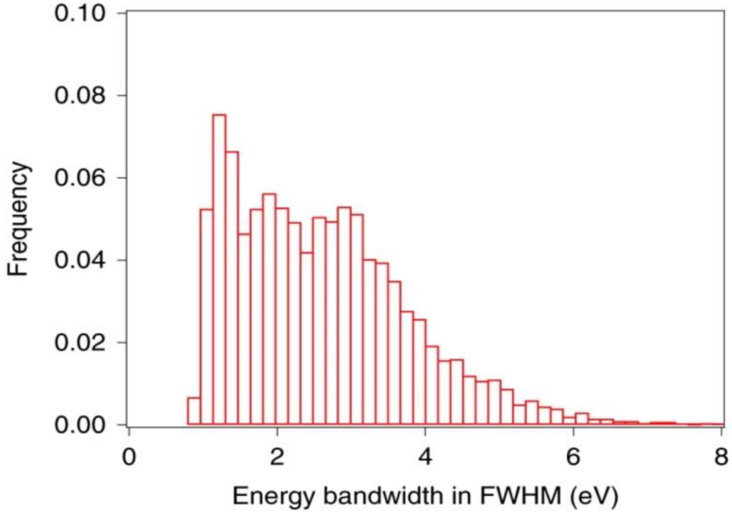


T. Hara et. al., *Nat. Commun.* **4** (2013) 2919

Self-seeding with reflective geometry



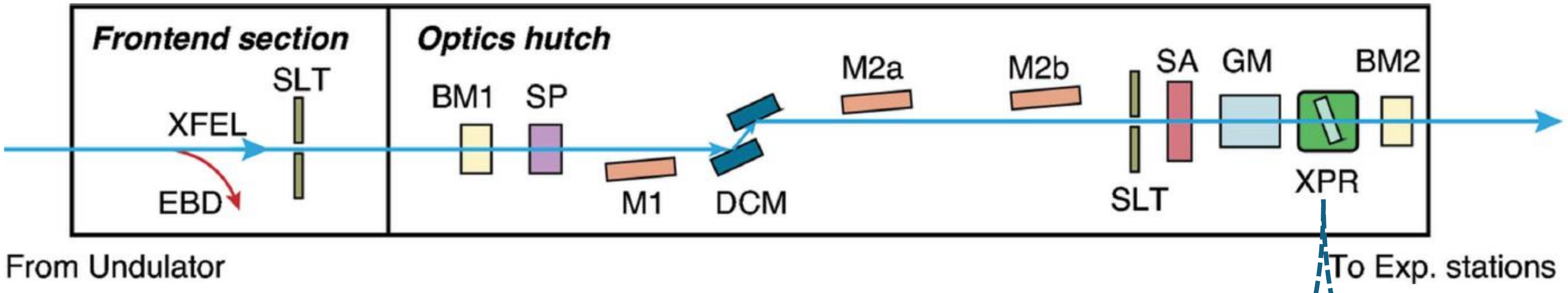


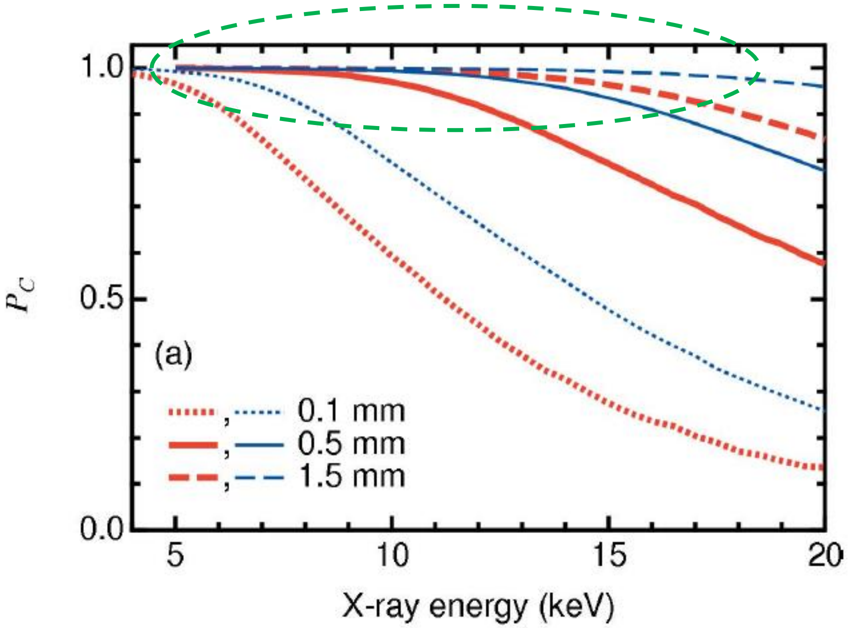


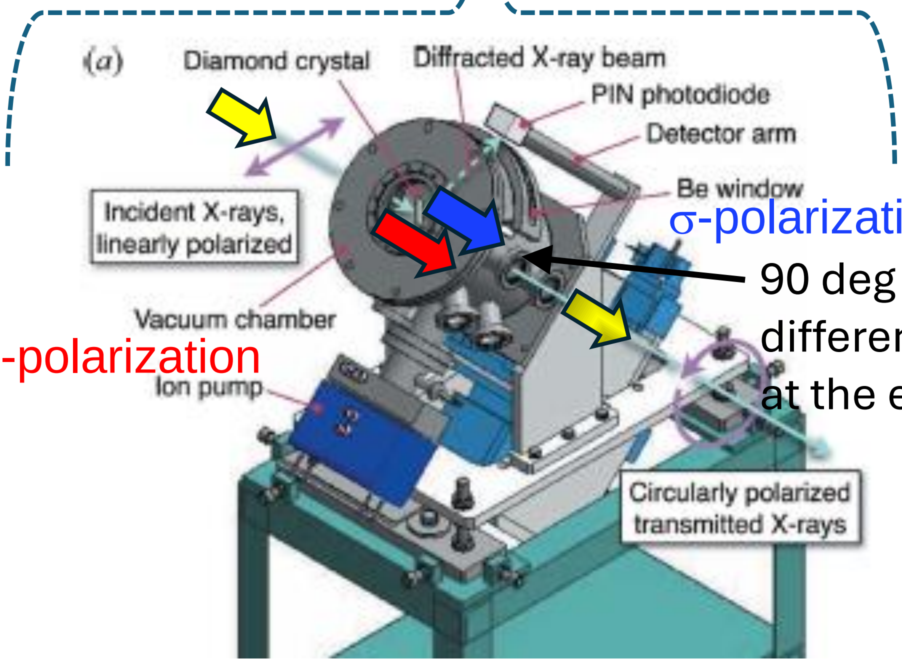
I. Inoue et. al., *Nat. Photon.* **13** (2019) 319-322

Circular-polarization XFEL

XPR(X-ray phase retarder)







σ-polarization

π-polarization

90 deg phase difference at the exit

M. Suzuki et. al., *JSR* **21** (2014) 466-472

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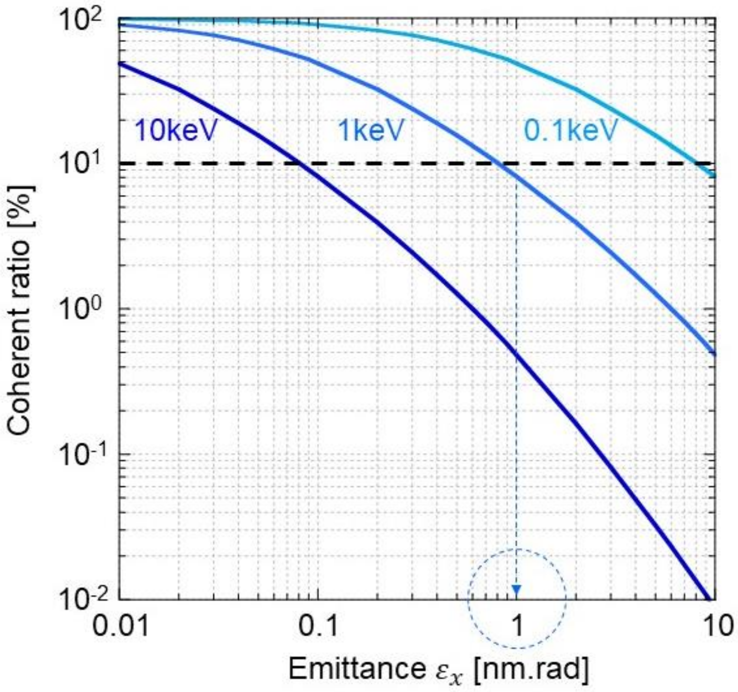
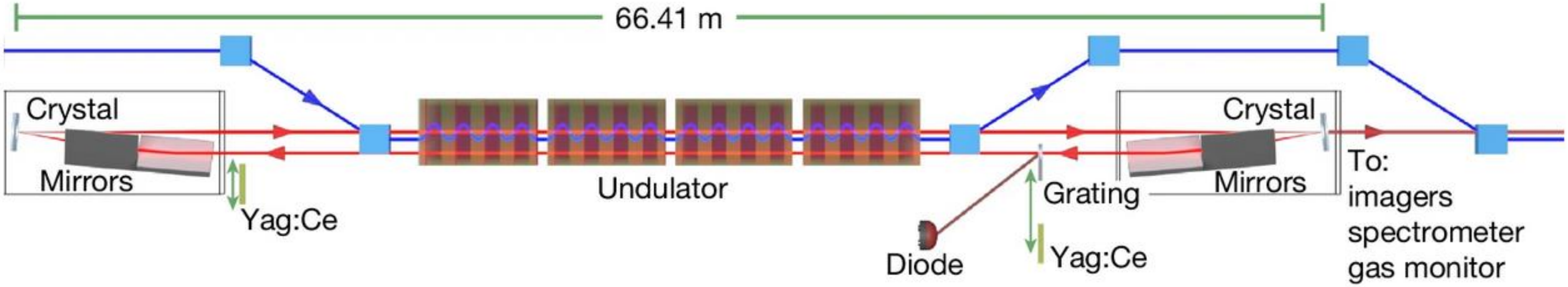
Post diffraction limited SR
- Longitudinally coherent x-ray generation-

The diffraction limited condition means the X-ray brilliance by undulator radiation is no longer enhanced even when natural emittance is reduced.

To dramatically increase the brilliance, paradigm-shift from “spontaneous radiation” to “longitudinally coherent radiation” is required.



Cavity-based FEL in a diffraction-limited SR



The first proof-of principle Experiment was performed at the SASE1 undulator line of the European XFEL. The X-ray cavity consists of two diamond crystals in Bragg reflection working close to backscattering geometry. The elements in the retro-reflector are aligned such that the beam after reflection returns at a distance of 2.67 mm from the incident beam inside the same vacuum pipe. The downstream retro-reflector unit (on the right) is adjustable to tune the cavity length. The electron beam (blue) is injected from the left using a magnetic chicane, and the X-ray pulse (red) is circulating in the cavity, overlapping with electron bunches that pass the undulator at 2.23 MHz.

Patrick Rauer et. al., *Nature* **650** (2026) 93-96

Towards brilliant atto-second X-ray generation

A frontier of practical “single” atto-second brilliant X-rays remains.

1) Tuesday 19th afternoon: “Attsecond FEL Physics” by Agostino Marinelli (SLAC)
2) Thursday 21st, morning: “Generation of tunable sub-femtosecond XFEL pulses by electron bunch recompression using reverse-energy chirp” by Kenji Yasutome (RIKEN)

Towards brilliant atto-second X-ray generation

A frontier of practical “single” atto-second brilliant X-rays remains.

1) ESASE(Enhanced SASE) scheme

   A. Zholents and W. Fawley, *PRL* 92, 224801 (2004); A. Zholents and G. Penn, *PRAB* 8, 050704 (2005); A. Zholents, *PRAB* 8, 040701 (2005); E. Saladi et. al., *PRAB* 9,050702 (2006); Y. Ding et. al., *PRAB* 12, 060703 (2009); J. Duris et. al., *Nat Photon* 14, 30-36 (2020)

2) Slotted foil scheme

   P. Emma et. al., *PRL* 92, 074801 (2004); A. Marinelli et. al., *APL* 111, 151101 (2017)

3) ESASE seeding scheme **T. Tanaka, *PRL* 110, 084801 (2013)**

4) Hard bunch compression scheme

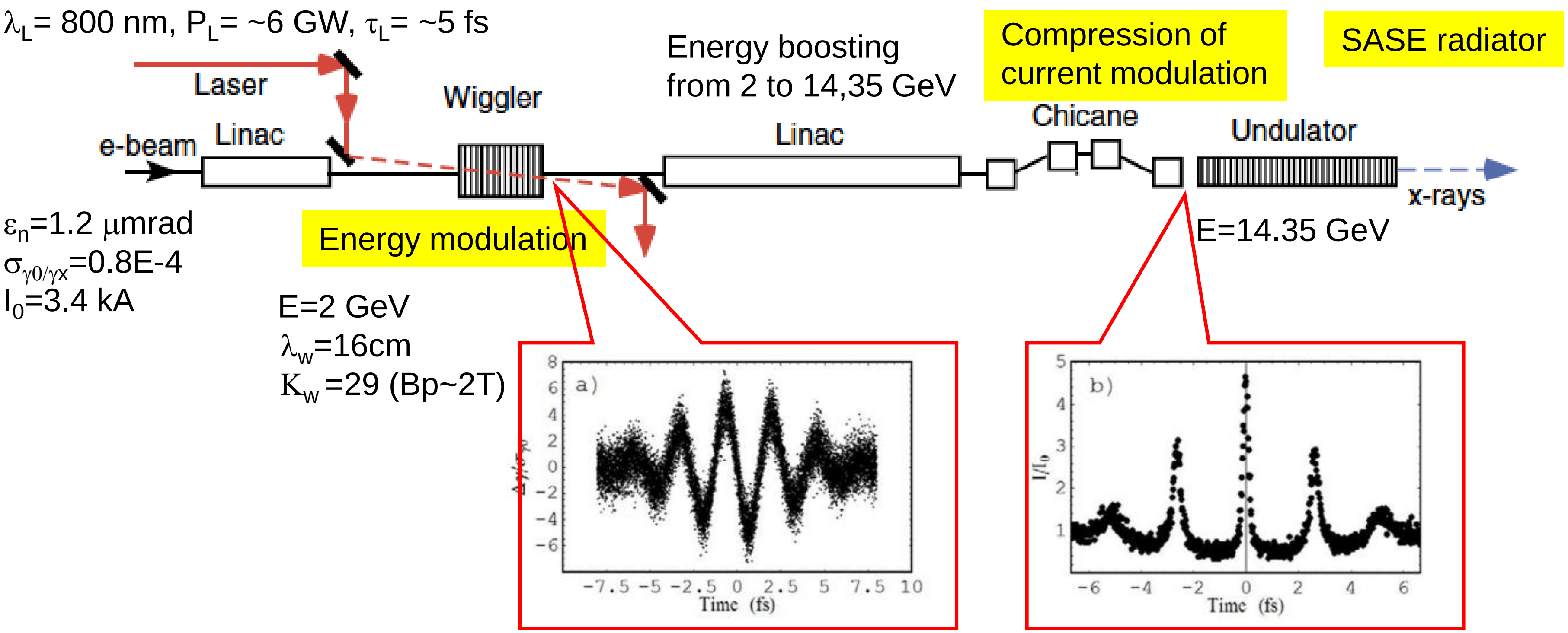
   S. Huang et. al., *PRL* 119, 154801 (2017); E. Prat et. al., *APL Photonics* 8, 111302 (2023); E. Prat et. al., *PRRes* 7, L042060 (2025)

5) Scheme using a reverse-chirp due to a space charge force

   J. Yan et. al., *Nat Photon* 18, 1293-1298 (2024)

6) Scheme using slippage over the undulator **T. Tanaka, *PRL* 114, 044801 (2015)**

ESASE(Enhanced SASE) scheme



λ_L= 800 nm, P_L= ~6 GW, τ_L= ~5 fs

Energy boosting
from 2 to 14,35 GeV

Compression of
current modulation

SASE radiator

Energy modulation

ε_n=1.2 μmrad
$\sigma_{\gamma 0/\gamma x}$=0.8E-4
I_0=3.4 kA

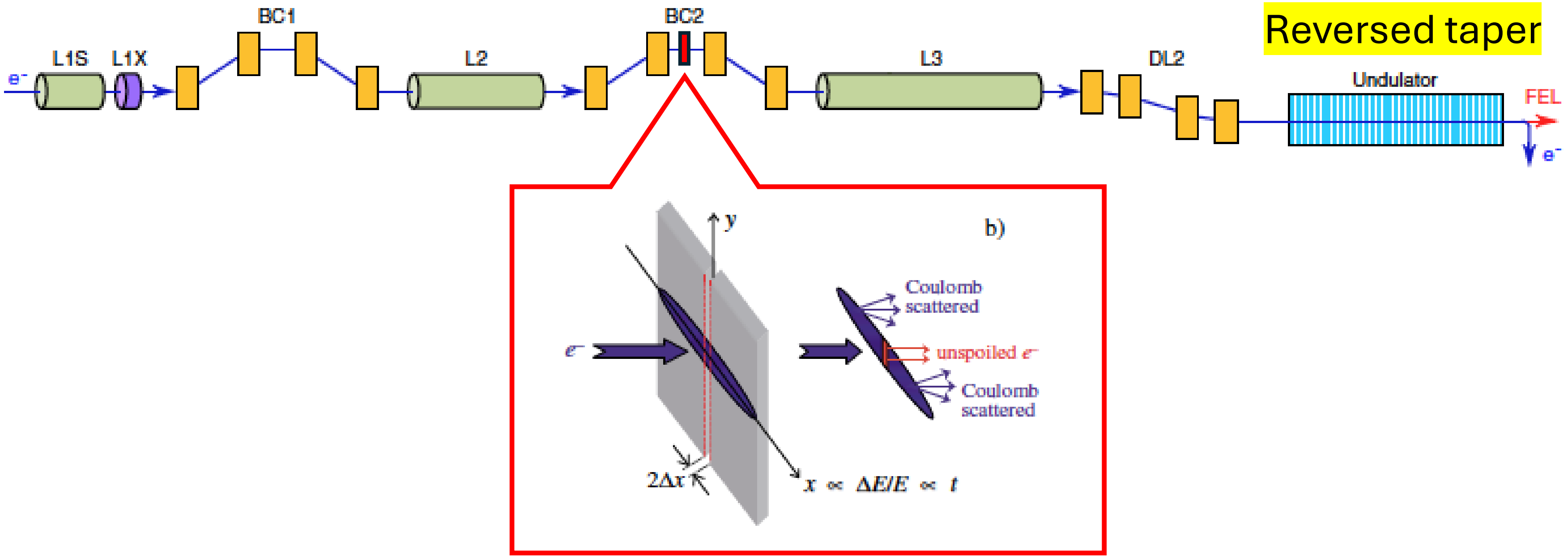
E=2 GeV
λ_w=16cm
K_w =29 (Bp~2T)

E=14.35 GeV

- Energy modulation by a high-power short-pulsed laser at the wiggler section
- Converting the energy modulation to the density modulation at the chicane with help of R56(bunch compression)
- Extracting a sub-femtosecond XFEL pulse from the largest current spike

A. Zholents, *PRAB* 8, 040701 (2005).

Slotted foil scheme

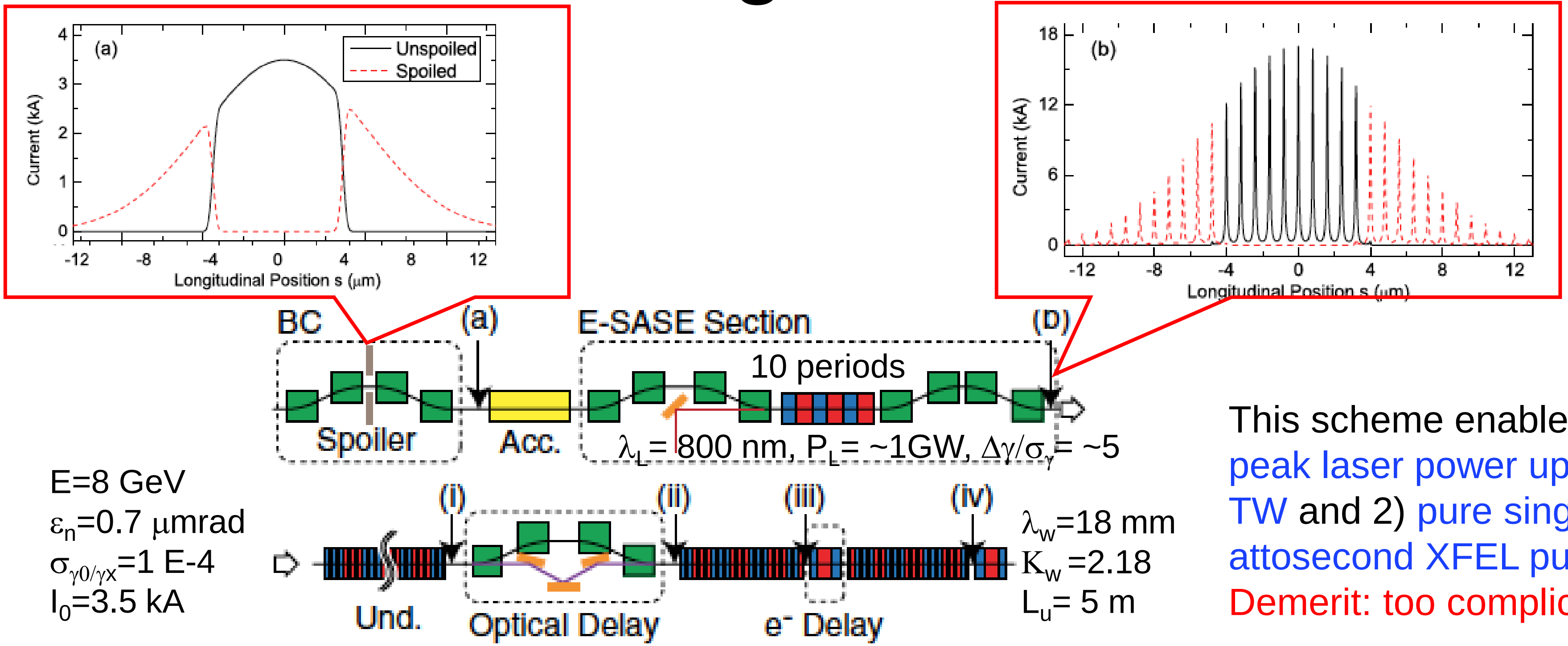


Reversed taper

- Simple scheme
- Control the lasing beam slice into a short pulse duration
- Low electron charge -> difficult to access high peak power

P. Emma et. al., *PRL* 92, 074801 (2004).

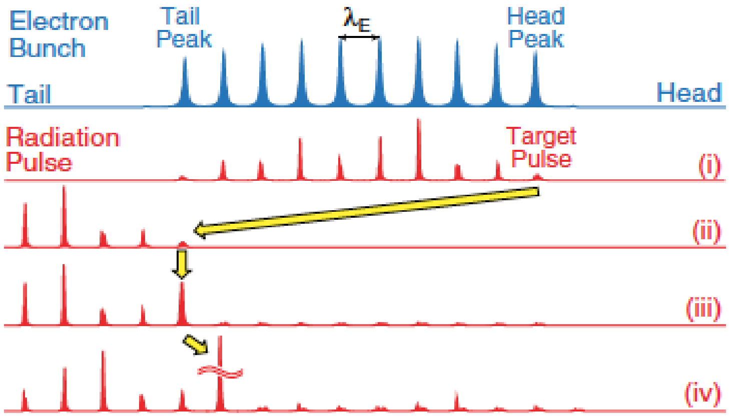
ESASE seeding scheme



E=8 GeV
ε_n=0.7 μmrad
$\sigma_{\gamma 0/\gamma x}$=1 E-4
I_0=3.5 kA

λ_w=18 mm
K_w =2.18
L_u= 5 m

This scheme enables 1) high peak laser power up to several TW and 2) pure single attosecond XFEL pulse
Demerit: too complicated system



Generating a series of electron density spikes by a ESASE process with slotted foil

Generating a seed laser by a undulator radiator

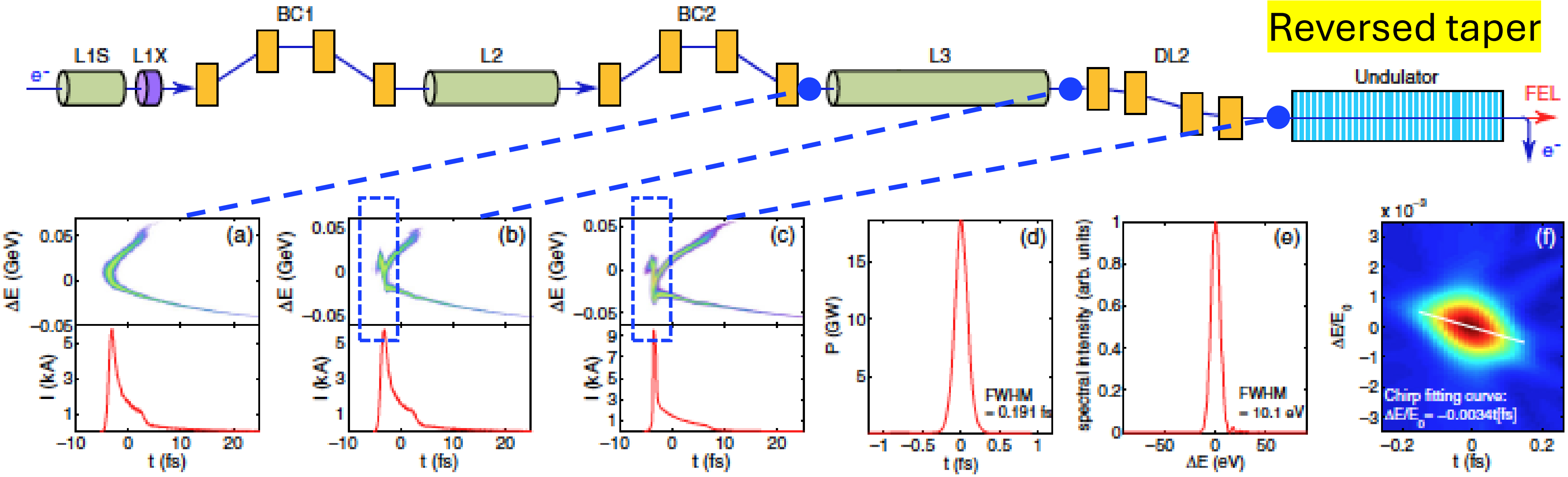
Adjusting seed laser timing to the tail electron peak

Enhancing seed laser intensity

Adjusting the next upstream peak timing to seed laser

T. Tanaka, *PRL* 110, 084801 (2013).

Hard bunch compression scheme



Reversed taper

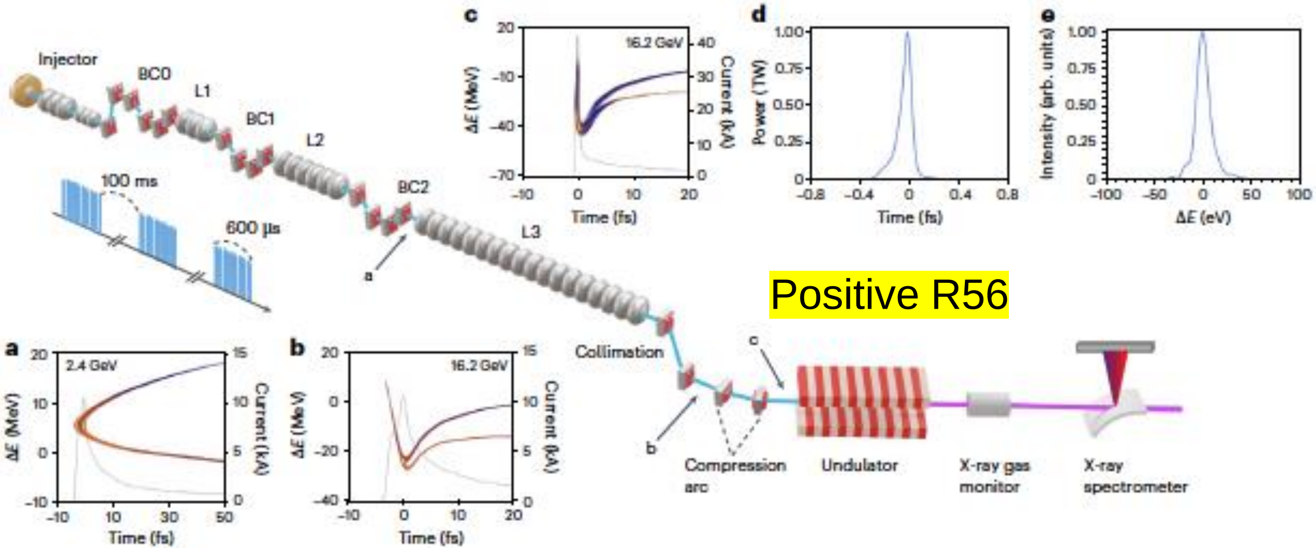
After BC2 L3 exit DL2 exit Simulated attosecond XFEL

- Low charge of 20 pC -> difficult to access high peak power
- Nonlinear hard bunch compression -> peaky peak
- Shortening XFEL pulse by limiting lasing only at the reverse chirp part by using the undulator reverse taper

S. Huang et. al., *PRL* 119, 154801 (2017).

Scheme using a reverse-chirp due to a space charge force

Additional bunch compression with positive R56



Positive R56

Normal energy chirp Reverse energy chirp

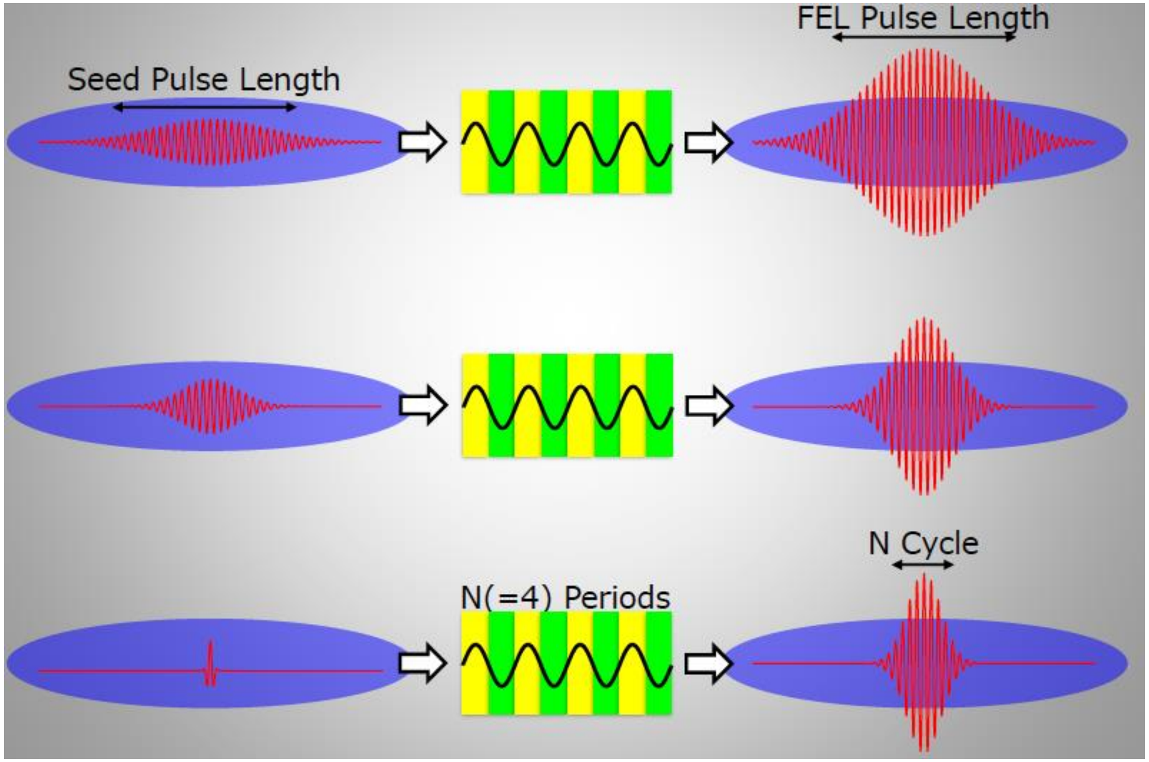
- Self-energy chirp modulation due to SPC -> rather stable operation
- Reverse-energy chirped electron bunch compressed using a positive R56 dogleg
- Small emittance degradation by bunch compression at higher electron energy
- Not optimized dogleg-> difficult accelerator parameter tuning

J. Yan et. al., *Nat Photon* 18, 1293-1298 (2024).

Scheme counteracting the slippage effect towards “single attosecond pulse”

Limit of FEL pulse length determined by a period number of “radiator”

How do we generate a shorter-pulsed, single attosecond FEL?

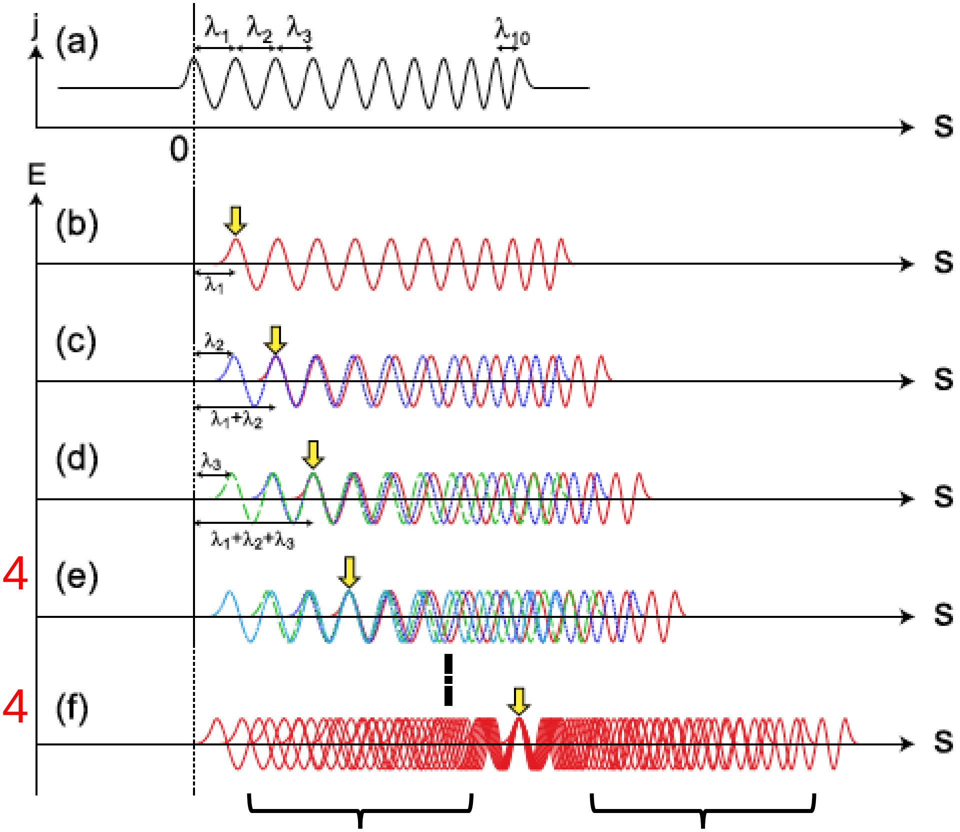


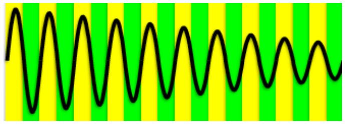
Invited talk(TUZD1) at IPAC2025 given by T. Tanaka.

Scheme counteracting the slippage effect towards “single attosecond pulse”

- Chirped micro-bunching with the separation varied from λ_1 to λ_{10}
- Ten period tapered undulator with the slippage changing from λ_1 to λ_{10}
- Dramatic pulse shortening effect by the phase cancellation

Chirped micro-bunching beam





10 period tapered undulator with slippages of $\lambda_1, \lambda_2, \lambda_3 \ldots \lambda_{10}$

Radiation from #1

Radiation from #1+2

Radiation from #1+2+3

Radiation from #1+2+3+4

Radiation from #1+2+3+4 …..+10

T. Tanaka, *PRL* 114, 044801 (2015).

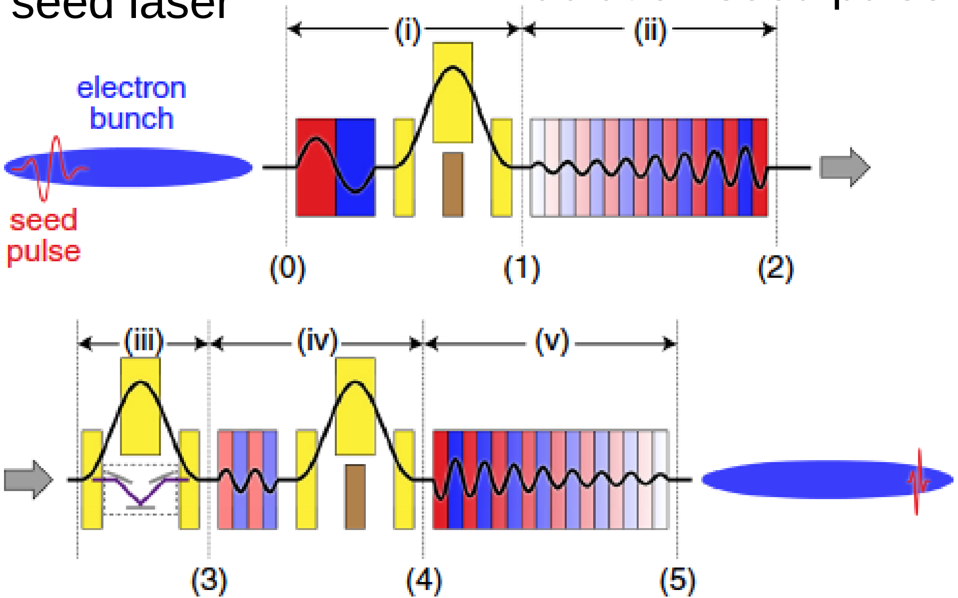
Damped by phase cancellation

Scheme counteracting the slippage effect towards “single attosecond pulse”

Generating single cycle density modulation

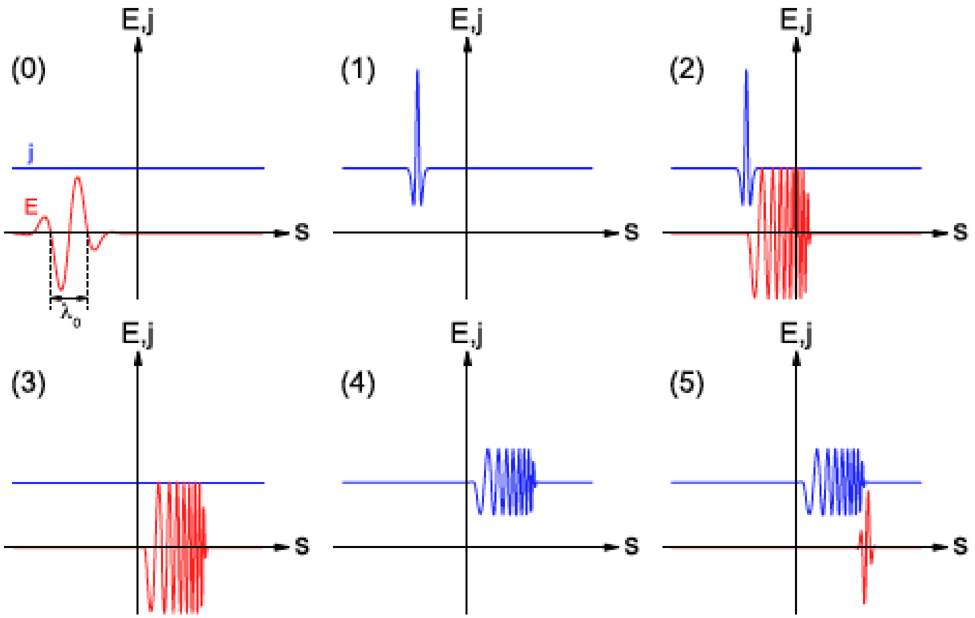
Single cycle seed laser

Generating chirped radiation seed pulse



Converting chirped radiation pulse to chirped micro-bunching

A few cycle short pulsed radiation



T. Tanaka, *PRL* 114, 044801 (2015).