Synchrotron Light Circular Machines & Free-Electron Lasers

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References

This presentation is associated to a written proceedings. References for the content (text and figures) of the presentation are given in the proceedings.

General references:

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Contents

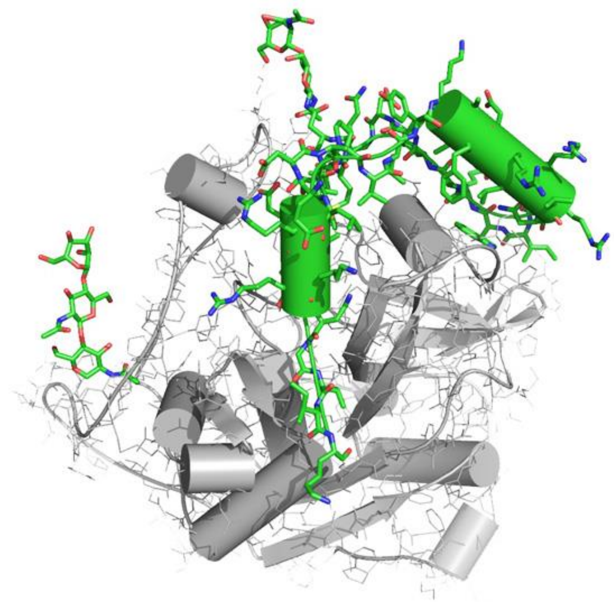
I. Introduction

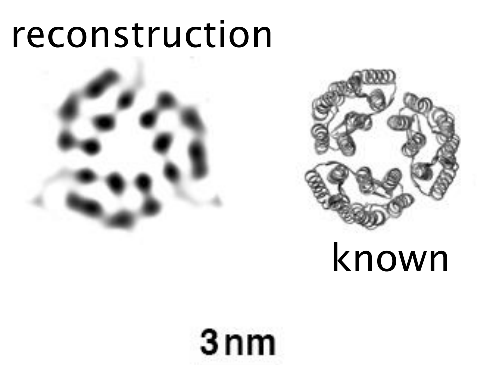
Overview

- Synchrotron light sources and X-ray free-electron laser (FEL) facilities are unique tools providing extremely brilliant X-rays that allow the study of matter with atomic spatial resolution.
- Synchrotron light sources consist of electron circular accelerators and produce synchrotron radiation in bending magnets and undulators.
- X-ray FEL facilities are based on electron linear accelerators and generate more intense and shorter pulses suitable for time-resolved experiments.
- In this presentation we describe synchrotron and X-ray FEL facilities:
  - Fundamental concepts related to synchrotron radiation, undulator radiation and FEL radiation.
  - Synchrotron light machines and X-ray FEL facilities: history and current facilities, typical layout, and electron beam dynamics and properties

Science with light sources

- Synchrotron machines and FELs are unique light sources to probe any kind of matter at atomic scales
- They can address fundamental research questions across the disciplines of physics, chemistry, materials and life sciences.
- Examples:
  - Crystallography to determine structure of biomolecules → discovery of new drugs for challenging diseases
  - Follow the steps of photosynthesis in plants → new energy solutions

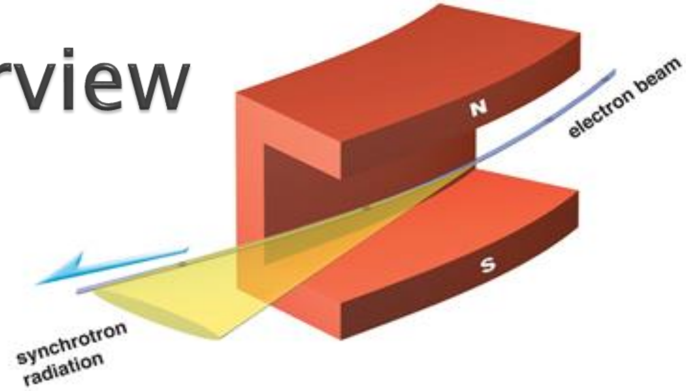




Ref. PNNL, FELs of Europe, European XFEL

II. From synchrotron radiation to FELs. Synchrotron radiation

Synchrotron radiation overview



- Accelerated charged particles emit electromagnetic radiation following Maxwell equations

- In the case of radially accelerated charges, the associated radiation is called **synchrotron radiation.**

- This phenomenon occurs in bending magnets and was first observed in synchrotron facilities, where the beam energy and magnet dipole strengths are ramped up *synchronously* → hence the name "synchrotron radiation"

- The radiated power is proportional to m^{-4} (m: charged particle mass)
  → in practice only relevant for electron machines!

- For electron machines, synchrotron radiation (SR) is boon and bane:
  - SR is the main obstacle for circular machines to reach higher energies
  - But SR (today) is also the main application of circular electron machines and thus the primary motivation to build them!
    → most of recent design work has gone into optimizing SR for experimental and industrial use

    → also the reason why many particle physics laboratories have become photon science laboratories (SLAC, DESY, PSI, Cornell...)

Radiation power of a charged particle

Larmor formula for radiated power (non-relativistic):

$$P = \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0}\left(\frac{d\vec{p}}{dt}\right)^2$$

Relativistic generalization: invariant formulation by changing the momentum $\vec{p}$ with the 4-momentum $P_\mu = (\frac{E_e}{c}, \vec{p})$

We replace $\left(\frac{d\vec{p}}{dt}\right)^2$ with $\left(\frac{dP_\mu}{d\tau}\right)^2 = \left(\frac{d\vec{p}}{d\tau}\right)^2 - \frac{1}{c^2}\left(\frac{dE_e}{d\tau}\right)^2$

with $\tau = \frac{1}{\gamma}t$ the time in the moving system

By doing that we find the radiation power of a charged particle

$$P = \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0}\left[\left(\frac{d\vec{p}}{d\tau}\right)^2 - \frac{1}{c^2}\left(\frac{dE_e}{d\tau}\right)^2\right]$$

Case 1. Linear acceleration

$$\frac{d\vec{p}}{dt'} \parallel \vec{p}$$

$$E_e^2 = m^2c^4 + p^2c^2 \longrightarrow E_e\frac{dE_e}{d\tau} = c^2p\frac{dp}{d\tau} \longrightarrow \frac{dE_e}{d\tau} = v\frac{dp}{d\tau}$$

$$E_e = \gamma mc^2,\ p = \gamma mv \ \rightarrow E_e = pc^2/v$$

We use this in the expression of power from the previous slide:

$$P = \left(\frac{e}{mc^2}\right)^2\frac{c}{6\pi\varepsilon_0}\left[\left(\frac{dp}{d\tau}\right)^2 - \frac{v^2}{c^2}\left(\frac{dp}{d\tau}\right)^2\right] = \left(\frac{e}{mc^2}\right)^2\frac{c}{6\pi\varepsilon_0}\left(\frac{dp}{d\tau}\right)^2(1-\beta^2)$$

$$= \left(\frac{e}{mc^2}\right)^2\frac{c}{6\pi\varepsilon_0}\left(\frac{dp}{\gamma d\tau}\right)^2 = \left(\frac{e}{mc^2}\right)^2\frac{c}{6\pi\varepsilon_0}\left(\frac{dp}{dt}\right)^2 = \left(\frac{e}{mc^2}\right)^2\frac{c\beta^2}{6\pi\varepsilon_0}\left(\frac{dE_e}{dz}\right)^2$$

$$p = \gamma mv = \gamma m\beta c \ \rightarrow pc = \beta E_e \rightarrow \frac{dp}{dt} = \frac{d(\frac{\beta E_e}{c})}{dt} = \frac{dE_e}{dt}\frac{\beta}{c} = \frac{dE_e}{dz}\beta$$

Example: acceleration with gradient 15 MeV/m: $P = 4\text{x}10^{-17}$ W

The radiation power associated to linear acceleration is negligible!

Case 2. Circular acceleration

$$\frac{d\vec{p}}{dt'} \perp \vec{p}$$

Energy is constant: $\frac{dE}{d\tau} = 0$

Acceleration: $\frac{dp}{dt} = \frac{m\gamma v^2}{R} = \frac{\beta^2 E_e}{R}$

$v = \beta c$

We use this in the expression of power from two slides before:

$$P = \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0} \left(\frac{d\vec{p}}{d\tau}\right)^2 = \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0} \left(\frac{\gamma d\vec{p}}{dt}\right)^2 =$$

$$= \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0} \left(\frac{\gamma\beta^2 E_e}{R}\right)^2 = \left(\frac{e}{mc^2}\right)^2 \frac{c}{6\pi\varepsilon_0} \left(\frac{\beta^2 E_e^2}{Rmc^2}\right)^2$$

$$\longrightarrow \boxed{P = \frac{e^2 c}{6\pi\varepsilon_0} \left(\frac{E_e}{mc^2}\right)^4 \frac{\beta^4}{R^2}}$$

$$P \propto E_e^4 / m^4$$

The radiation power associated to circular acceleration (synchrotron radiation) is not negligible. In fact, it can be used as a powerful tool to investigate matter!

Energy loss per turn

$$U_0 = P t_{turn} = P \frac{2\pi R}{v}$$

If β≈ 1: $$U_0(keV) = \underbrace{10^{33} \frac{e}{3\varepsilon_0}\left(\frac{e}{mc^2}\right)^4}_{} \frac{[E(GeV)]^4}{R(m)}$$

≈ 88.5 (electrons)

≈ 7.8×10^{-12} (protons)

An electron loses ~10^{13} more SR power than a proton → SR sources use electrons and not protons

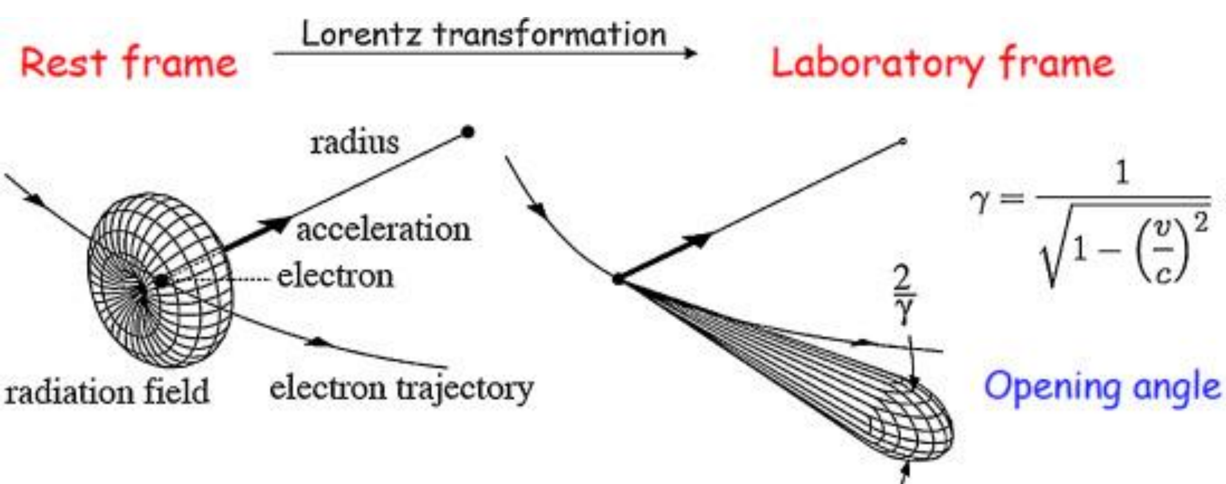
Some Examples:

- **Swiss Light Source (SLS), electrons:**
  - E = 2.4 GeV, R = 5.7 m → U_0 = 515 keV per electron
  - max. current I = 400 mA, $P = U_0 I$ = 206 kW, to be resupplied by RF system!
- **LEP-II, electrons**
  - E = 100 GeV, R = 3026 m, I = 6 mA → U_0 = 2.9 GeV, P = 17.4 MW(!)
- **LHC, protons**
  - E = 7 TeV, R = 2804 m, I = 580 mA → U_0 = 6.6 keV, P = 3.8 kW – *not negligible!*

→ Electron synchrotrons are limited by RF power (that needs to be supplied to compensate energy loss due to SR)

Properties of SR: angular distribution

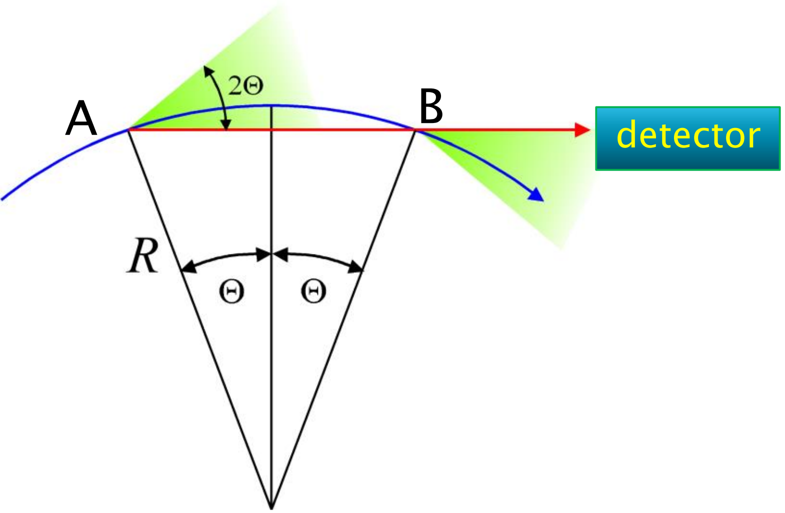
- The particle will emit radiation mostly in the directions perpendicular to acceleration. The radiation emission pattern follows a characteristic donut shape in the rest frame
- Due to the Lorentz transformation from the rest frame to the laboratory system, the donut shape emission is heavily distorted towards forward emission with an opening angle of $1/\gamma$
- Assume photon emitted perpendicular to the direction of acceleration (x) and motion (z). In the rest system: $p_y' = E'/c$
- Lorentz transformation to lab system: $p_y = p_y' \quad p_z = \gamma p_y'$
- Emission angle in the lab frame: $\tan\Theta = \frac{p_y}{p_z} = \frac{1}{\gamma}$



$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0 c^2}$$

Example: ESRF (France): Electron energy 6 GeV ⇒ Θ = 85 μrad, or 1 cm beam spot 60 m from the source point!

Properties of SR: time structure



- From the opening angle we can estimate how long a sample will be illuminated
- The time difference between the first (emitted at A) and the last photon (emitted at B) corresponds to the time delay between electron and photon (from A to B):

$$\Delta t = \frac{2R\Theta}{c\beta} - \frac{2R\sin\Theta}{c}$$

With: $\theta = \frac{1}{\gamma}$, $\sin\Theta \approx \Theta - \frac{\Theta^3}{6}$, $\frac{1}{\beta} = \frac{1}{\sqrt{1-1/\gamma^2}} \approx \frac{1}{1-1/(2\gamma^2)} \approx 1 + \frac{1}{2\gamma^2}$

We get for the **pulse duration** $\Delta t \approx \frac{4R}{3c\gamma^3}$

- Typical photon frequency: $\nu_{\text{typ}} = \frac{1}{\Delta t}$
- **Typical photon energy:** $E_{\text{typ}} = h\nu_{\text{typ}} \approx \frac{3ch}{4R}\gamma^3$

Example: ESRF (France):
Electron energy 6 GeV,
$R = 23$ m $\Rightarrow \Delta t = 6.3\text{e}{-20}$ s,
$E_{\text{typ}} = 65$ keV

Properties of SR: radiation spectrum & critical energy

- The exact radiation spectrum of synchrotron radiation follows a modified Bessel function (first derived by J. Schwinger).

- The **critical energy E_c** divides the spectrum into two halves of equal integrated power. It is related to the typical energy by

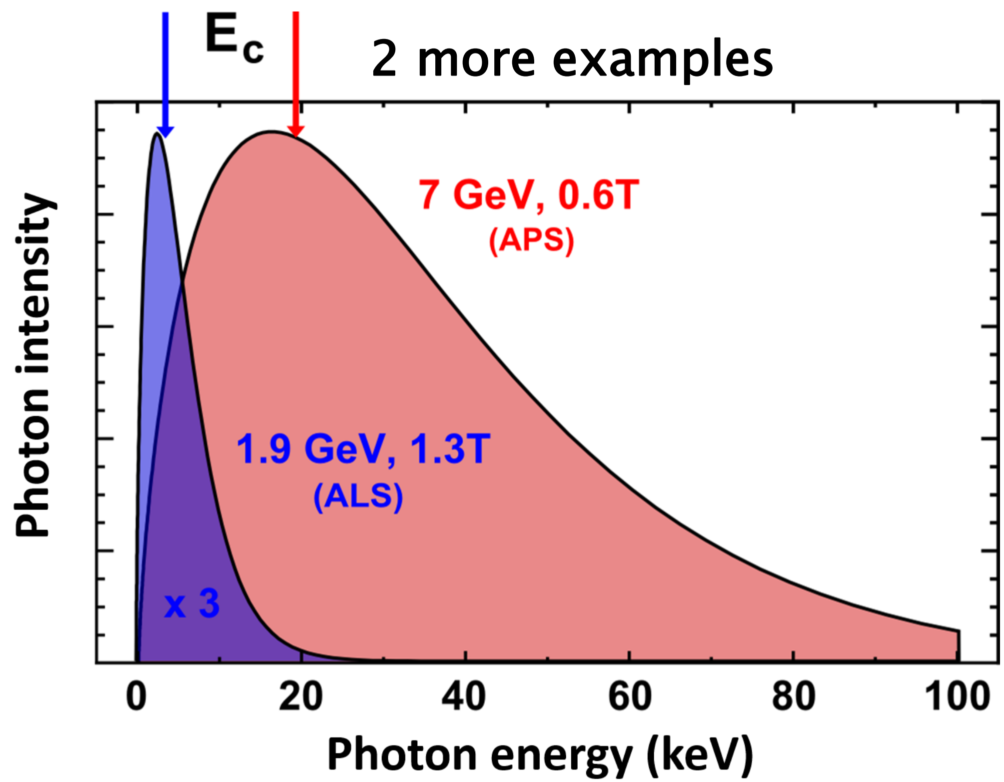
$$E_c = \frac{E_{typ}}{\pi} \approx \frac{3c\hbar}{2R}\gamma^3$$

- A practical formula is:

$$E_c\,(\text{keV}) = 0.665\; B\,(\text{T})\; E_e^{\,2}\,(\text{GeV})$$

The higher the electron energy → the higher the photon energy

Example: ESRF (France):
Electron energy 6 GeV, $B = 0.86$ T
$\Rightarrow E_c = 21$ keV $(= E_{typ}/\pi)$

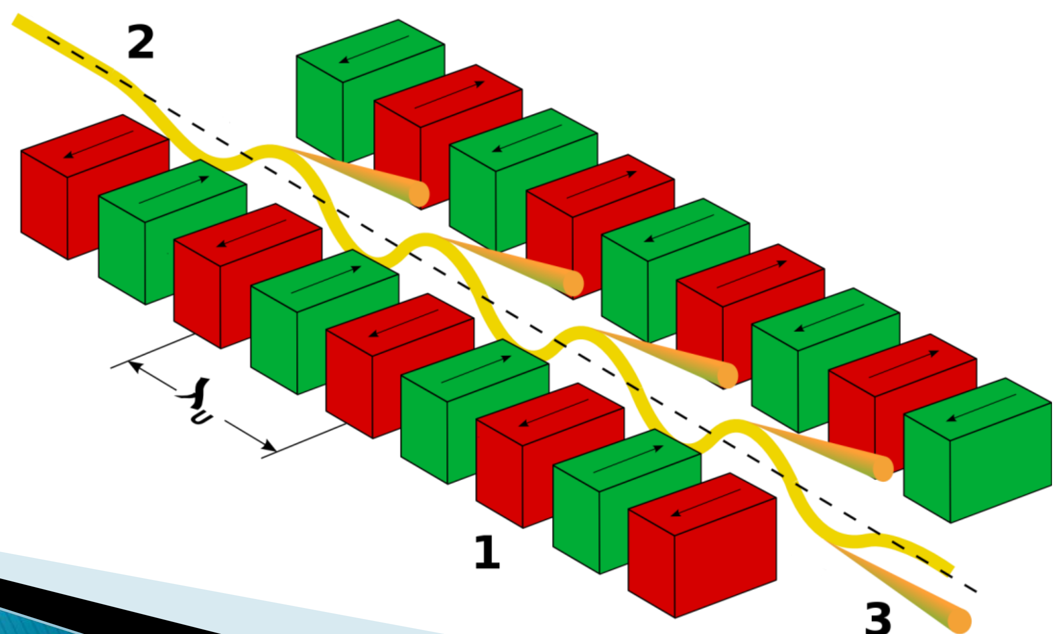


SR spectrum has a broad bandwidth !

II. From synchrotron radiation to FELs. Undulator radiation

Undulator radiation

- Undulators are periodic structures of dipole magnets with alternating polarity. An undulator is defined by the number of bending magnets N and the period λ_u (with typical values of few cms)
- The radiation emitted in undulators has higher power and better quality than the radiation emitted in an individual bending magnet.
- A main advantage: the deflection alternates so that the global electron trajectory is straight (in contrast to the curved trajectory in bending magnets) → increase of the radiation flux at the experimental station



Undulator Field

- Transverse magnetic field which switch polarity multiple times, defining the undulator period λ_u

- On-axis field:

Planar Undulator

$$\vec{B} = B_0 \begin{pmatrix} 0 \\ \cos(k_u z) \\ 0 \end{pmatrix}$$

Helical Undulator

$$\vec{B} = B_0 \begin{pmatrix} \cos(k_u z) \\ \sin(k_u z) \\ 0 \end{pmatrix}$$

$$k_u = \frac{2\pi}{\lambda_u}$$

Here we limit ourselves to planar undulators

The field is normally described by the undulator parameter

$$K = \frac{eB_0}{mck_u}$$

K is typically of the order of 1

$$K \approx 0.93 \cdot B_0[\mathrm{T}] \cdot \lambda_u[\mathrm{cm}]$$

Motion in the undulator

- Lorentz Force: $\vec{F} = e \cdot (\vec{v} \times \vec{B})$

Dominant field in y

Dominant motion in z (~$\beta_z c$)

$$F_x = e(-v_z B_y) = -ec\beta_z B_0 \cos(k_u z)$$

$$F_x = \frac{d}{dt} p_x = \gamma mc \frac{d}{dt} \beta_x$$

From these 2 equations and after some algebra the transverse and longitudinal motion of the electrons can be derived

Transverse

$$\beta_x = -\frac{K}{\gamma} \sin(k_u z)$$

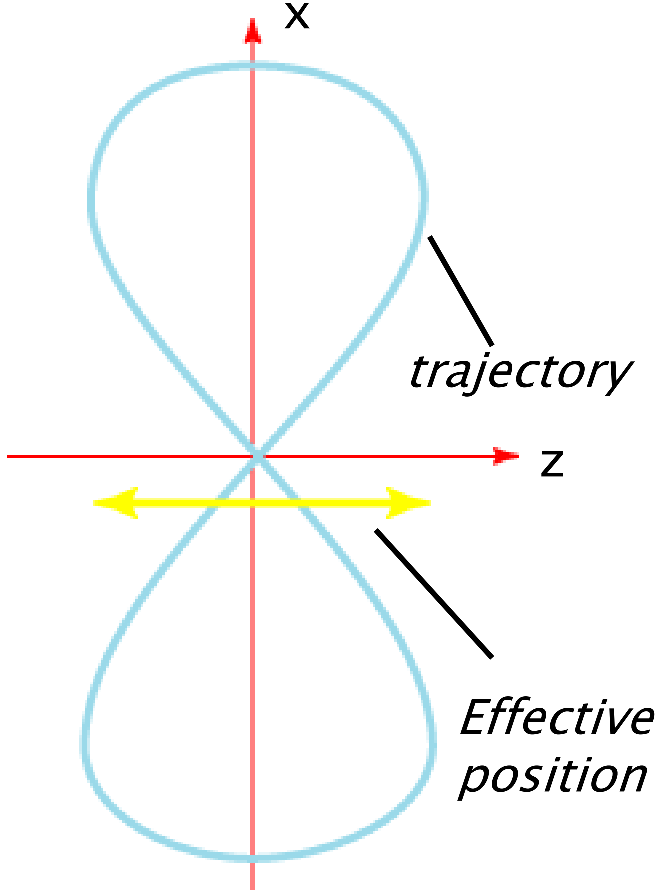
Longitudinal

$$\beta_z = \langle \beta_z \rangle + \frac{K^2}{4\gamma^2} \cos(2k_u z)$$

Average over one period

$$\langle \beta_z \rangle = 1 - \frac{1 + K^2/2}{2\gamma^2}$$

In the Co-moving frame



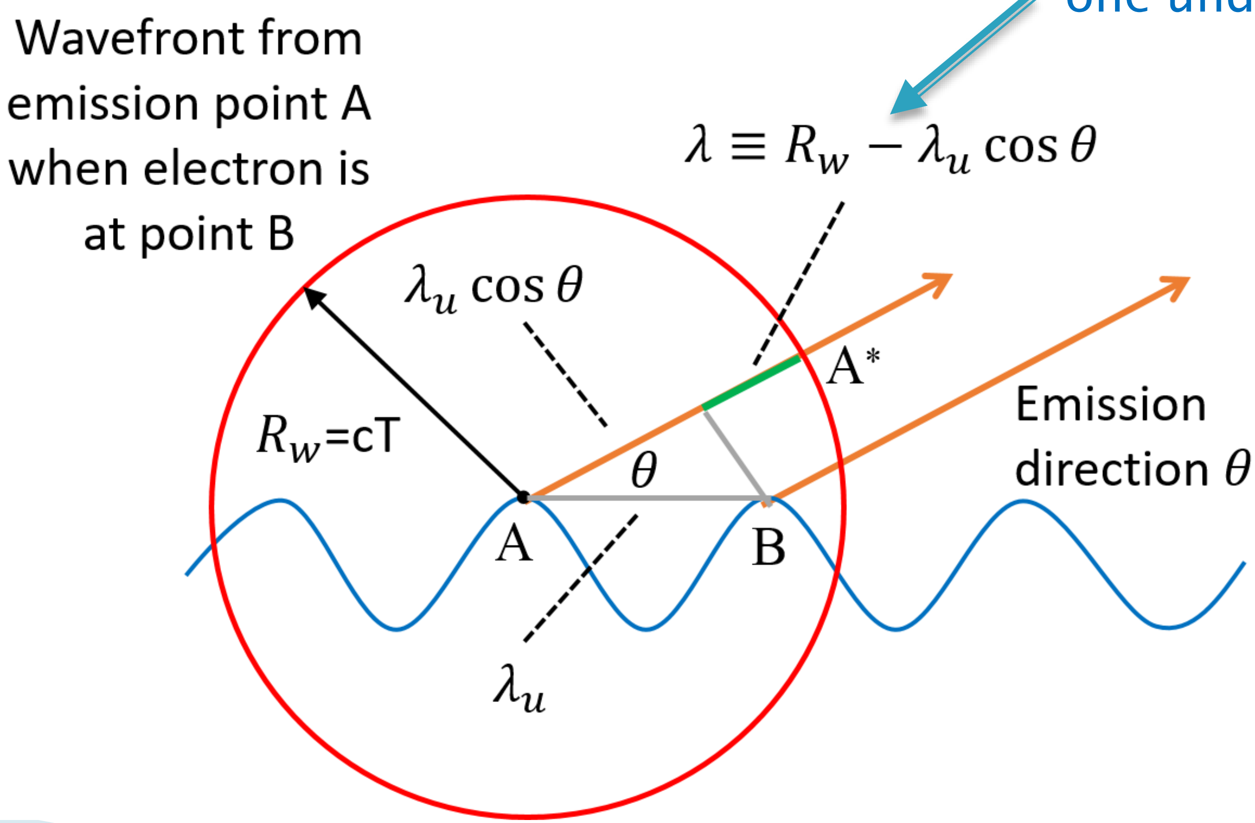
- Longitudinal wiggle has twice the period.
- Causes a figure "8" motion in the co-moving frame.

In a helical undulator the longitudinal motion is constant

Resonance Condition (I)

Condition to have a constructive interference between the radiation emitted by the same electron at different undulator positions

The electron must slip back by exactly one radiation wavelength (or a multiple n) over one undulator period



Resonance Condition (II)

$$n\lambda = R_w - \lambda_u \cos\theta$$

$$\frac{1}{1-x} = 1 + x + x^2 + \dots$$

$$1)\ R_w = cT = c\frac{\lambda_u}{\langle\beta_z\rangle c} = \frac{\lambda_u}{\langle\beta_z\rangle} = \lambda_u \frac{1}{1-\frac{1+K^2/2}{2\gamma^2}} \approx \lambda_u\left(1+\frac{1+K^2/2}{2\gamma^2}\right)$$

$$\langle\beta_z\rangle = 1 - \frac{1+K^2/2}{2\gamma^2}$$

For small angles

$$2)\ \lambda_u \cos\theta \approx \lambda_u\left(1-\frac{\theta^2}{2}\right)$$

$$\cos(x) = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \dots$$

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

Wavelength increases with emission direction θ

In the forward direction ($\theta=0$) we obtain the so-called resonance condition

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

The Resonant Wavelength

- The radiation wavelength is much shorter than undulator wavelength (γ^2 factor)

- The wavelength can be controlled by
  - **Changing the electron beam energy,**
  - **Varying the magnetic field** (requires K significantly larger than 1)

- Example (SwissFEL): an undulator period of 15 mm, a K-value of 1.2 and an energy of 5.8 GeV (γ=11000) would give 1 Å radiation

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

Undulators & wigglers. Introduction

- Historically, periodic structures of dipoles with alternating polarity were called either undulators or wigglers, depending on their field strength:
  - $K > 1$ (large deflections): **wigglers**
  - $K < 1$ (small deflections): **undulators**

- The consistency with which the dipoles could be manufactured was still limited at that time. The relatively poor achievable field quality had only a limited effect at small fields ($K < 1$) whereas it mattered a lot at larger field strengths ($K > 1$).

- Nowadays modern fabrication techniques provide sufficient field quality even for large K values, and the distinction no longer makes sense.

- The two types of devices, undulators and wigglers, are collectively called insertion devices (ID).

Undulators & wigglers. Spectrum

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

$E_c\,(\text{keV}) = 0.665\ B\,(\text{T})\ E_e^{\ 2}\,(\text{GeV})$

- Harmonic content of the undulator radiation depends on K (or B):
  - K~1: spectral output confined to a few harmonic lines, with peaks at the harmonics of the resonant frequency.
  - K>1: harmonic content increases.
  - The effective cutoff for the harmonic generation is given by the critical energy of the dipoles.

- An electron will create a radiation pulse with length equal to Nλ (because of the slippage). Due to the longer pulse, the spectral width will decrease proportionally to the number of periods.

$$\frac{\Delta\lambda}{\lambda} \approx \frac{1}{nN}$$

For instance, 1% bandwidth at the fundamental wavelength (n=1) for 100 periods

Undulators & wigglers. Spectrum with errors

- In practice, the bandwidth is limited by the intrinsic broadening due to the field quality. From the resonance condition, the relative bandwidth associated to a variation in undulator field (substitute K by $\Delta K + K$)

$$\frac{\Delta\lambda}{\lambda} \approx \frac{2\Delta K K}{2 + K^2}$$

- For large Ks $\frac{\Delta\lambda}{\lambda} \approx \frac{2\Delta K}{K}$ For small Ks $\frac{\Delta\lambda}{\lambda} \approx \frac{K^2\Delta K}{K}$

- We can now understand the historical distinction between undulators (K $<$ 1) and wigglers (K $>$ 1), since the former could provide smaller bandwidth broadening with the same relative field error $\frac{\Delta K}{K}$

Undulators & wigglers. Spectral power

Without field errors $\frac{\Delta\lambda}{\lambda} \approx \frac{1}{nN}$ With errors $\frac{\Delta\lambda}{\lambda} \approx \frac{2\Delta K K}{2 + K^2}$

- **Because of the bandwidth reduction and the increase in radiated power, both proportional to the number of bending magnets N, the spectral power in an undulator will increase as N^2 compared to a bending magnet**

- This is true as long as the bandwidth is not limited by field errors. In this case, the spectral power will only increase proportionally to N.

- Again, this was historically one of the main reasons to distinguish between:
  - wigglers ($K > 1$): spectral power proportional to N
  - undulators ($K < 1$): spectral power proportional to N^2

Undulators & wigglers. Coherence angle

- So far we assumed a fixed emission angle.

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

- If we consider all allowed emission angles there will be an effective spectral broadening according to the resonance condition. This can give rise to overlaps in the harmonic content such that the spectrum appears continuous.

- A measure of the acceptable opening angle of the emission to limit this spectral broadening is given by the so-called coherence angle.

- It is found by equating the spectral width due to slippage (and field quality) to the spectral broadening due to off-axis emission given by the resonance condition. Ignoring the field quality effect:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda(\theta_c) - \lambda(0)}{\lambda(0)} \quad \longrightarrow \quad \theta_c = \frac{\sqrt{\frac{\Delta\lambda}{\lambda}(1 + K^2/2)}}{\gamma} \approx \frac{\sqrt{\frac{1}{Nn}(1 + K^2/2)}}{\gamma}$$

Undulators & wigglers. Emission angle

$$\theta_c = \frac{\sqrt{\frac{\Delta\lambda}{\lambda}(1+K^2/2)}}{\gamma} \approx \frac{\sqrt{\frac{1}{Nn}(1+K^2/2)}}{\gamma}$$

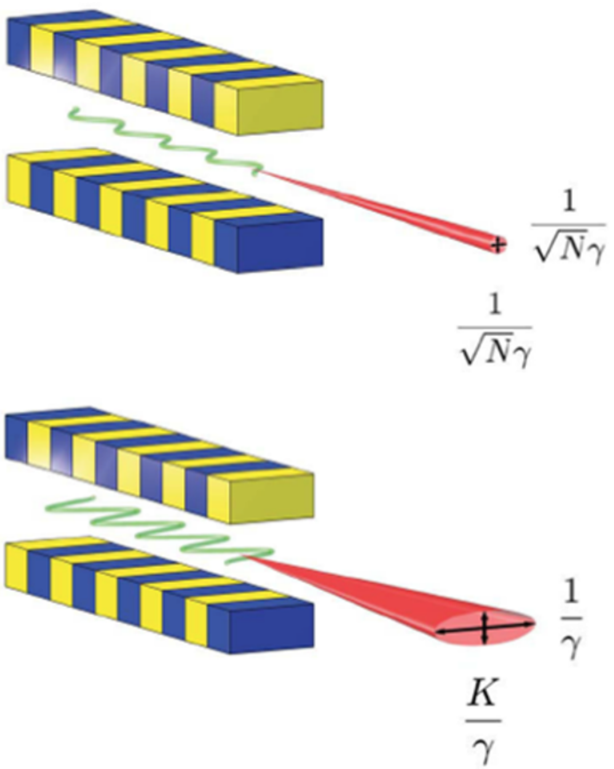
- Undulators: small Ks $\theta_c \approx \frac{1}{\sqrt{Nn}\gamma}$

  The coherence angle for a given frequency is reduced by a factor of $\sqrt{N}$ with respect to the opening angle of bending-magnet radiation

- Wigglers: large Ks and large field errors ($\Delta\lambda/\lambda \sim 1$) $\theta_c \approx \frac{K}{\gamma}$

  The coherence angle is the general opening angle times K. Unlike in the above undulator case and like a dipole magnet, all frequencies are produced at all emission angles

Undulators & wigglers. Summary



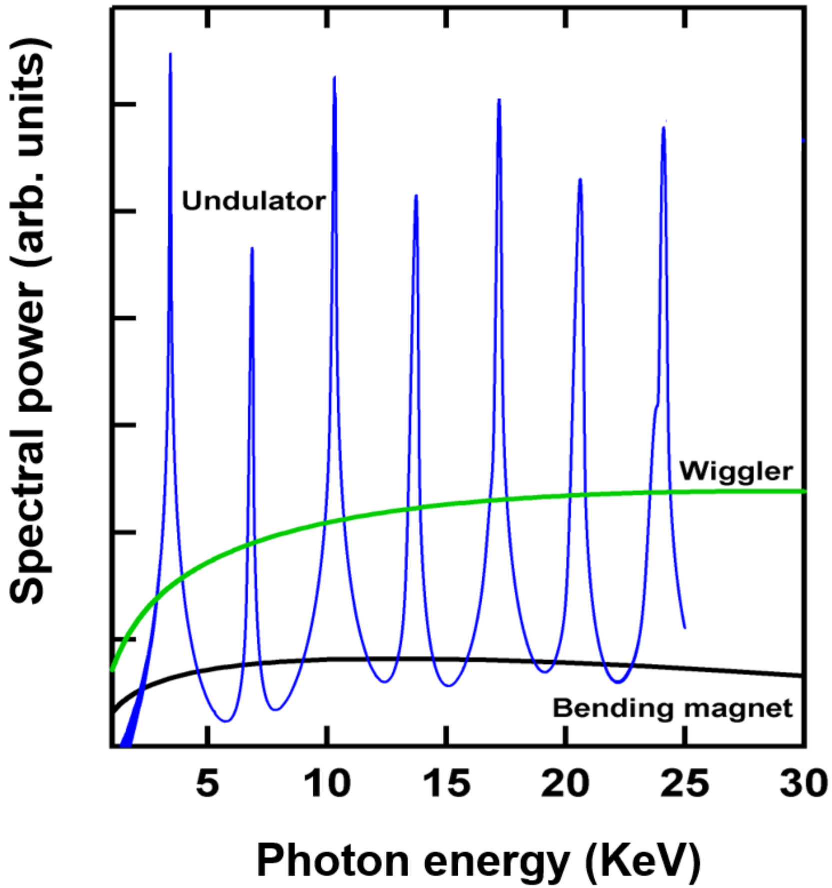
Undulator

K<1

Wiggler

K>1 and large ΔK

Emission cones defined by coherence angles



Undulator: peaks in the spectrum

Wiggler: smooth curve result of overlapping harmonics, including broadenings due to field quality and large emission angles

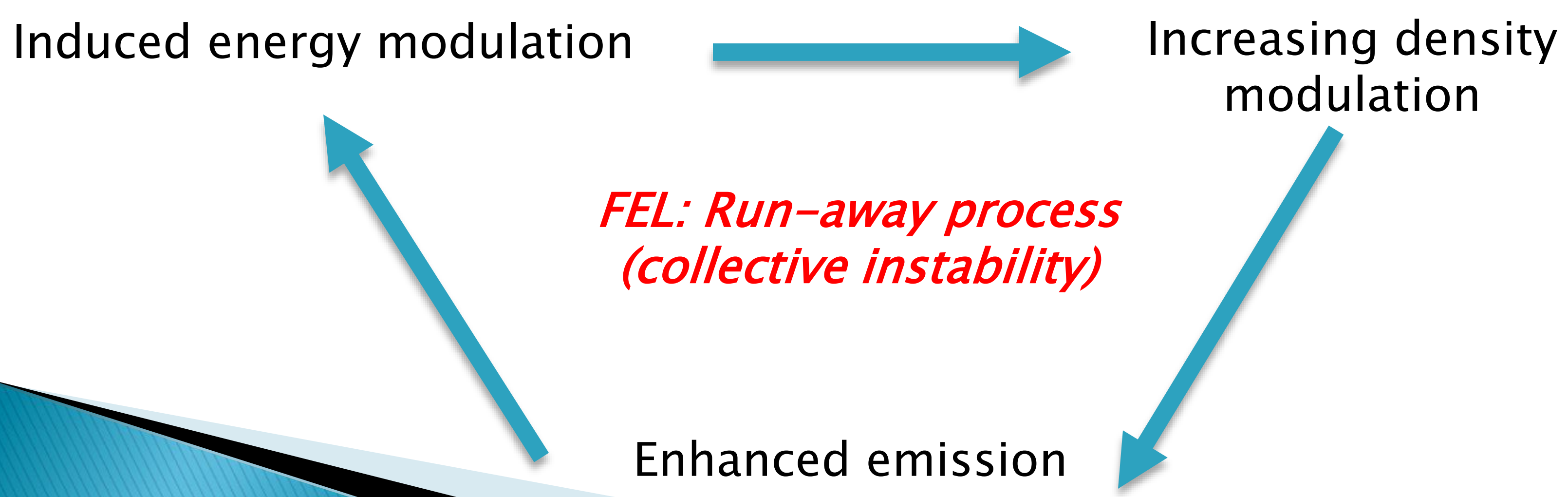
II. From synchrotron radiation to FELs. Free-electron lasers

Introduction

- Having described the synchrotron radiation produced in bending magnets and in undulators, we will now explain how an electron beam traveling through an undulator beamline generates radiation following the free-electron laser (FEL) process.
- In an FEL, there is not only a coherent contribution of the radiation produced in each undulator period, but also a coherent addition of the radiation produced by each electron.
- In this case, the coherence is related to the formation of particle distributions with dimensions smaller than the resonant wavelength (called microbunching).
- Because of this, the radiation power is proportional to the square number of electrons within the cooperation length of the FEL process.
- This implies that FEL radiation power is orders of magnitude higher than the power of standard undulator radiation.

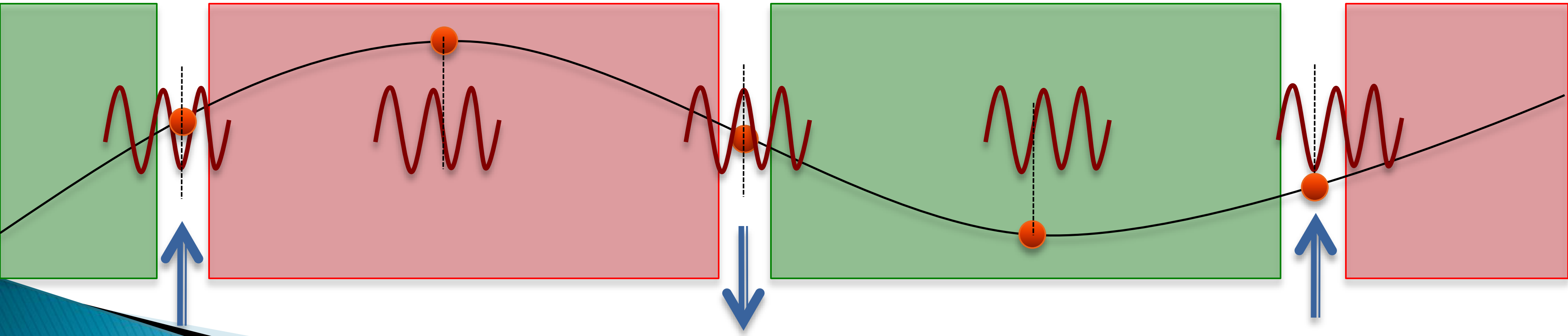
Overview

- The FEL process starts with an initial radiation field (in the standard FEL configuration is associated to the spontaneous undulator radiation produced by the electron beam).
- This field induces an energy modulation to the electron beam with a period equal to the radiation wavelength λ
- The energy modulation is then converted to density modulation (or microbunching), also with a period equal to λ
- This microbunching results into an increase of the emitted radiation, which contributes to enhance the energy modulation, and so on



Coupling between electrons and photons

- The transverse oscillation of the electrons allows the coupling between the electrons and the photons
- The energy transfer is proportional to $\vec{v}_\perp \vec{E}$
- The electron moves either with or against the field line, losing or gaining energy depending on the sign of $\vec{v}_\perp \vec{E}$
- In the resonance condition, the direction of energy transfer remains constant over many periods. For instance, after half undulator period the radiation field has slipped half wavelength, both velocity and field have changed sign and the direction of energy transfer stays the same.



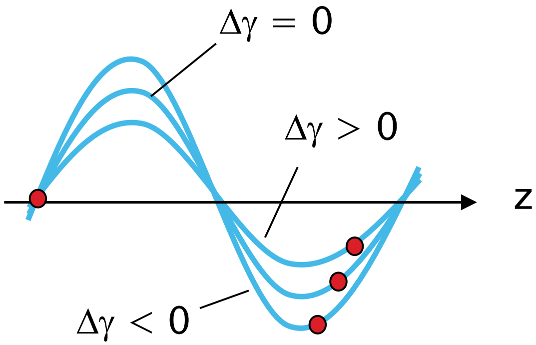
Energy modulation & microbunching

- The energy change of an electron depends on its phase ϕ

$$\frac{d}{dz}\gamma = -\frac{ef_c K E_0}{2\gamma mc^2}\sin\phi$$

f_c: coupling factor (<1)

- Electrons with positive phase loose energy, while electrons with negative phases will gain energy. This will cause an energy modulation of the electron beam
- Electrons gaining energy will move faster, while electrons losing energy will fall back. For small energy deviations:



$$\frac{d}{dz}\phi = 2k_u\frac{\Delta\gamma}{\gamma}$$

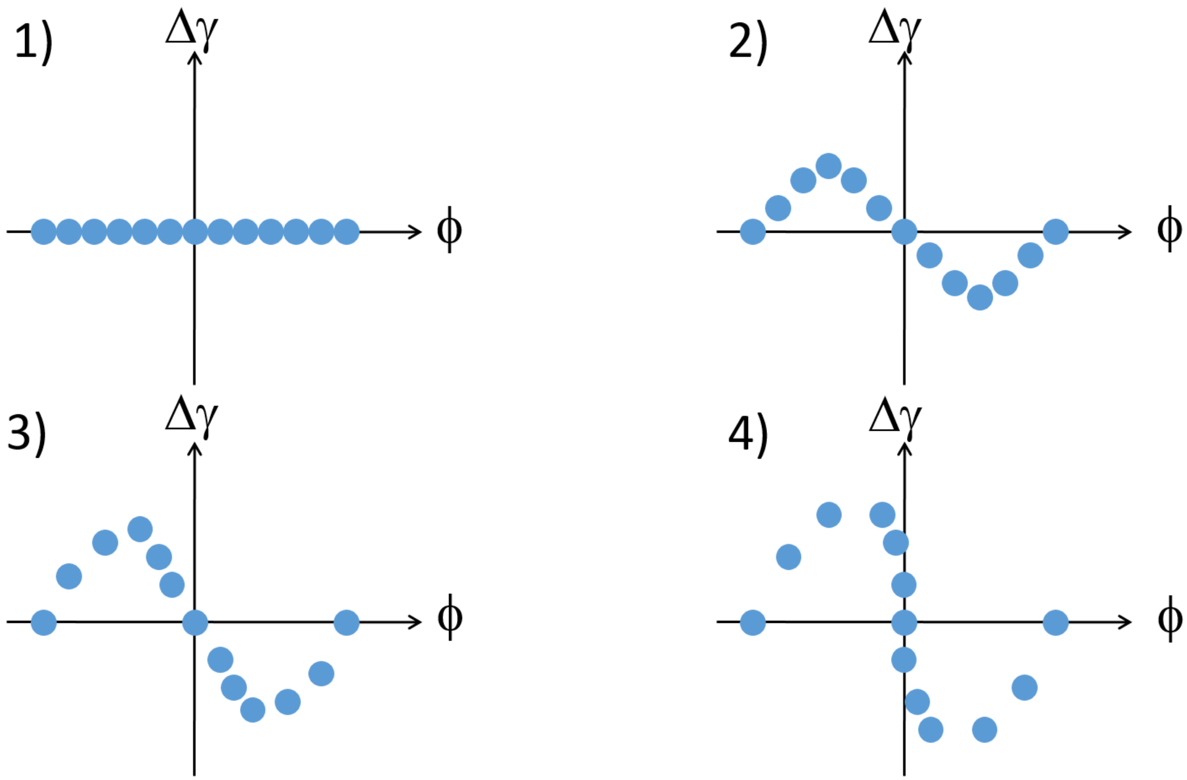
- Because of this effect the electrons move together → density modulation or microbunching

Motion in Phasespace

$$\frac{d}{dz}\gamma = -\frac{ef_c K E_0}{2\gamma mc^2}\sin\phi$$

$$\frac{d}{dz}\phi = 2k_u\frac{\Delta\gamma}{\gamma}$$

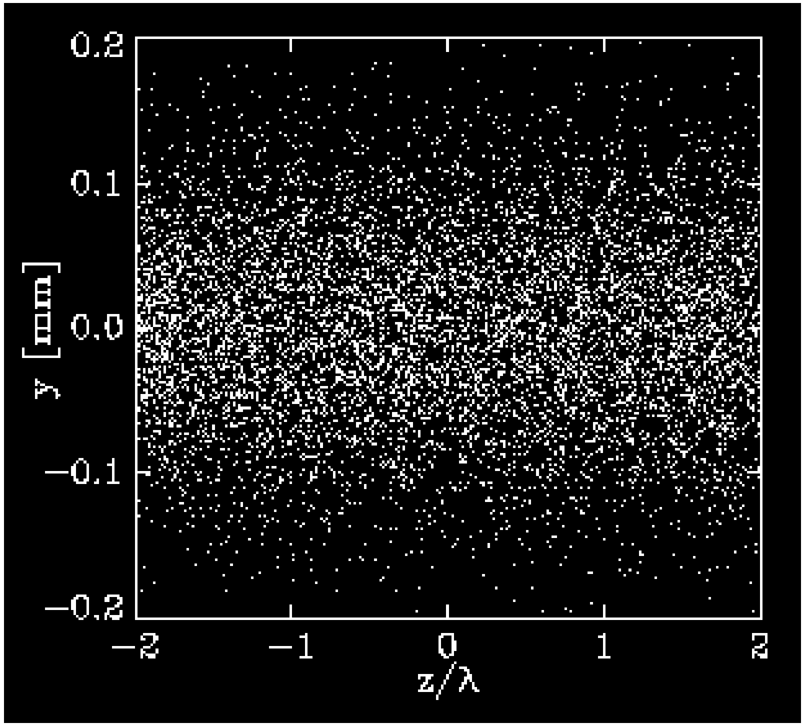
- Wavelength typically much smaller than bunch length.
- Electrons are randomly spread out initially over all phases.



Thanks to microbunching all electrons emit coherently.

Microbunching

Transverse position



Slice of electron bunch (4 wavelengths)

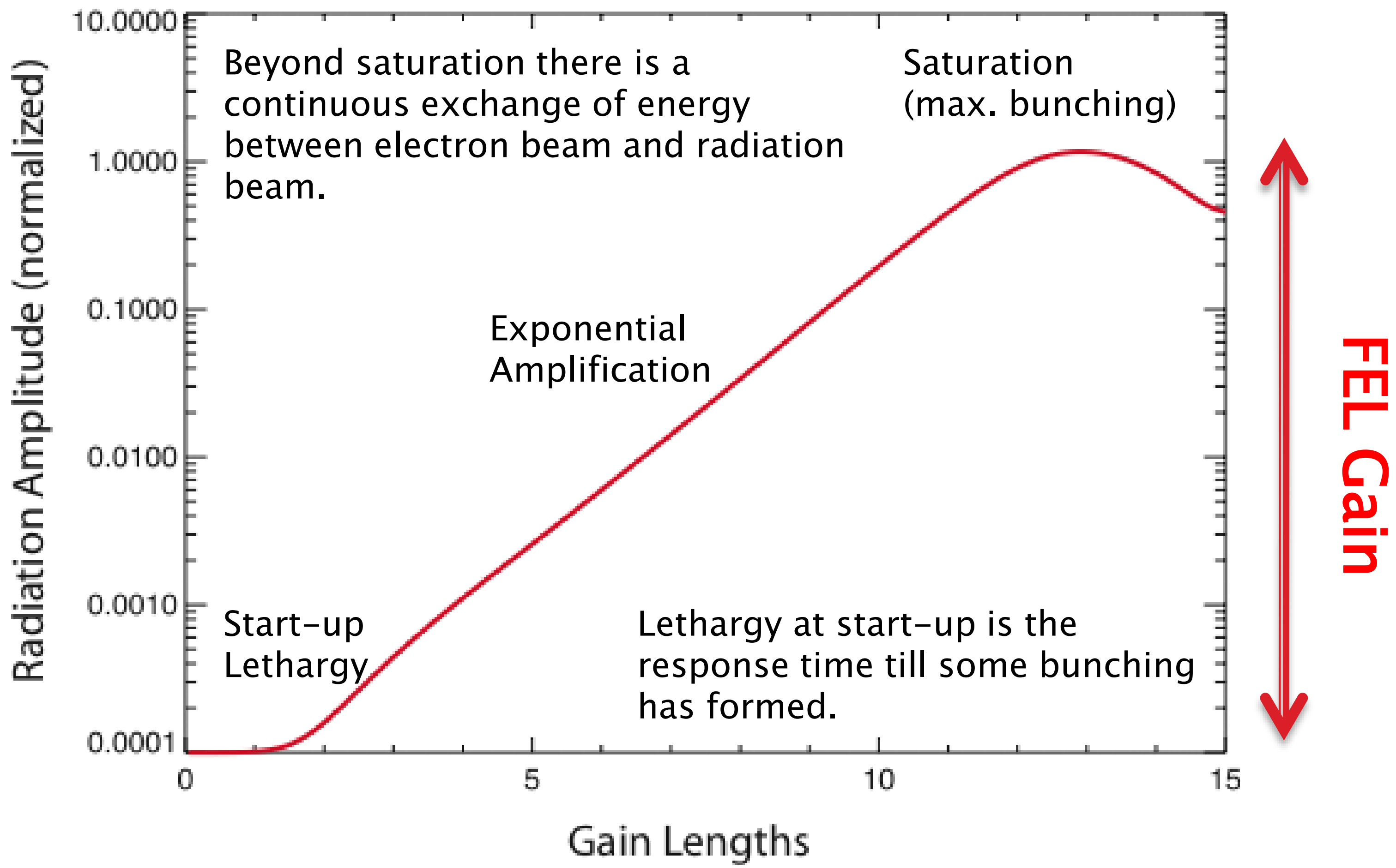
3D Simulation for FLASH FEL over 4 wavelengths

Frame moving with electron beam through 15 m undulator

Wiggle motion is too small to see. The 'breathing' comes from focusing to keep beam small.

Microbunching has periodicity of FEL wavelength. All electrons emit coherently.

The Generic Amplification Process



Gain length (L_g): distance so that the power gets multiplied by a factor of e (in exponential regime)

FEL Modes

- SASE FEL (Self-Amplified Spontaneous Emission)

Spontaneous emission (shot noise)
is a broadband seed of “white noise”

- FEL Amplifier (starts with an input signal)

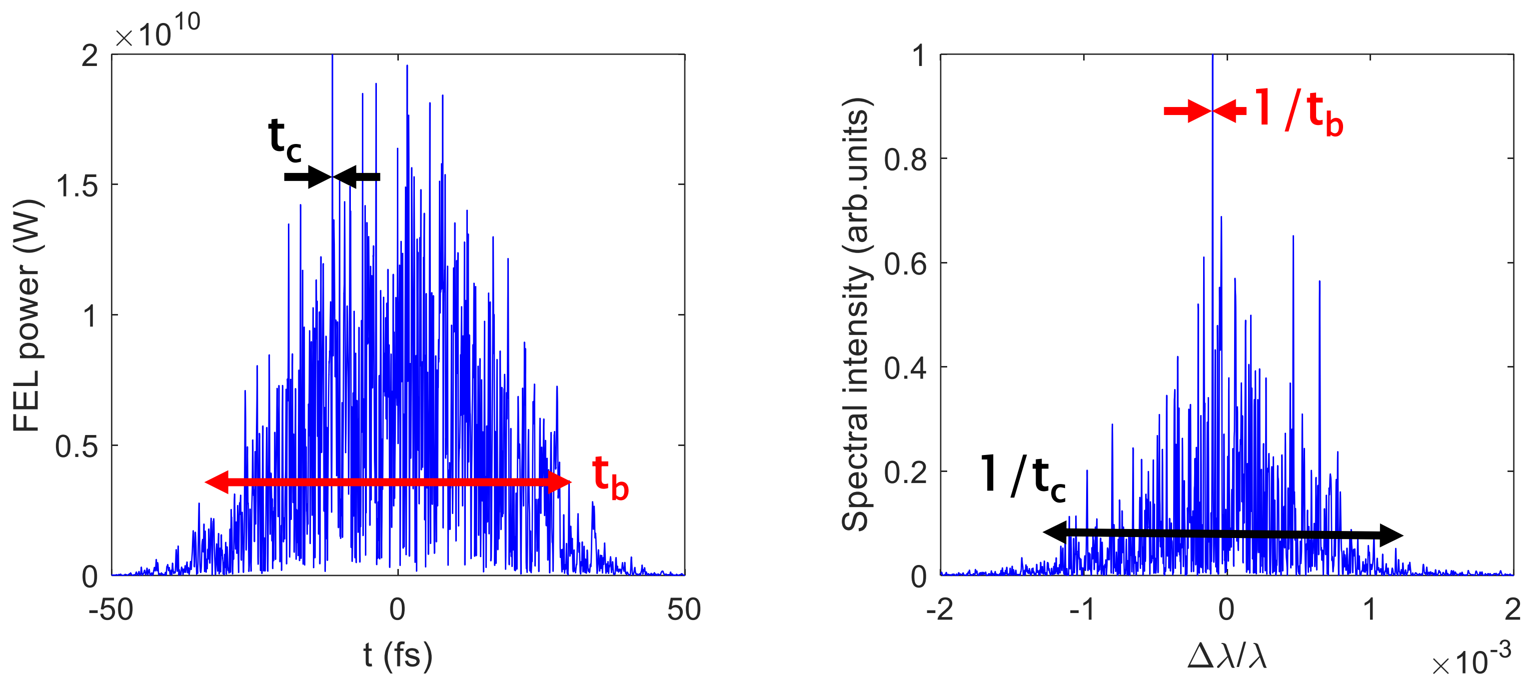
Seed must be above shot noise power (~kW for X-rays).
Output resembles the characteristics of the seed

Most FEL facilities are based on the
SASE process due to its simplicity

SASE FELs

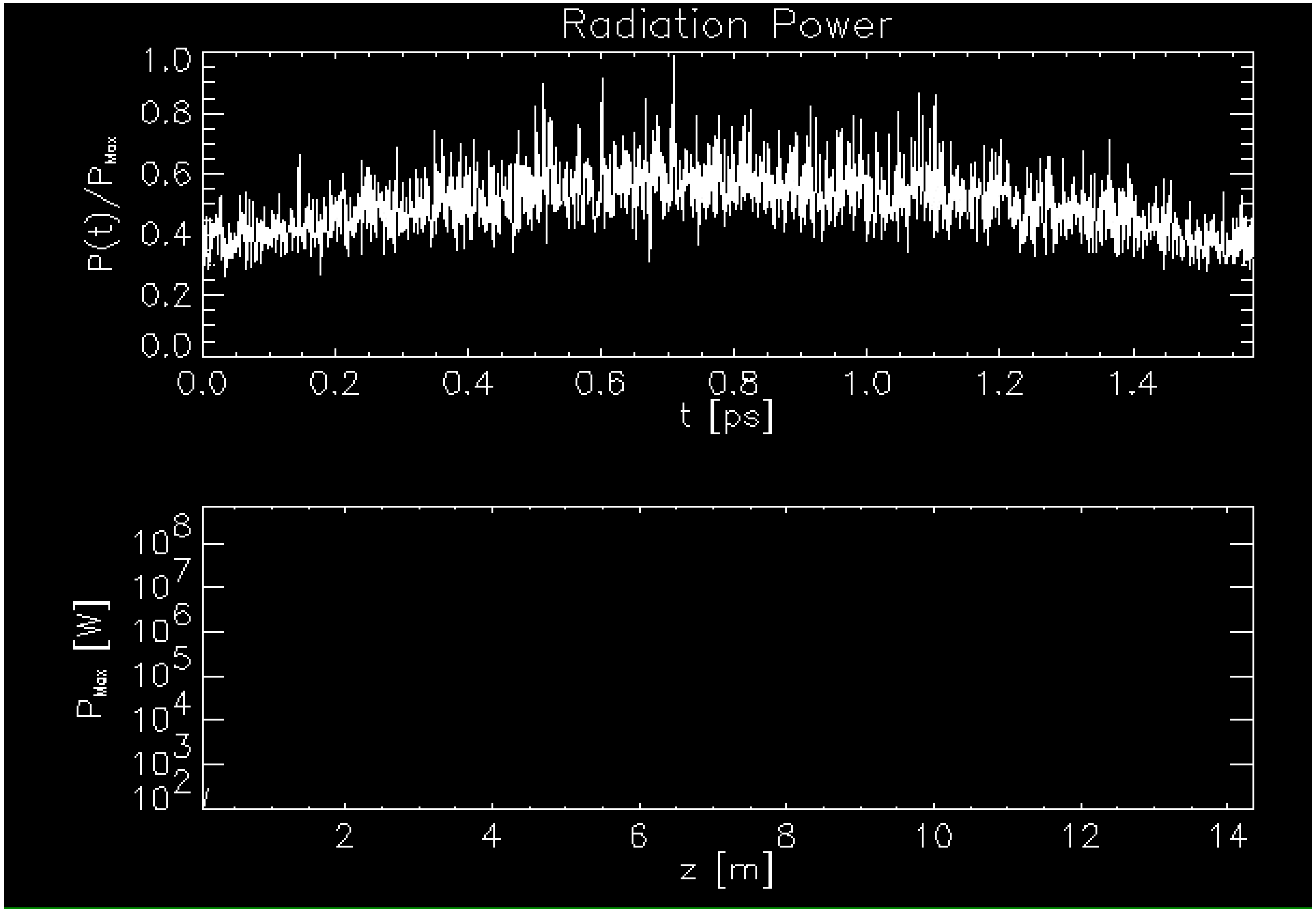
- FEL starts with the broadband signal of spontaneous radiation (almost a white noise signal)
- SASE-FEL radiation is coherent in the transverse direction but not in the longitudinal one → spikes in spectrum and time profile.
- The FEL bandwidth is of the order of the FEL parameter (see later)

SwissFEL simulation for 0.1 nm radiation



- Spike width in time corresponds to full spectral width
- Full pulse duration corresponds to spike width in spectrum

Typical Growth of SASE Pulse

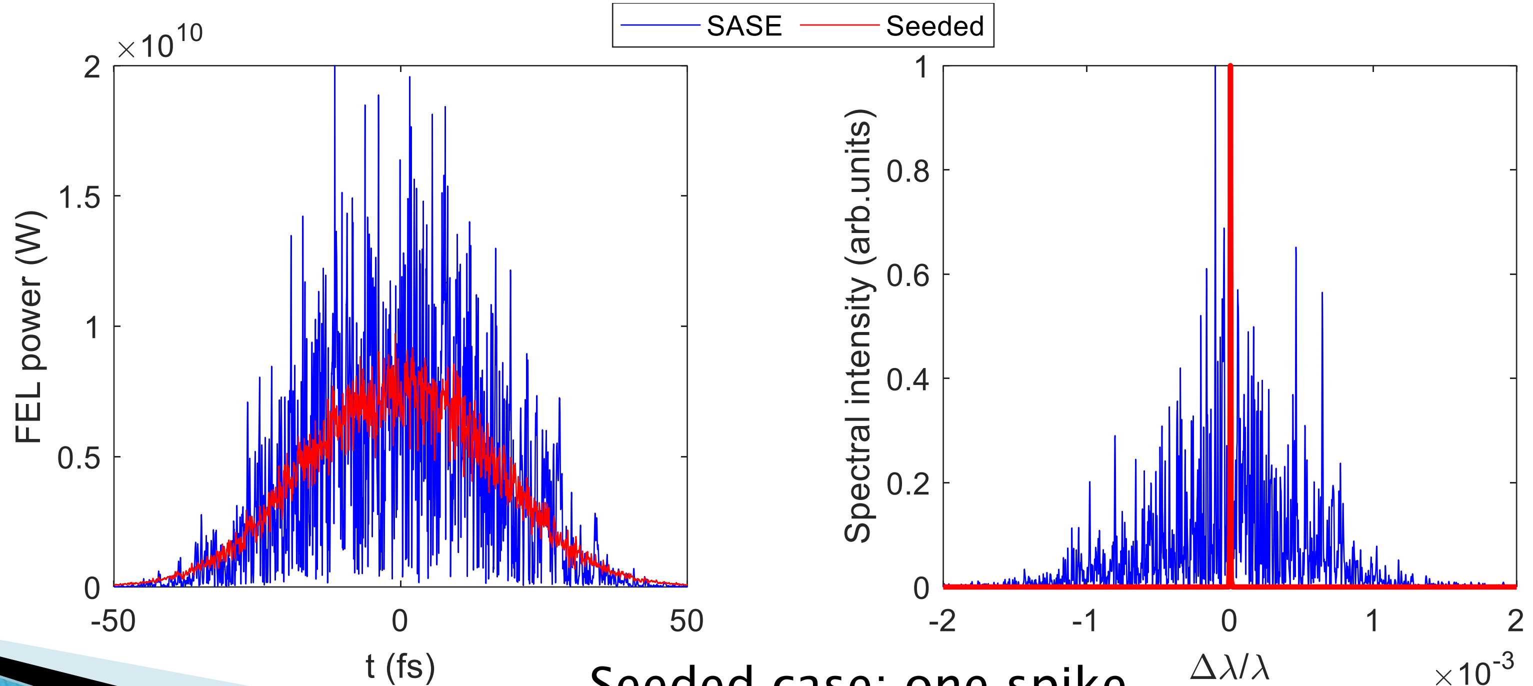


Simulation for FLASH FEL

Seeded FELs

- The output radiation resemble the characteristics of the seed. For example, if the seed has a single mode in spectrum and time, the output radiation will also consist of a single mode.
- Seeding is used to improve the longitudinal coherence or to reduce the bandwidth of SASE-FELs. Fully coherent pulses can be obtained with the seeded-FEL process.
- There are various seeding methods: self-seeding and external seeding

SwissFEL simulation for 0.1 nm radiation



Seeded case: one spike, bandwidth highly reduced

The Pierce Parameter ρ

- FEL parameter ρ. Typical values for X-rays= 10^{-4} – 10^{-3}

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4k_u\sigma_x}\right)^2 \frac{I}{2I_A}\right]^{\frac{1}{3}}$$

f_c: coupling factor (~0.9 for planar undulator)
I: electron peak current
σ_x: transverse beam size
I_A: Alfven current (~17 kA)

- Scaling of 1D theory

Gain length

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

Efficiency

$$P_{FEL} \approx \rho P_{beam}$$

SASE Spike Length

$$L_c = \frac{\lambda}{4\pi\rho}$$

Bandwidth

$$\frac{\Delta\omega}{\omega} = 2\rho$$

Electron beam requirements (X-rays)

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

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4k_u\sigma_x}\right)^2 \frac{I}{2I_A}\right]^{\frac{1}{3}}$$

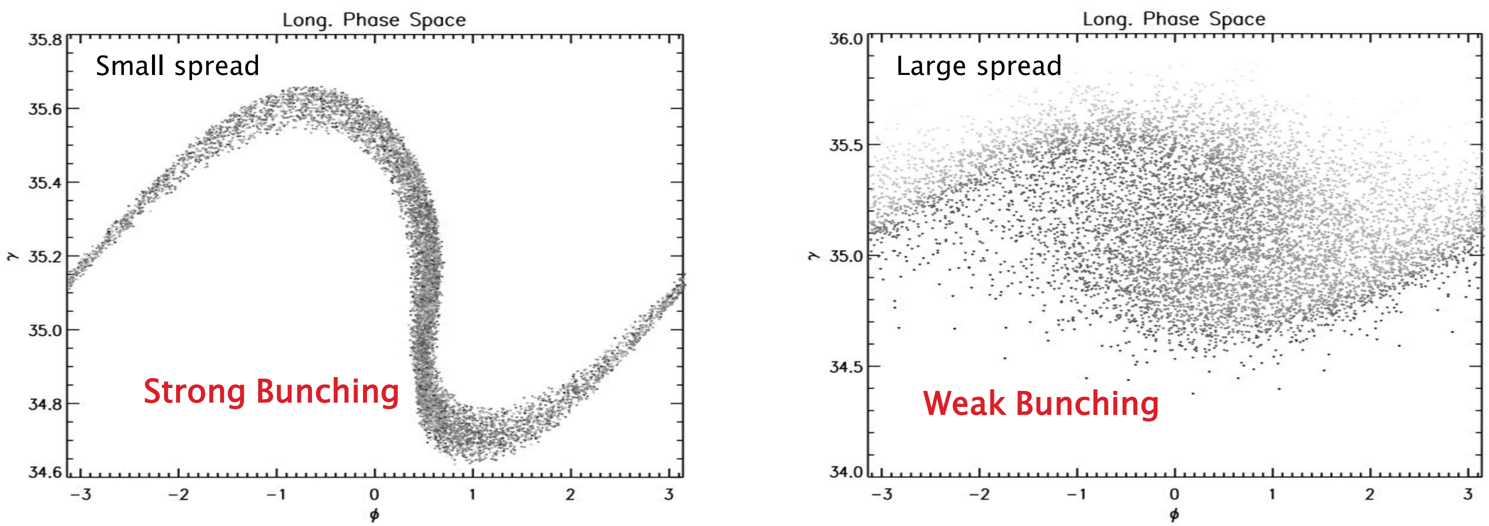
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\rho}$$

$$P_{FEL} \approx \rho P_{beam}$$

- The electron beam energy needs to be at the GeV level for X-rays
- A better FEL performance, i.e. higher powers and shorter gain lengths, are obtained for larger ρ parameters. We want:
  - large peak currents (at the kA level or 10s of fs electron pulse durations)
  - small transverse beam sizes (10s of μm)
  - larger undulator fields K (but require higher electron beam energies for the same wavelength)
- Additionally:
  - Lower energy spreads (10^{-3} – 10^{-4}, see next slides)
  - Low emittances (< 1 μm, see next slides)
  - Transverse overlap between electrons and photons → orbit alignment at the μm level

Energy Spread

- Only electrons within the FEL bandwidth can contribute to FEL gain.
- Consequently, the relative energy spread of the electron beam needs to be smaller than the ρ parameter for an efficient FEL amplification



Energy spread constraint:

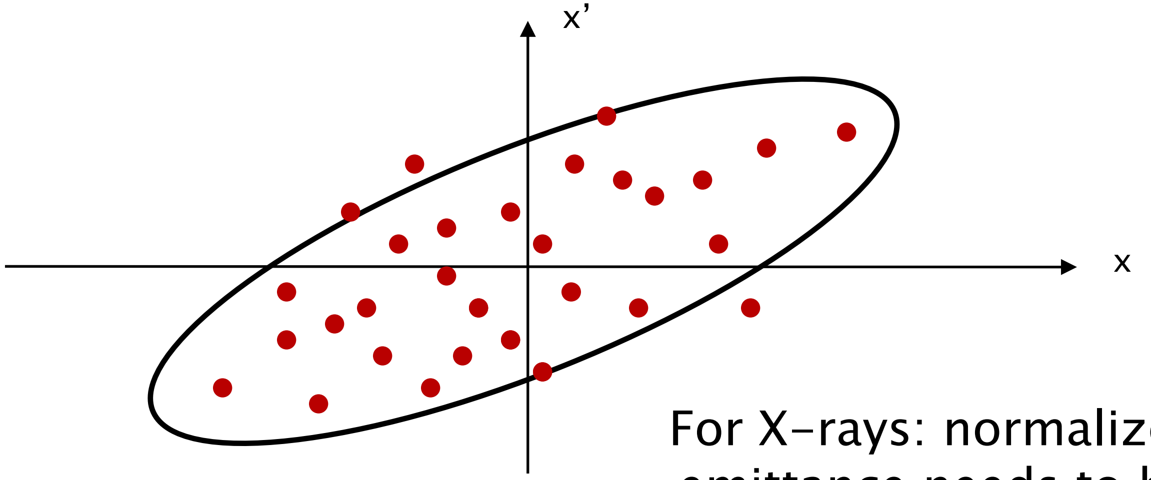
$$\frac{\sigma_\gamma}{\gamma} << \rho$$

For X-rays: relative energy spread needs to be smaller than 10^{-3} – 10^{-4}

Emittance

- The emittance of the electron beam is the area in the phase space x–x' (or y–y')
- The radiation "emittance" of the fundamental mode of the field is $\lambda/4\pi$.
- Electrons enclosed on this effective phase-space ellipse of the photons will emit coherently into the fundamental mode
- Electrons outside this ellipse will emit into higher modes and will not contribute to the amplification of the fundamental mode.

Emittance constraint: $$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$$



For X-rays: normalized emittance needs to be smaller than ~1 μm

Summary of requirements

- FEL performance is determined by the electron beam: the current, the size, the energy spread and the emittance, i.e. the electron charge density in 6D.

$$\rho = \frac{1}{\gamma_0}\left[\left(\frac{f_c K}{4 k_u \sigma_x}\right)^2 \frac{I}{I_A}\right]^{\frac{1}{3}}$$

$$\frac{\sigma_\gamma}{\gamma} << \rho \qquad \frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$$

- For X-rays, the electron beam needs to have:
  ~GeV energies ~kA peak currents 0.01–0.1% energy spreads
  ≤ μm normalized emittances tens of μm beam sizes
- There are currently no electron sources that can produce such bunches directly. Instead they have to be accelerated and compressed.
- State-of-the-art X-ray FEL facilities employ linear accelerators to provide the drive electron beam (see next chapter).
- Circular accelerators are not capable of delivering the required electron beam properties (in particular not the high peak current).

III. X-ray sources

Brilliance

- The figure of merit of many X-ray experiments is the brilliance or spectral brightness.
- We distinguish between peak brilliance (useful for time-resolved measurements) and the average brilliance over time.

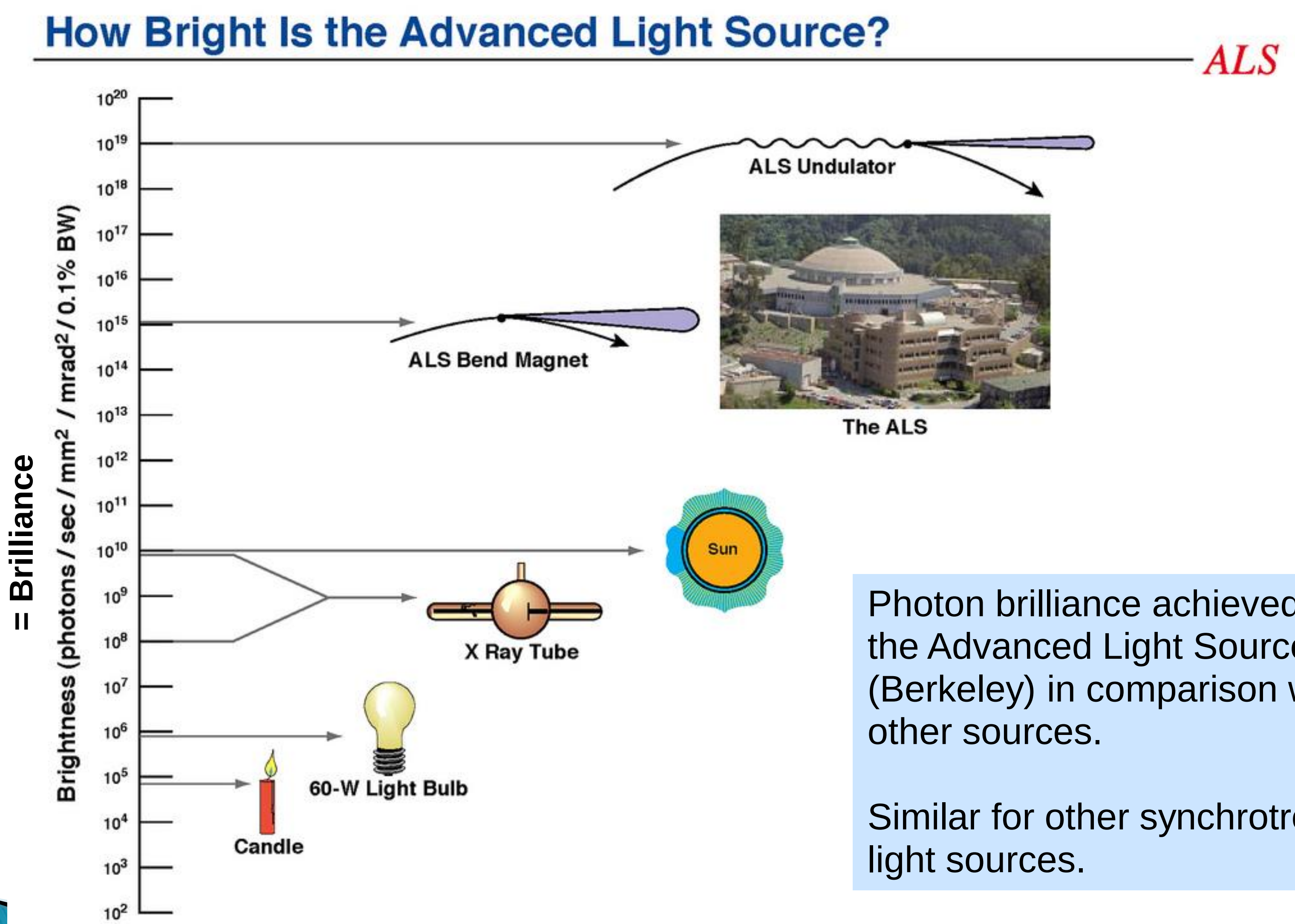
$$B \propto \frac{N_p}{\Delta t \sigma_r {\sigma'}_r \frac{\Delta\lambda}{\lambda}}$$

- The peak brilliance takes into account:
  - the number of photons N_p per time unit Δt (use second)
  - the angular divergence of the photons ${\sigma'}_r$ (in mrad^2)
  - the cross-sectional area of the photon beam σ_r (use mm^2)
  - the number of photons falling within a certain bandwidth (BW) of the central wavelength $\frac{\Delta\lambda}{\lambda}$ (0.1% are customary)
- Therefore the awkward but appropriate unit for brilliance is:

photons / s / mm^2 / mrad^2 / 0.1% (BW)

- The average brilliance is the peak brilliance multiplied by the photon pulse duration and the repetition rate of the source

Brilliance comparison



Photon brilliance achieved at the Advanced Light Source (Berkeley) in comparison with other sources.

Similar for other synchrotron light sources.

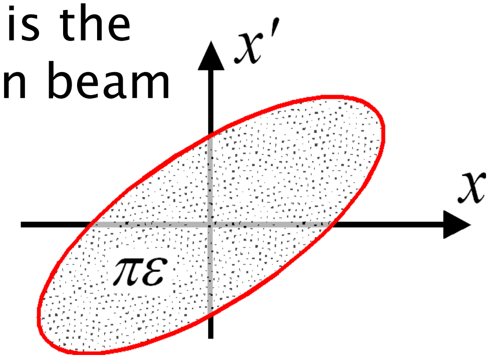
Importance of the emittance

- The product of the photon beam size and divergence is at best the diffraction emittance $\lambda/(4\pi)$, corresponding to the emission from a single electron.

$$B \propto \frac{1}{\sigma_r \sigma'_r} \qquad \sigma_r \sigma'_r \geq \frac{\lambda}{4\pi}$$

- The product of the radiation beam size and divergence is the convolution of the diffraction emittance and the electron beam transverse emittance

$$B \propto \frac{1}{\frac{\lambda}{4\pi} \otimes \varepsilon}$$

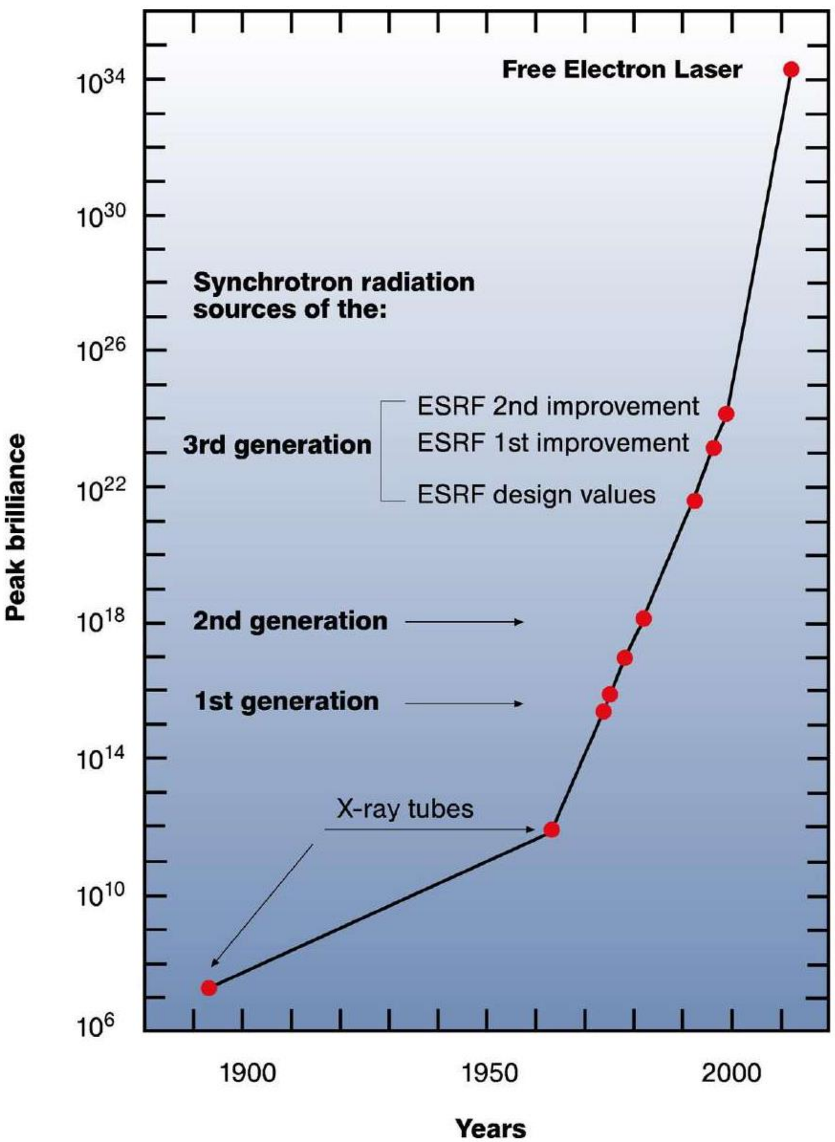


- The electron beam emittance adds up to the diffraction emittance in squares.

Smaller emittance → higher brilliance

- When the electron beam emittance is much smaller than the photon emittance, the mode is diffraction limited.

Historical evolution of peak brilliance

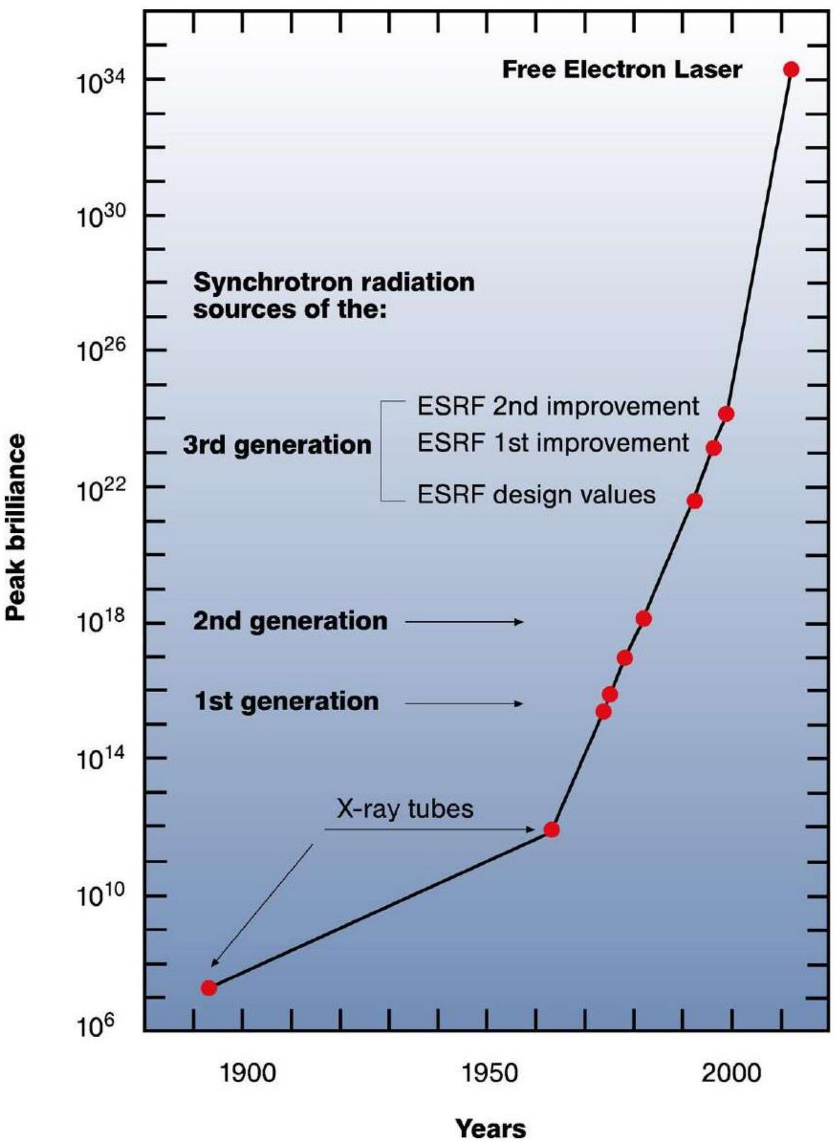


- Synchrotron radiation machines of different generations are based on circular accelerators and can provide a peak brilliance up to 10^{25}.
- X-ray FEL facilities are based on linacs. Thanks to the increased pulse energies, shorter pulses, and lower bandwidths, FELs provide peak brilliances much higher than synchrotron facilities (up to 10^{35})
- Synchrotrons have higher repetition rates and longer pulses → difference in average brightness is reduced to 10-100.
- The values of the figure consider SASE-FELs. Seeded-FELs have demonstrated the possibility to reduce the bandwidth and therefore to increase the brilliance by 10-100.

Synchrotron light machines

Synchrotron light machines History and current facilities

History of synchrotrons



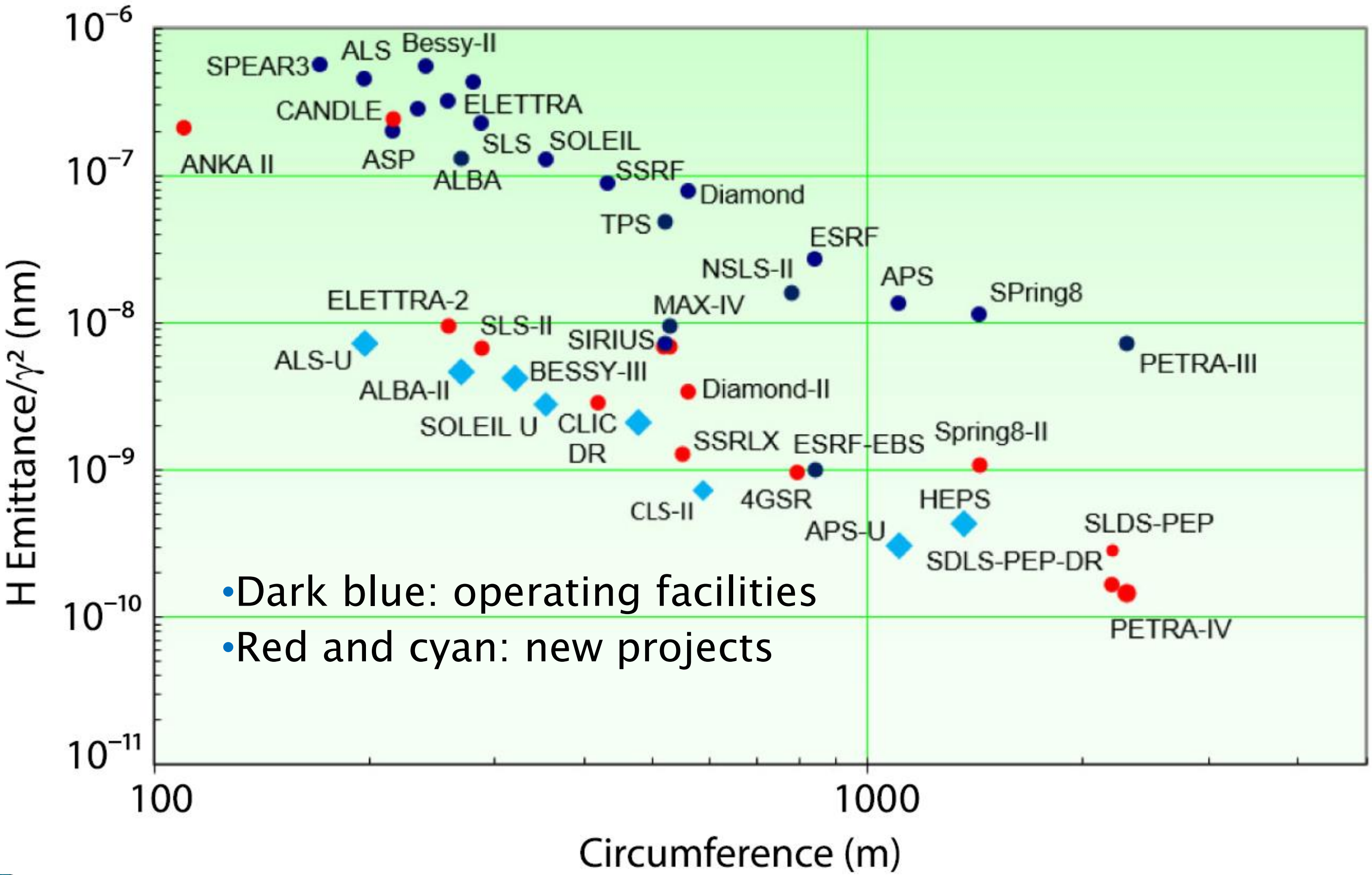
- **1st generation:** parasitic use of synchrotrons built for particle physics (bending magnet radiation)
- **2nd generation:** dedicated synchrotrons built for photon science (bending magnet radiation)
- **3rd generation:** dedicated storage rings with insertion devices (wigglers and undulators) and improved emittance. Example: ESRF (France)
- **4th generation:** further emittance improvement by using multi-bend achromats (MBA). Pioneer: MAX-IV

(Free-electron lasers are also called 4th generation light source)

Synchrotron Light Sources Around the World

- There are around 50 synchrotron light sources around the world (operational or under construction)
- There are about 15 new projects based on 4th generation designs (MBA lattice)

Trends in storage-ring lattice design



From *[A. Streun et al, PRAB 26, 091601, 2023]*

Main parameters of some SR facilities

Name	Starting operation year	Energy (GeV)	Circumference (m)	Current (mA)	Emittance (nm)
Spring-8 (Japan)	1997	8	1436	100	3.0
APS (USA)	1995	7	1104	100	3.0
ESRF (France)	1994	6	844	200	3.8
Petra-III (Germany)	2009	6	2304	100	1
Diamond (UK)	2007	3	565	300	3.22
SSRF (China)	2009	3	432	500	2.61
Alba (Catalonia)	2012	3	269	200	4.33
NSLS-II (USA)	2015	3	792	500	0.55
TPS (Taiwan)	2016	3	518	500	1.6
MAX-IV (Sweden)	2017	3	528	500	0.33
Sirius (Brazil)	2020	3	518	500	0.25
SLS (Switzerland)	2001	2.4	288	400	5

Synchrotron light machines
Layout

Layout of SR facilities

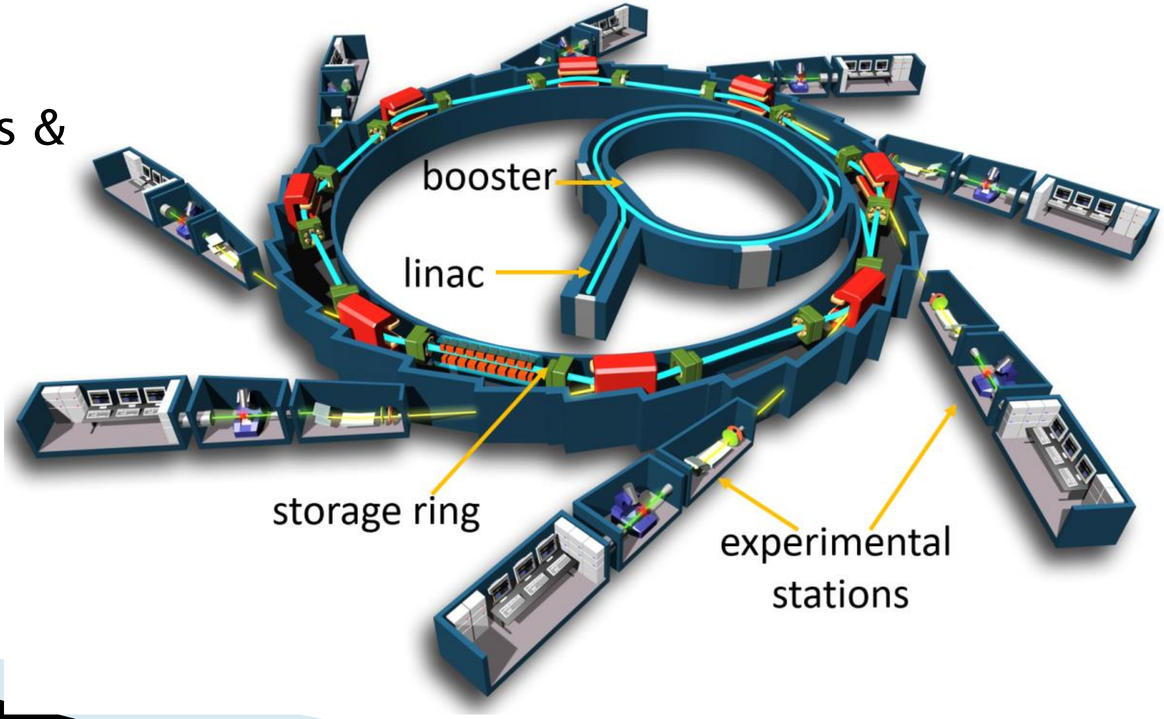
There are 4 main parts in a SR facility:

1. Linac:
   - Electron source (cathode) &
   - RF sections: acceleration up to ~100 MeV

2. Booster:
   - RF cavities to accelerate the beam to its final energy (several GeV)

3. Storage ring
   - Accumulation of electrons &
   - Production of SR in bending magnets and undulators

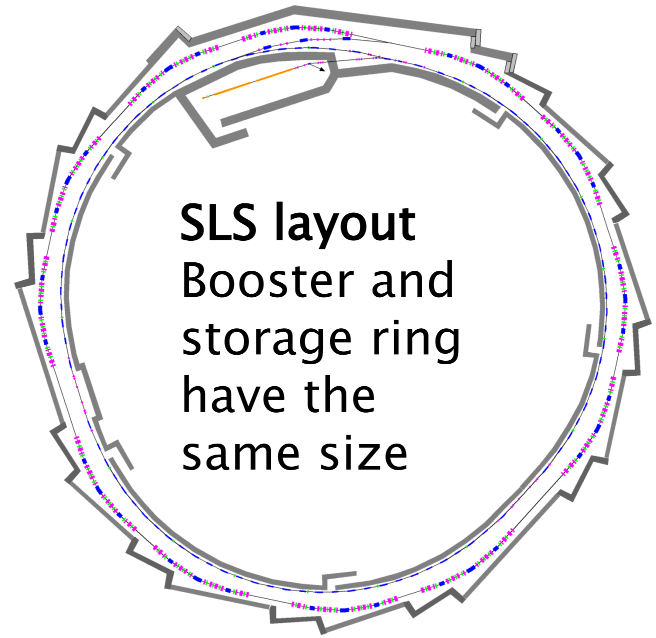
4. Experimental stations
   - Use of SR



Booster size

The booster ring can be of the same size or smaller than the storage ring. The former case is the typical choice of modern machines. Advantages:

- Saving on building space and shielding (the booster and the storage ring can be placed in the same tunnel)
- Improved transverse emittance (the total bending field can be distributed to a large number of small magnets).
- Cleaner injection into the storage ring and a simpler booster-ring transfer line.
- Lower power consumption for top-up injection



SLS layout
Booster and storage ring have the same size

Top-up: the booster injects electrons periodically to keep a constant beam intensity in the ring. It guarantees a constant heat load on all accelerator components → better stability

Other aspects

- RF cavities in the storage ring resupply the energy lost by the electrons due to the emission of synchrotron radiation.
- The energy of the electrons in the storage ring is of several GeV. Higher electron beam energies allow higher photon energies and higher radiation fluxes but also require higher magnetic strengths (or larger circumference) and higher power consumption of the RF system to replenish the loss of energy.
- The radiation is produced in bending magnets and insertion devices placed in the straight sections of the storage ring.
- The storage rings typically incorporate a variety of undulators covering a wide spectrum of synchrotron light between ultra-violet to hard X-rays.
- Synchrotron light machines operate with a relatively large number of experimental stations. As an example, in the SLS there are presently16 beamlines in user operation.

Synchrotron light machines
Electron beam properties and dynamics

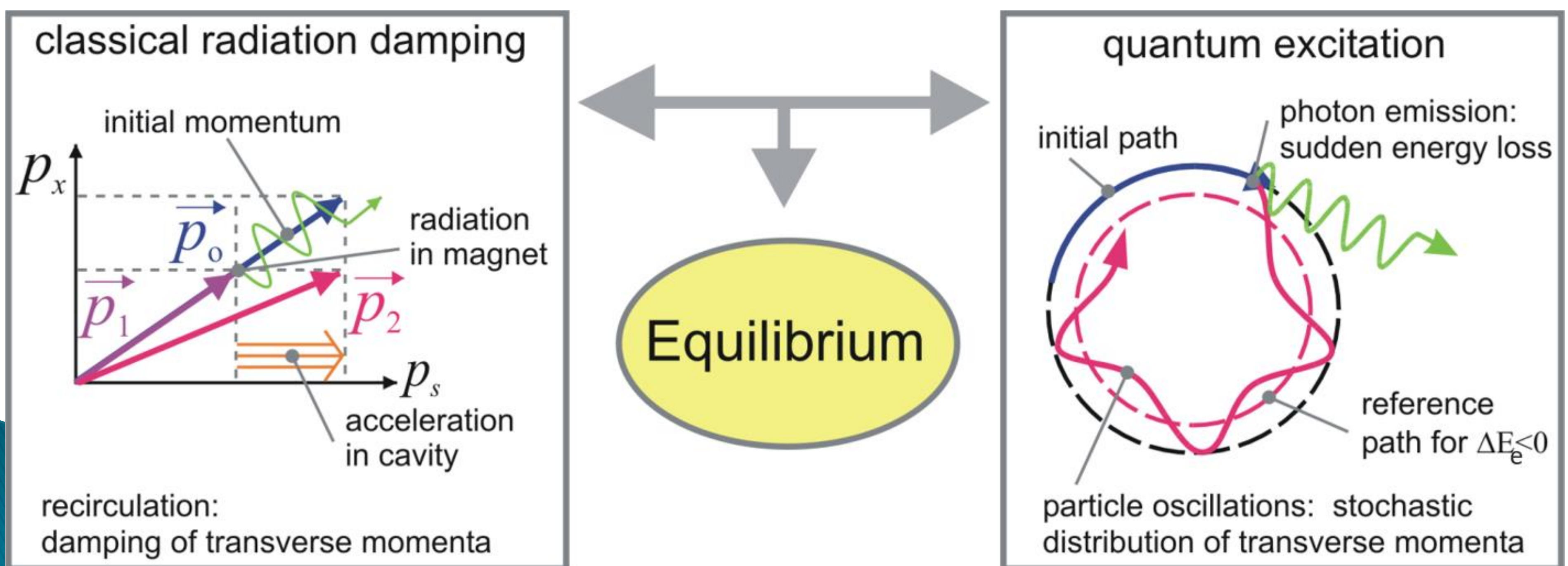
Equilibrium

- The emission of synchrotron radiation by the electrons in the storage ring gives rise to both **radiation damping** and **quantum excitation**.
- Classical radiation damping is related to the continuous loss of energy of the electrons in bending magnets and wigglers or undulators and its compensation in the RF cavities.
- Energy is also lost in discrete units or “quanta,” i.e., photons whose energy and time of emission vary randomly. This randomness introduces a type of noise or diffusion, causing a growth of the oscillation amplitudes of the electrons.
- **The distribution of the electrons in the storage ring, (i.e., emittance, pulse duration and energy spread), are determined by the equilibrium between radiation damping and quantum excitation.**

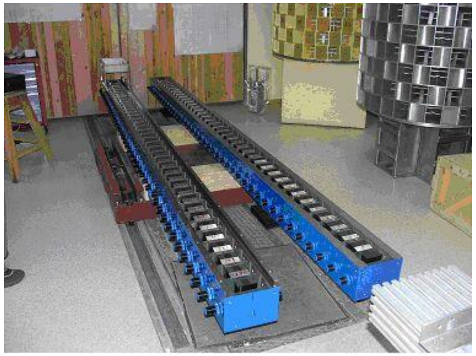
Equilibrium transverse emittance

The continuous emission of SR causes a momentum reduction in both longitudinal and transverse directions. The RF cavities restore only the longitudinal momentum → the transverse momenta and the emittance are reduced.

Due to quantum emission of radiation, some electrons lose energy and follow different paths due to the finite dispersion in the lattice, causing the emittance to increase.



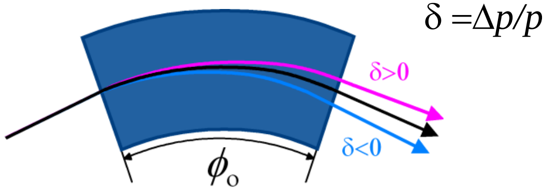
Emittance Optimization



- **Maximize radiation damping**
  - increase radiated power ⇨ pay with RF-power
    - High field bending magnets
    - Damping wigglers (DW)

- **Minimize quantum excitation**
  - keep off-momentum orbit close to nominal orbit

$$\text{Dispersion} = \frac{\text{orbit}}{\text{momentum}} = \frac{X}{\Delta p / p}$$



⇨ minimize dispersion at locations of radiation (bends)

- **Multi-Bend Achromat lattice (MBA).** Many short (= small deflection angle) bends to limit dispersion growth.
- **Longitudinal Gradient Bend (LGB)**
  highest radiation at region of lowest dispersion and v.v.

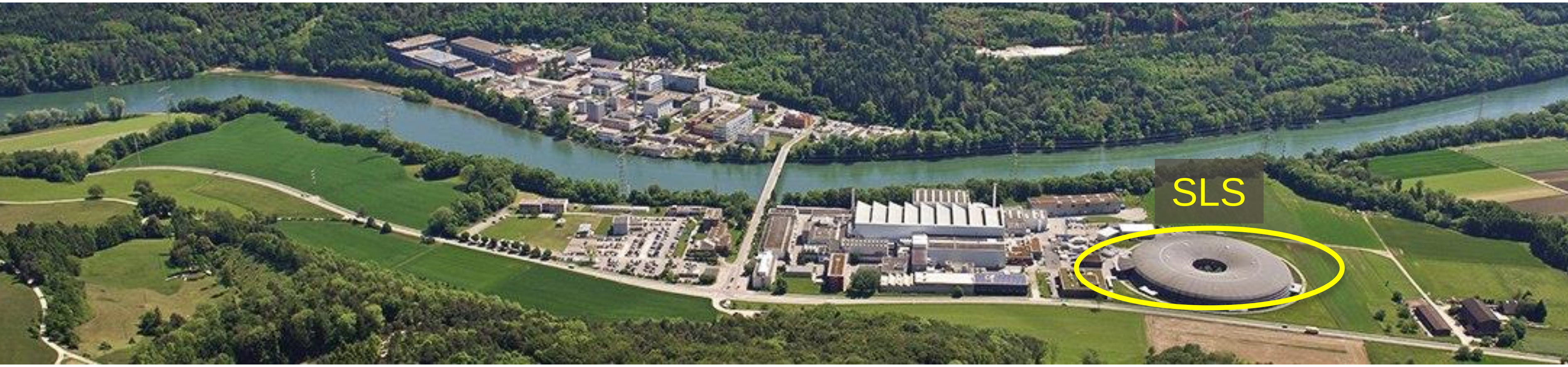
3rd generation light sources: emittance of few nm
4th generation (MBA, LGB, DW): emittance < 1 nm

Other properties

- **Vertical emittance.**
  - The theoretical vertical dispersion is zero, since the design dispersion is only horizontal.
  - In practice, the emittance is dominated by magnet alignment errors. Third-generation machines typically achieve vertical emittances on the order of 1% or less of the horizontal emittance. SLS example: 1 pm.
- The **bunch length** and the **energy spread** of the electrons are also the result of the equilibrium between radiation damping and quantum excitation. Bunches are typically a few mm long, while relative energy spreads are usually at the 0.1% level.
- The accumulated **currents** typically amount to a few hundred mA (averaged over a full turn).
- Synchrotrons operate at relatively high bunch **frequencies**. For example, SLS works with a 500 MHz repetition rate.
- The design and operation optimization of synchrotron light sources includes addressing many issues such as chromaticity correction and the optimization of beam lifetime and dynamic aperture.

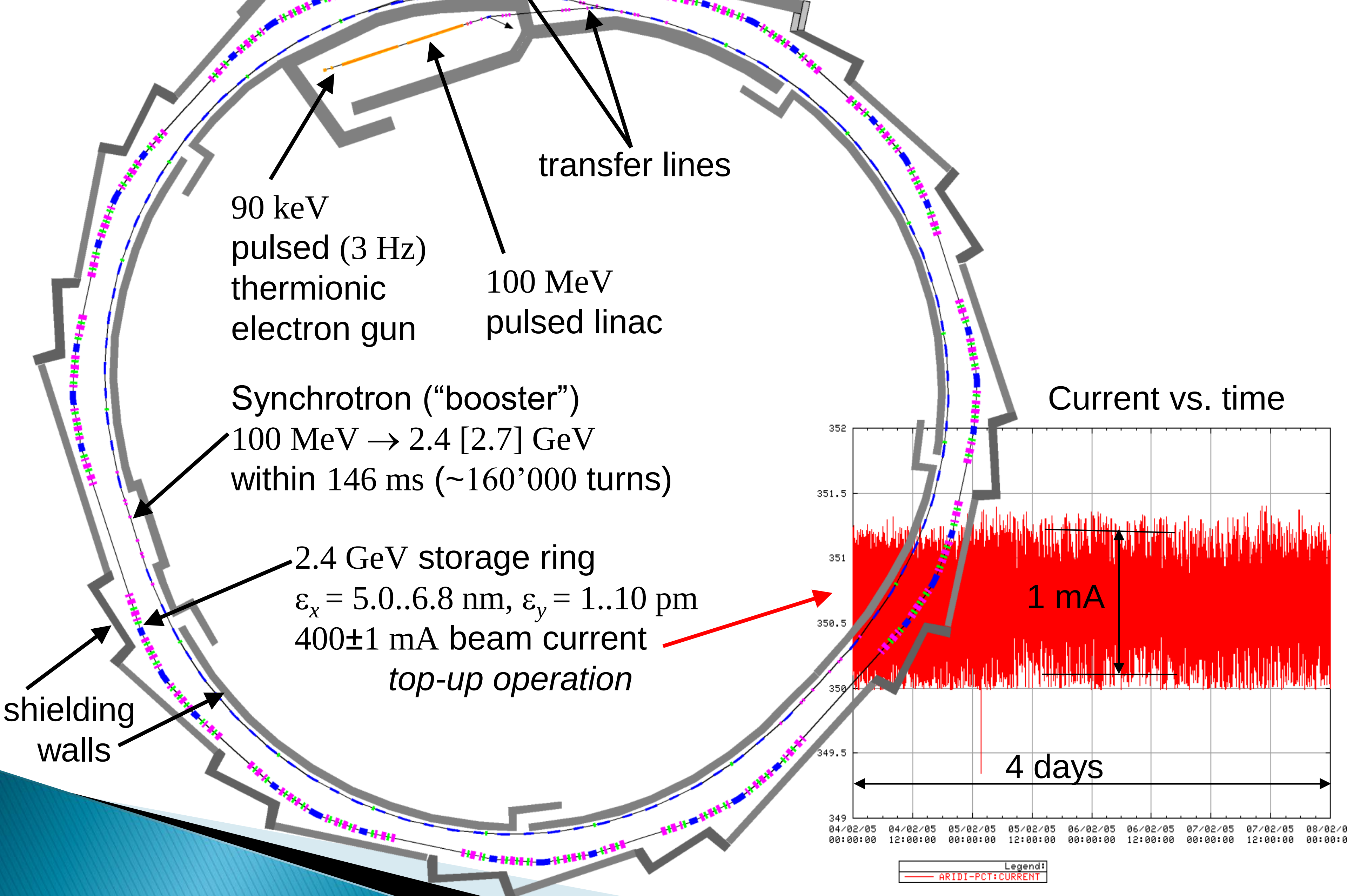
Synchrotron light machines
The Swiss Light Source (SLS)

Overview



- Third-generation synchrotron light source in Switzerland (Villigen) with 16 beamlines in operation
- Middle facility (2.4 GeV, 288 m circumference).
- Design focused on beam brightness, flexibility (wide wavelength spectrum) and stability.
- Planning started in 1991. Project approved in 1997.
- First light from the storage ring at December 2000.
- SLS operation finished in September 2023
- Upgrade based on MBA lattice planned for 2025. Budget: 130 MCHF.

Layout



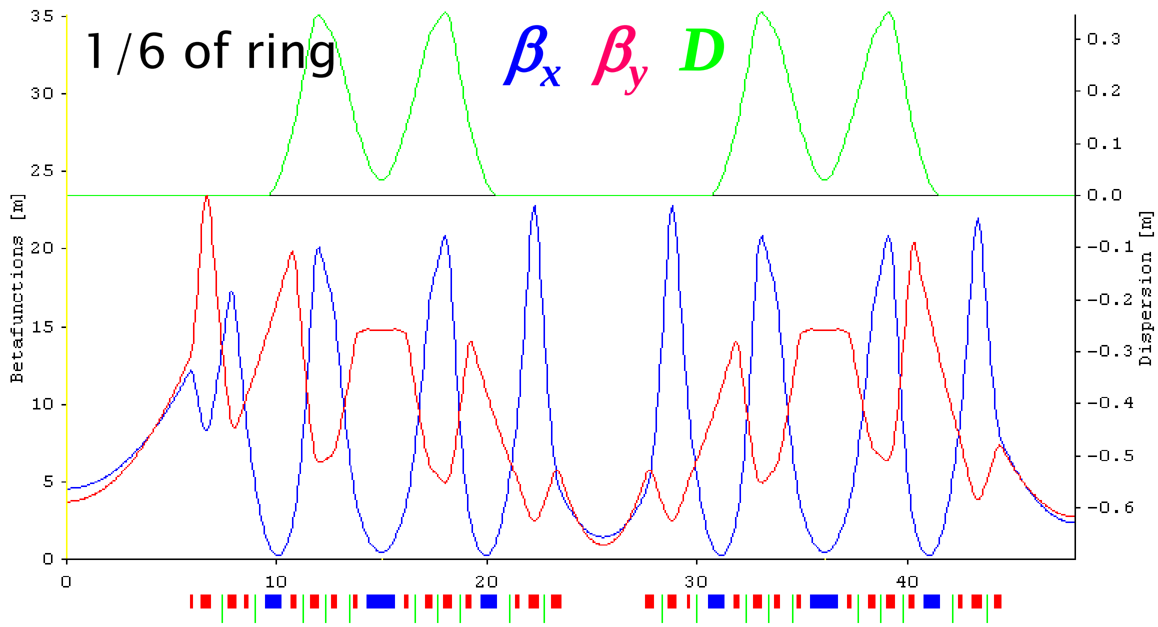
transfer lines
90 keV
pulsed (3 Hz)
thermionic
electron gun
100 MeV
pulsed linac
Synchrotron ("booster")
100 MeV → 2.4 [2.7] GeV
within 146 ms (~160'000 turns)
2.4 GeV storage ring
ε_x = 5.0..6.8 nm, ε_y = 1..10 pm
400±1 mA beam current
top-up operation
shielding
walls
Current vs. time
1 mA
4 days
352
351.5
351
350.5
350
349.5
349
04/02/05 00:00:00
04/02/05 12:00:00
05/02/05 00:00:00
05/02/05 12:00:00
06/02/05 00:00:00
06/02/05 12:00:00
07/02/05 00:00:00
07/02/05 12:00:00
Legend:
ARIDI-PCT:CURRENT

Storage ring lattice and parameters

12 TBA:

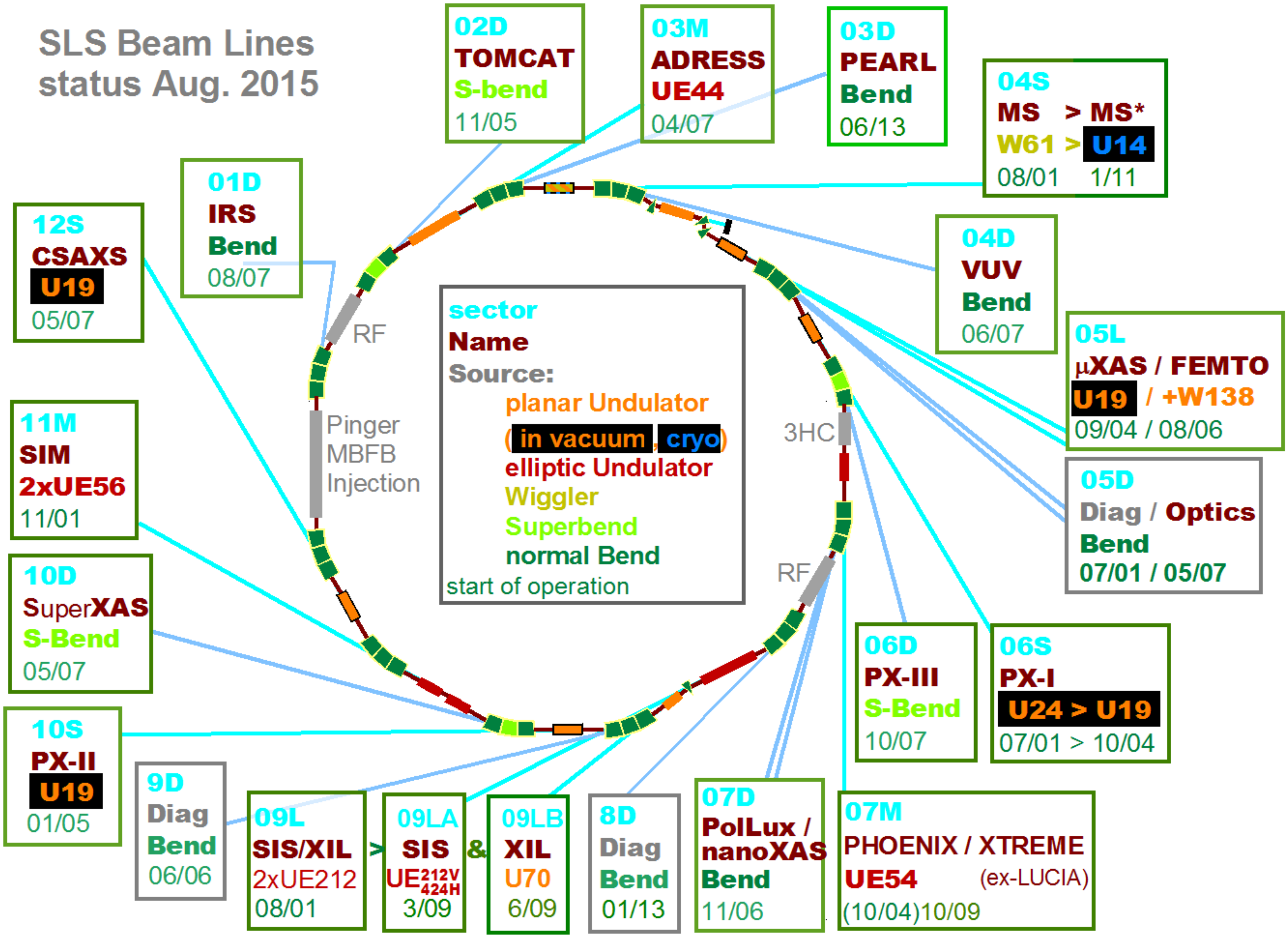
12 straights:

3 x 11.5 m
3 x 7.0 m
6 x 4.0 m



Energy	**2.4 GeV**		Mom. compaction	**$6.3 \cdot 10^{-4}$**
Emittance	**5 nm rad**		Radiation loss	**512 keV**
Circumference	**288 m**		Lattice type	**TBA**
Radio frequency	**500 MHz**		Energy spread	**$8.9 \cdot 10^{-4}$**
Tunes	**20.41 / 8.17**		rms bunch length	**3.5 mm**
Chromaticities	**-66 / -21**		Beam current	**400 mA**

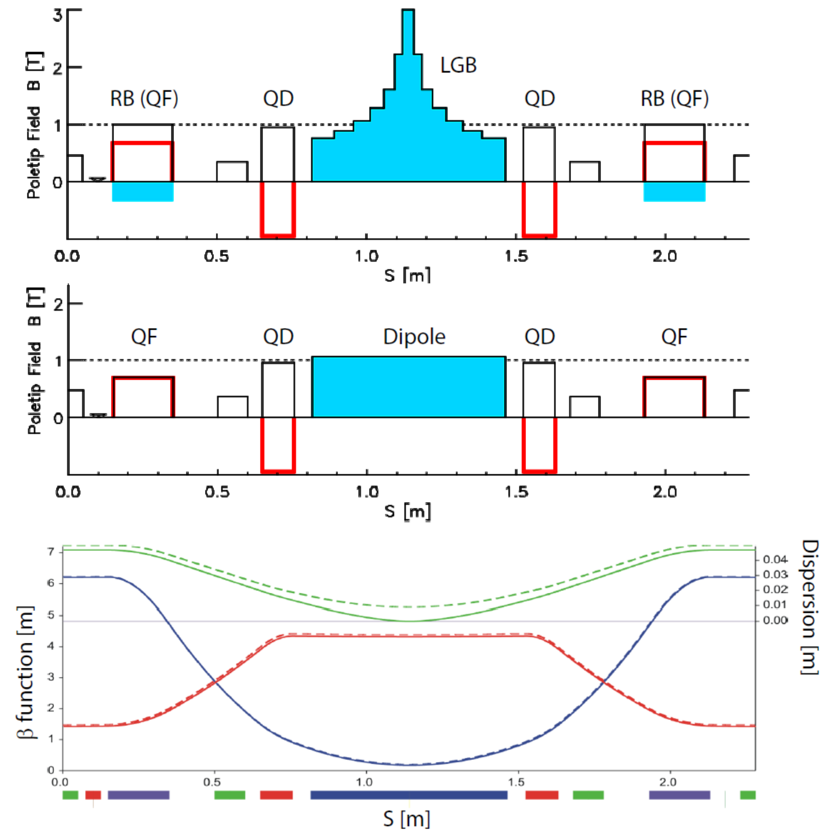
Experimental stations



Upgrade: SLS-2 lattice design concept

- Goal
  - factor ~40 lower emittance
    - Triple Bend Achromat → 7BA (factor ~10)
    - **Longitudinal Gradient Bend + Reverse Bend (factor ~4)**
- Constraints
  - keep hall & tunnel.
  - re-use injector: booster & linac.
  - keep source positions.
- Challenge: *small circumference*

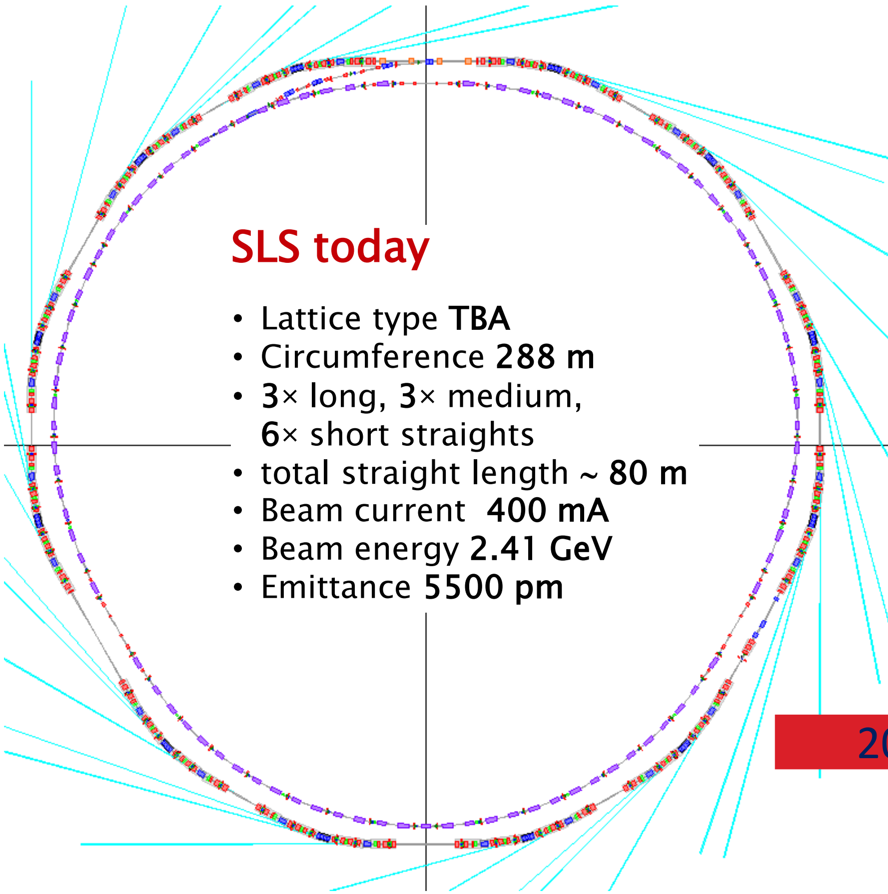
More info in *[A. Streun et al, PRAB 26, 091601, 2023]*



LGB-RB cell vs TME cell

Reverse bend allows to control dispersion function without changing the beta function

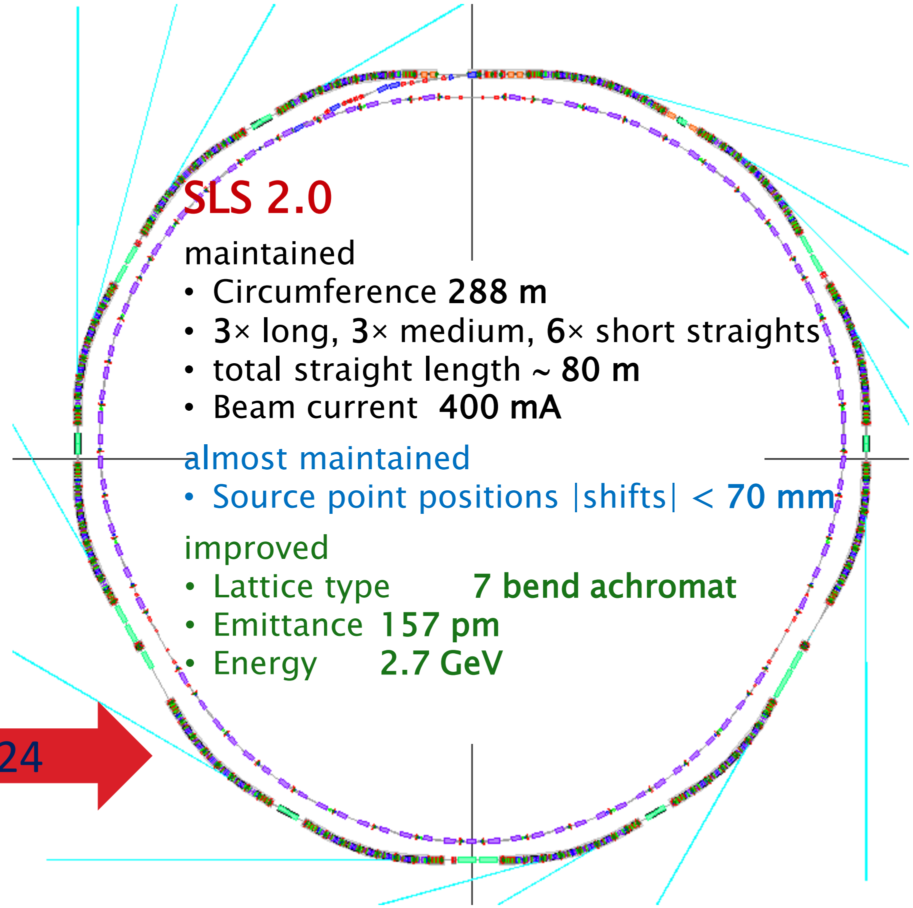
SLS → SLS 2



SLS today

- Lattice type **TBA**
- Circumference **288 m**
- 3× long, 3× medium, 6× short straights
- total straight length ~ **80 m**
- Beam current **400 mA**
- Beam energy **2.41 GeV**
- Emittance **5500 pm**

2024 →



SLS 2.0

maintained

- Circumference **288 m**
- 3× long, 3× medium, 6× short straights
- total straight length ~ **80 m**
- Beam current **400 mA**

almost maintained

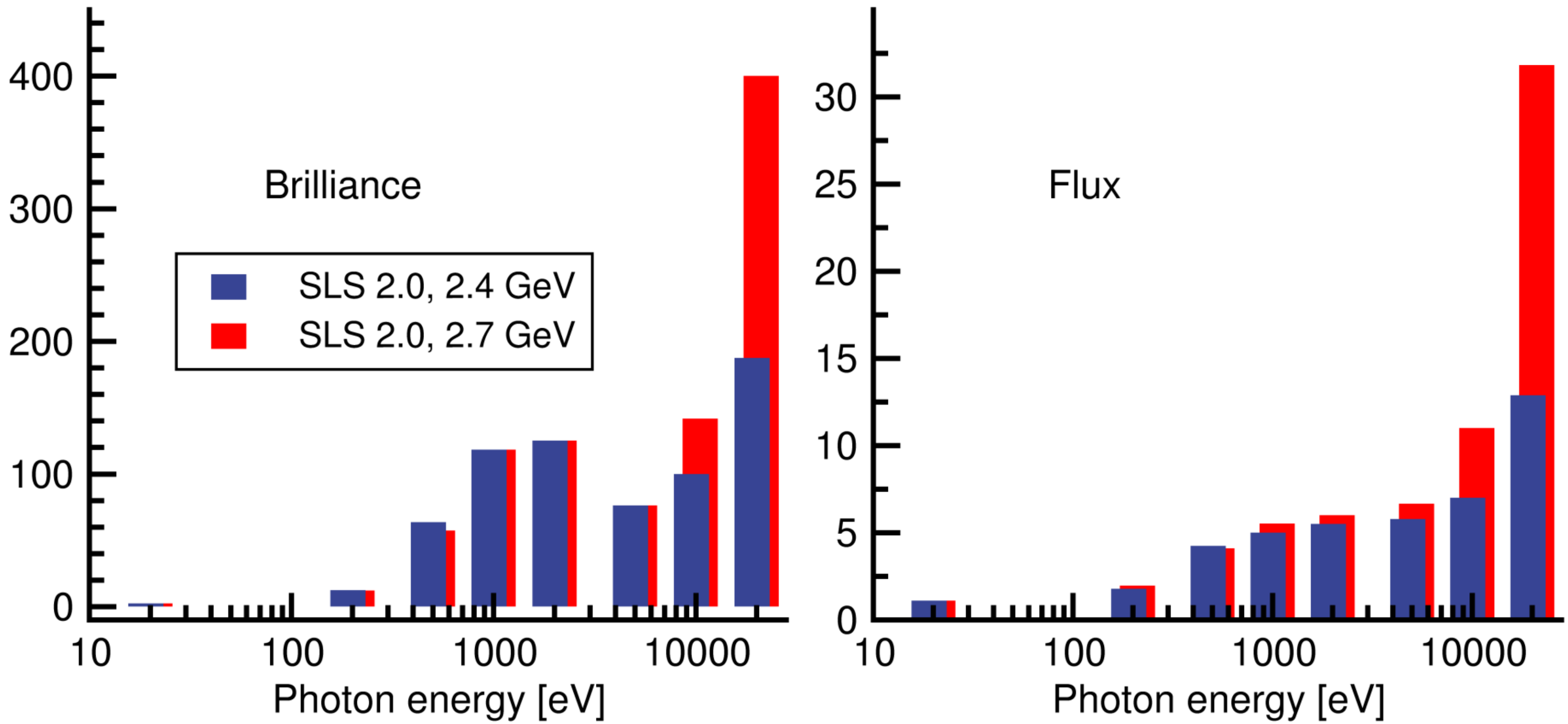
- Source point positions |shifts| < **70 mm**

improved

- Lattice type **7 bend achromat**
- Emittance **157 pm**
- Energy **2.7 GeV**

Courtesy of H. Braun

Improvements from SLS to SLS 2



Courtesy of H. Braun

Synchrotron light machines
Stability

Stability: noise sources

Short term (<1 hour):

- Ground vibration induced by human activities
- Mechanical devices like compressors and cranes
- External sources like road traffic
- ID changes (fast polarization switching IDs <100 Hz)
- Cooling water circuits
- Power supply (PS) noise …

Medium term (<1 week):

- Slight movement of the vacuum chamber (or even magnets) due to changes of the SR induced heat load
- Water cooling
- Tunnel and hall temperature variations (day/night variations) …

Long term (>1 week):

- Ground settlement and seasonal effects (temperature, rain fall) resulting in alignment changes of accelerator components including girders and magnets.

Stability: requirements

Typical stability requirements for selected measurement parameters common to a majority of experiments

Measurement parameter	Stability requirement
Intensity variation ΔI/I	<0.1% of normalized I
Position and angle accuracy	<1% of beam σ and σ′
Energy resolution ΔE/E	<0.01 %
Timing jitter	<10% of critical t scale
Data acquisition rate	$\approx 10^{-3}$–10^{5} Hz

These requirements lead to:
sub-micron tolerances for the positional and angular stability of the electron beam @ the ID source points over a large frequency range f: **10^{-5}–$10^{2(3)}$ Hz** (timescale: msecs – hours/days):

$$\sigma_{cm} < 1\mu m \text{ and } \sigma'_{cm} < 1\mu rad$$

Stability: main cures

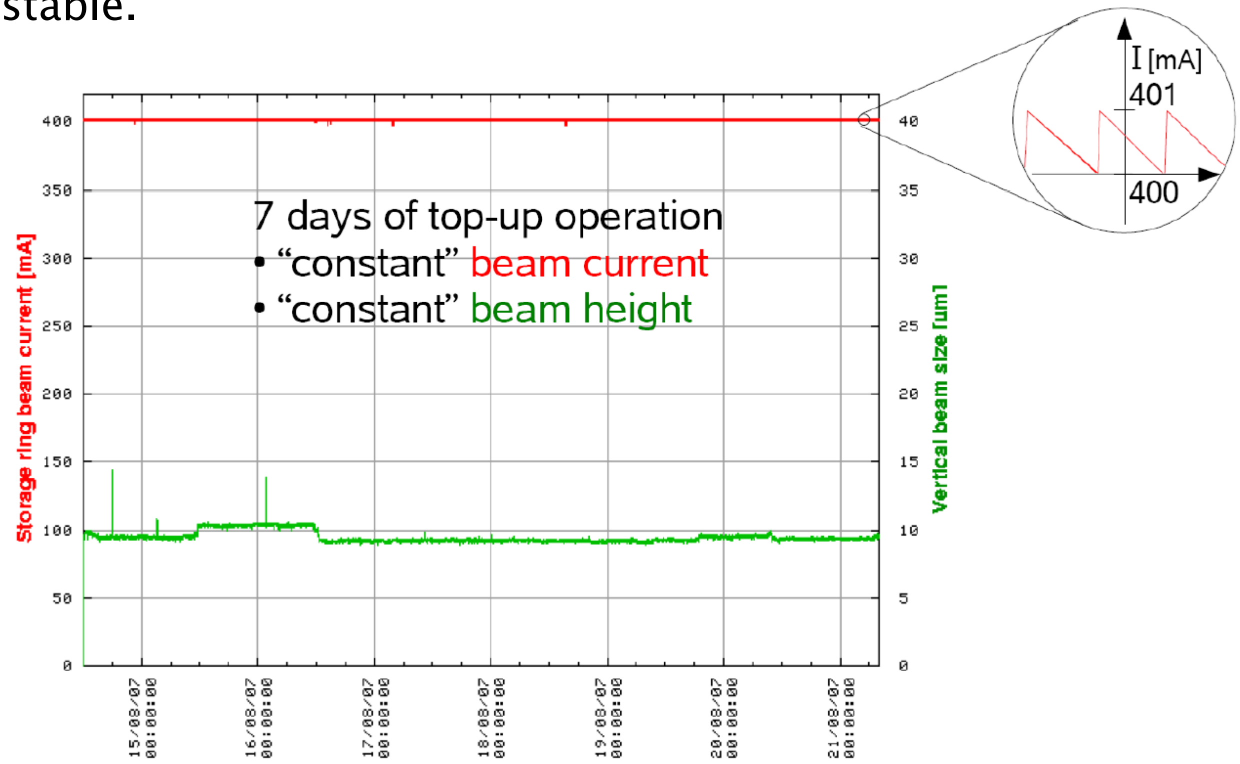
- **Top-up operation**

"Continuously inject small amount of current". It guarantees a constant electron beam current and thus a constant heat load on all accelerator components

- **Beam-based alignment**

Find golden orbit (mostly through the center of magnets to minimize optics distortions and steering). Example: record orbit variation when magnet strength is varied.

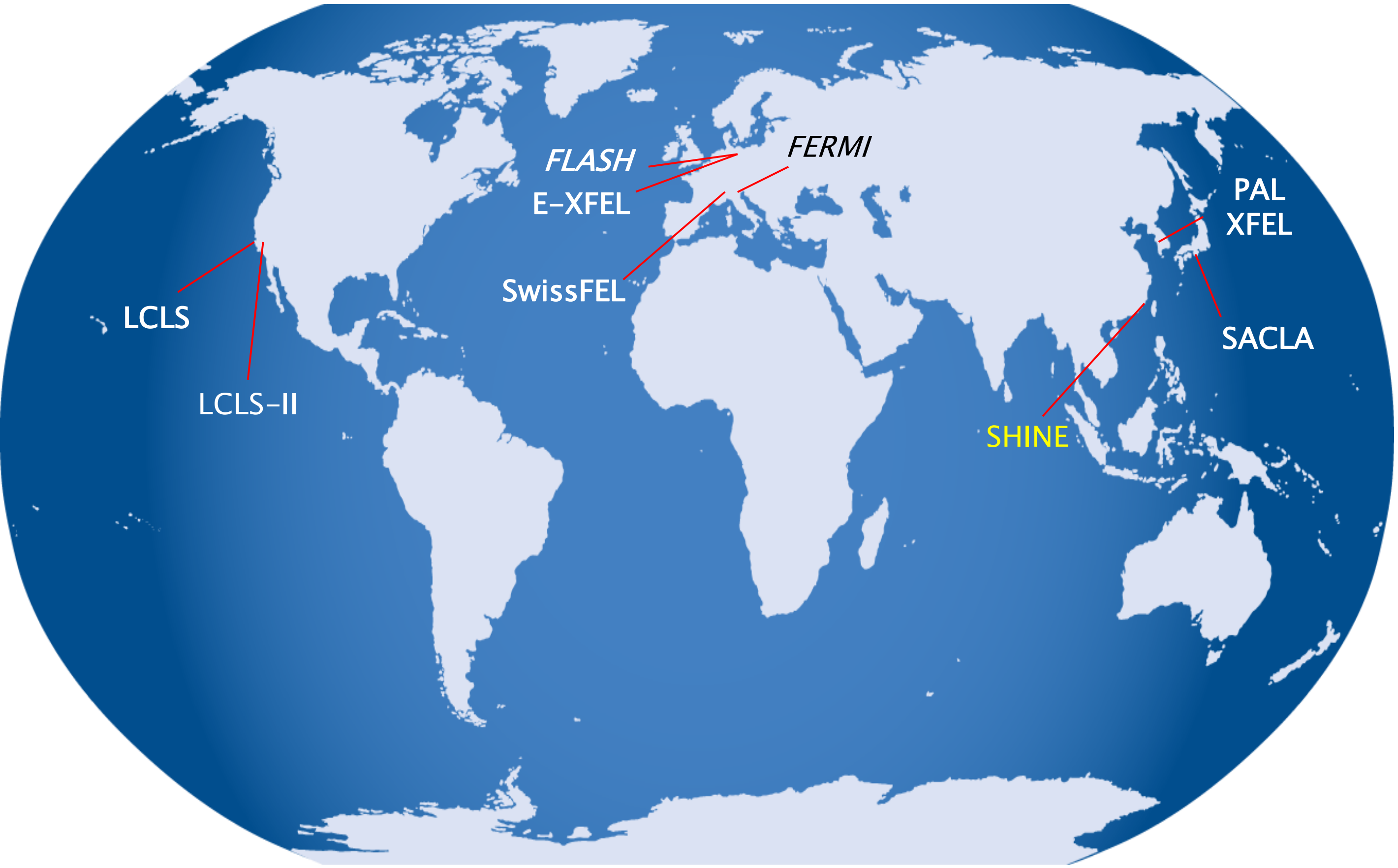
- **Fast orbit feedbacks (global and local).**
- To keep golden orbit stable.



X-ray FEL machines

X-ray FEL machines History and current facilities

X-ray FEL Projects Around the World



- All present facilities are based on SASE, except FERMI.
- Most facilities have the option of self-seeding

- FLASH: first soft X-ray, high rep rate (MHz), 2007
- LCLS: first hard X-ray, 2009. LCLS2: high rep rate, 2023.
- SACLA: compact hard X-ray, 2011
- FERMI: first soft X-ray seeded-FEL, 2013
- PAL-XFEL: hard X-ray with low (20 fs) timing jitter, 2016
- E-XFEL: hard X-ray, high rep rate, 2017
- SwissFEL: compact hard X-ray, low emittance, 2017
- SHINE: hard X-ray, high rep rate, from 2025

Hard X-ray FELs comparison

	LCLS *1	SACLA *2	PAL-XFEL *3	E-XFEL *4	SwissFEL 5*
Country	USA	Japan	Korea	Germany	**Switzerland**
Starting oper. year	2009	2010	2017	2017	**2018**
Energy (GeV)	14.3	8.5	10	17.5	**5.8**
Length (km)	3.0	0.75	1.1	3.4	**0.74**
Pulses per second	120	60	60	27000	**100**
Normalized emittance (nm)	400	1000	550	<600	**200**
Construction cost (M$) *6	415	370	400	1600	**280**

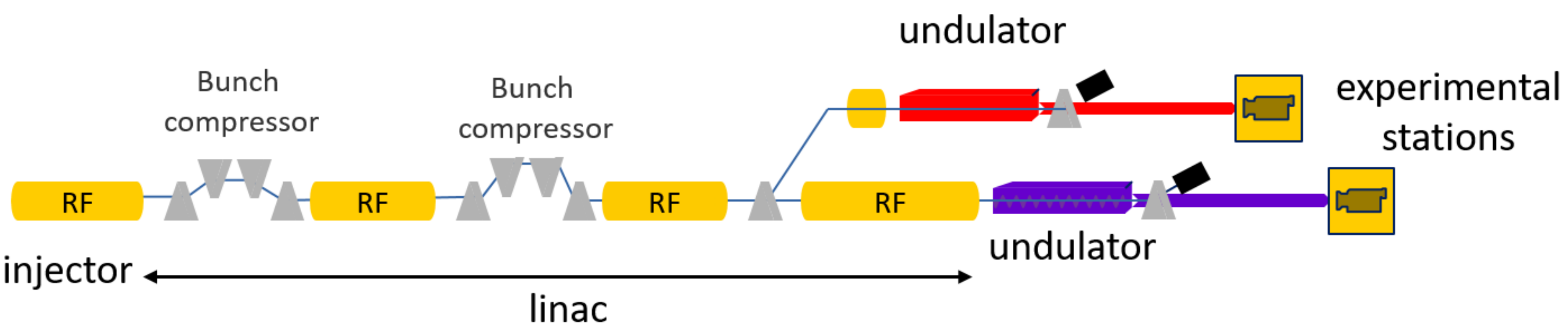
*1: *[P. Emma et al, Nat. Phot. 4, 641 2010]*
*2: *[T. Ishikawa et al, Nat. Phot. 6, 540, 2012]*
*3: *[H. Kang et al, Nat. Phot. 11, 708, 2018]*
*4: *[W. Decking et al, Nat. Phot. 14, 391, 2020]*
*5: *[E. Prat et al, Nat. Phot. 14, 748, 2020]*
*6: *[E. Cartlidge, Science 354, 6308, 22, 2016]*

X-ray FEL machines Layout

Layout of X-ray FEL facilites

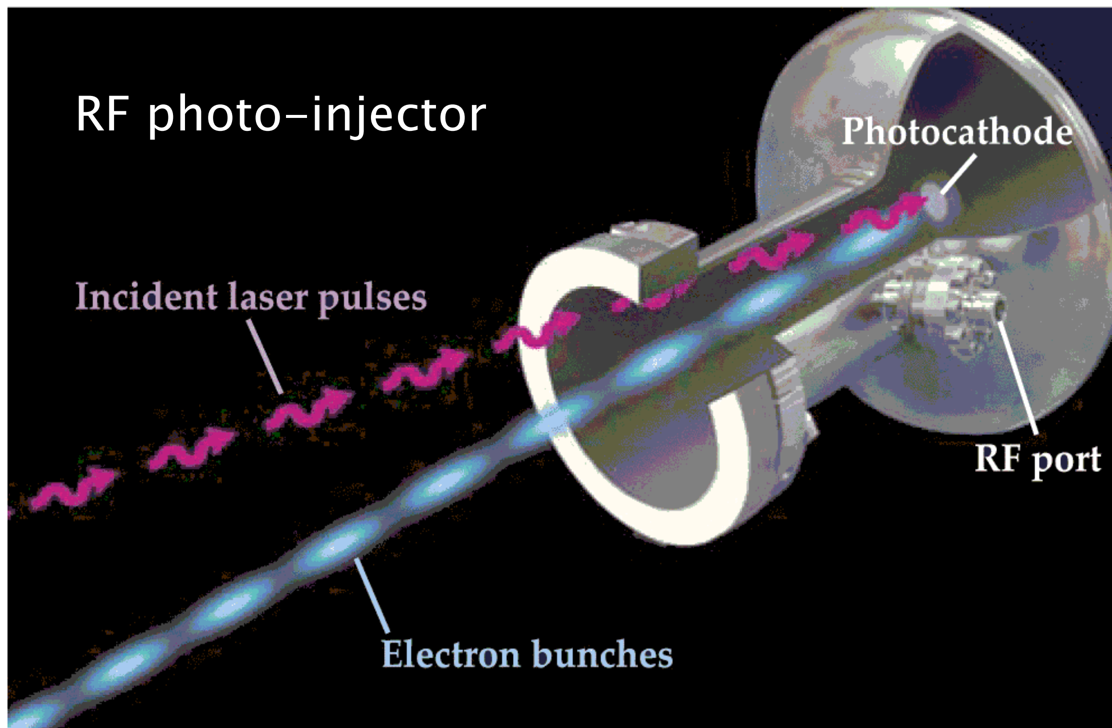
There are 4 main parts in an FEL facility:

1. Injector: production of electron beams with
   - low energy (5–10 MeV)
   - low energy spread (~1e^{-4})
   - low emittance (<1 μm),
   - low peak current (10–20 A; e.g. 100–200 pC in 10 ps)
2. Linac:
   - acceleration (to ~GeV energies) with radiofrequency (RF) cavities &
   - bunch compression (to kA bunches with 10s of fs), done in 2–3 stages
3. Undulator: several (>10) modules, each few meters long and with a period of few cm
4. Experimental stations (use of FEL radiation)



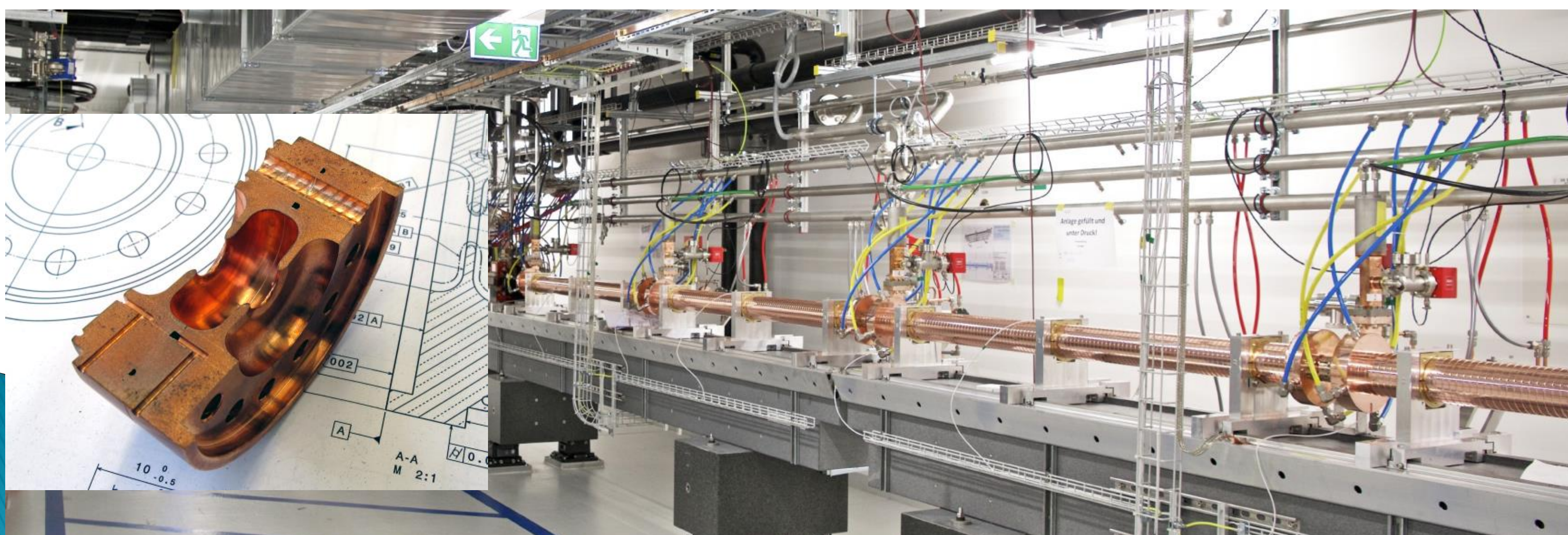
Electron sources

- RF photo-injectors are normally used to generate high-brightness electron beams
- Electrons are produced via the photo-electric effect by a laser of a proper wavelength impinging on a photocathode mounted inside an RF gun.
- Final energy of the electrons is of few-several MeV, peak current of 10-20 A
- Cathode material: copper, sometimes with Cs_2Te coating (higher quantum efficiency)



Linac

- The accelerating frequency is in the GHz range. For instance, LCLS uses S-band (~3 GHz) while SACLA and SwissFEL use C-band (~6 GHz).
- Higher frequencies permit acceleration of the beam over shorter distances → more compact linac.
- The linac can consist of normal-conducting RF cavities (“warm” technology) or superconducting ones (“cold” technology).
- In the latter case, many more pulses per second can be accelerated (e.g., 27 000 pulses per second at the European XFEL with superconducting RF compared to 100 pulses per second at SwissFEL with normal RF).



X-ray FEL machines
Electron beam properties and dynamics

Introduction

- In linac-based X-ray FELs the electron beam properties are not the result of an equilibrium due to the emission of synchrotron radiation as in circular accelerators.
- The properties are defined at the electron source, i.e., the RF photoinjector.
- The normalized emittances will ideally be preserved through the linac according to Liouville's theorem. Liouville's theorem will not be fulfilled and the beam emittances will be increased in the presence of some deteriorating stochastic effects such as non-linear space-charge forces or emission of coherent synchrotron radiation.
- The main goal in designing and operating an FEL facility is:
  1. Produce a high-brightness electron beam at the injector
  2. Accelerate and compress the beam in the linac while preserving its quality as much as possible.

Emittance optimization

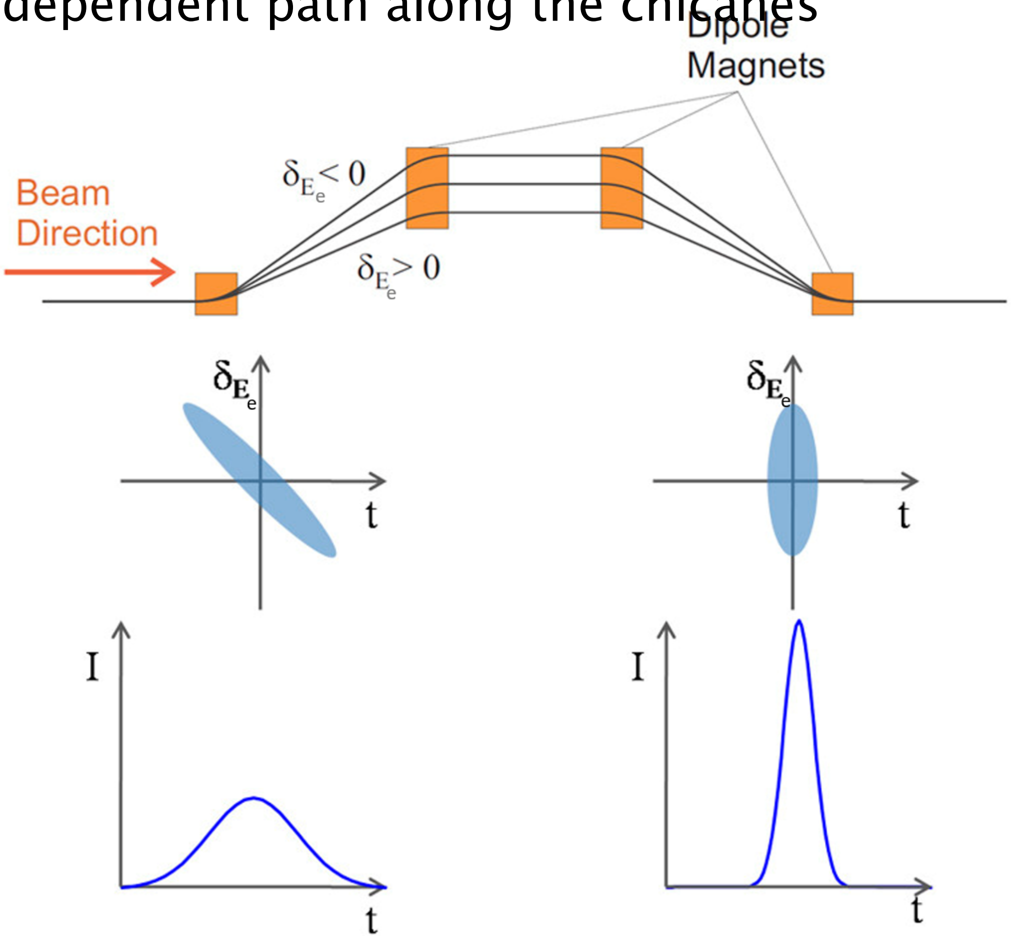
- The RF photoinjector produces electron beams with typical energies between 5 and 10 MeV, peak currents of 10–20 A, low normalized emittances (μm or below) and energy spreads of few keV.
- The emittance of the source is determined by three different components:
  1. intrinsic emittance of the cathode (depending on the laser size)
  2. space-charge forces
  3. RF field effects in the gun.
- The gun gradient is set as high as possible with available technology. At SwissFEL, the maximum field is 100 MV/m, giving 7.1 MeV at the gun exit.
- The gun is equipped with a solenoid magnet used to focus the electron beam.
- The laser spot size and the field generated by the gun solenoid are optimized to counteract the contributions of the intrinsic emittance (smaller for smaller spot size) and space charge (smaller for larger spot size) to the final emittance.

Bunch compression

Principle

1. Energy chirp generation with RF
2. Transport through magnetic chicanes

Compression thanks to the energy-dependent path along the chicanes



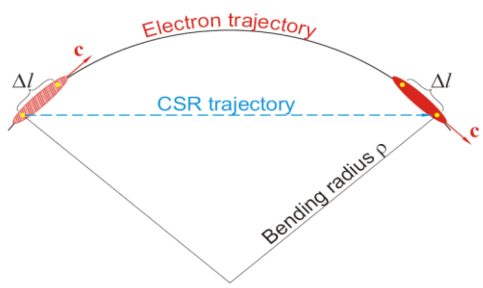
Where to compress?

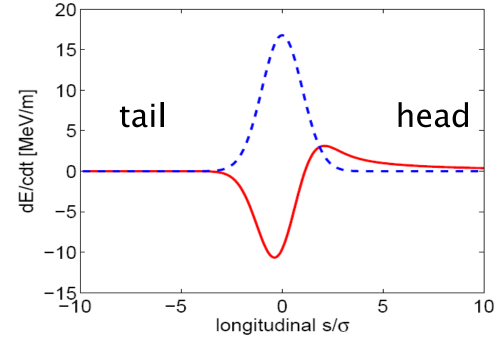
- Early compression→ high charge density beams at low energies→ emittance increase
- Late compression→ transport of long bunches trough the linac → emitance increase (due to RF-curvature, wake fields, …)

- Typically: compression done in 2 or 3 stages
  - 1st bunch compressor at few hundreds of MeV
  - 2nd bunch compressor at more than 1 GeV
  - Both stages compressing by a factor of ~10

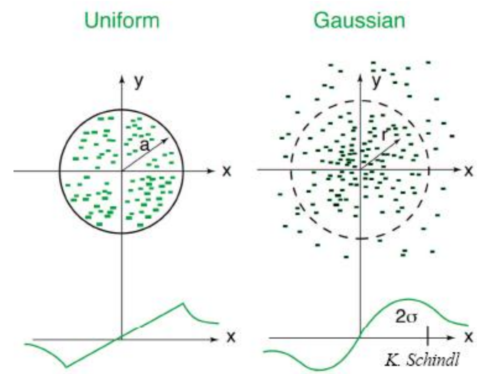
Self Interactions

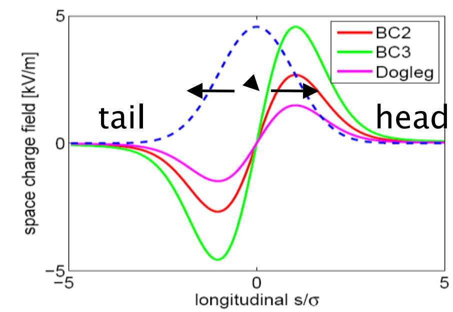
- High charge densities give rise to strong electro-magnetic fields generated by the electron bunches. Electrons within the bunch experience these fields.
- Coherent Synchrotron Radiation



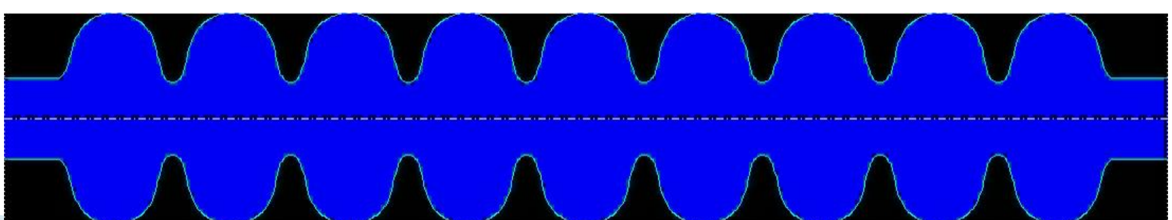


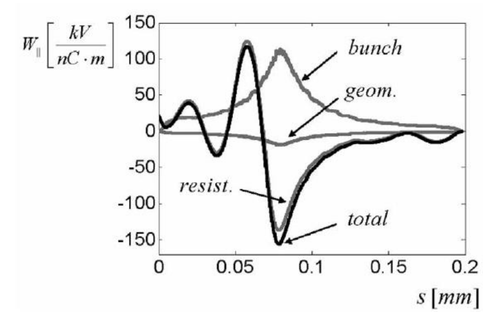
- Space Charge fields





- Wake fields





X-ray FEL machines
SwissFEL

Overview

- X-ray FEL project at PSI with 3 beamlines
  - Aramis (hard X-ray), Athos (soft X-ray), Porthos (new hard X-ray)
- Compact hard X-ray (~700 m) and cost-effective facility driven by electron beam with low energy (6 GeV), short undulator period (15 mm) and ultra-low emittance.
- Budget ~300 MCHF (~100 MCHF more for Porthos)
- First ideas around 20 years ago, construction started in 2013, Aramis commissioning started in 2016.
- Aramis first users since 2018, official user operation since 2019.
- Athos first users since 2021, official user operation since 2022.
- Porthos: from ~2030

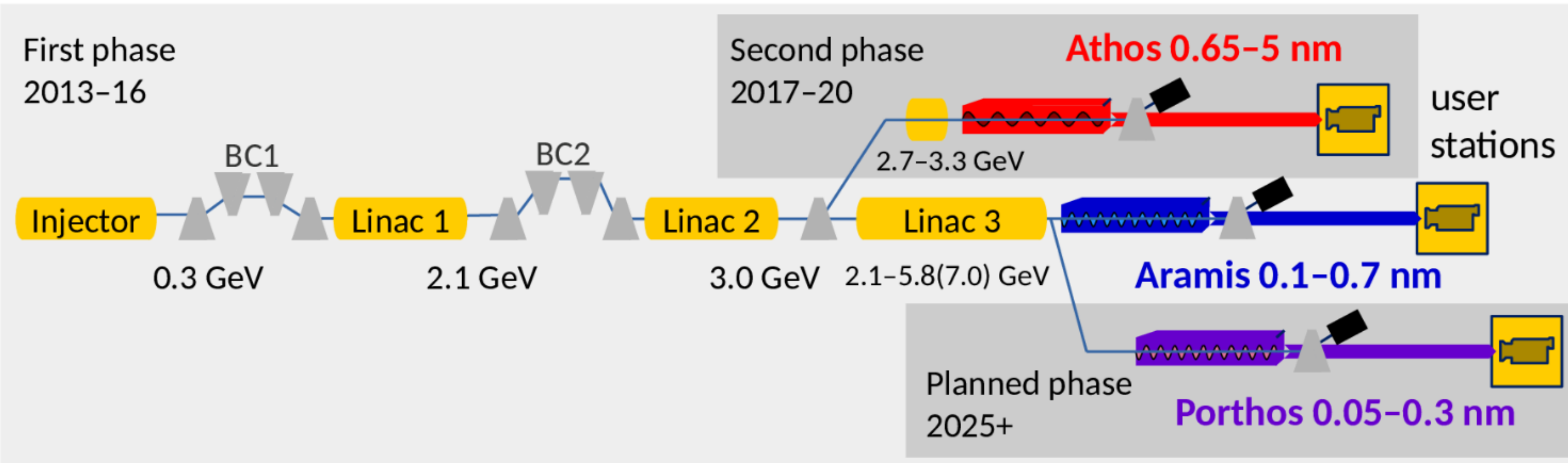
Layout and parameters

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, APPLE-X undulators

First users 2021



Linac:

Pulse duration : 1–20 fs

Electron energy : up to 5.8 GeV (7–8 GeV after upgrade)

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz, 2 bunches (3 bunches after upgrade)

Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, in-vacuum, variable-gap undulators

First users 2018

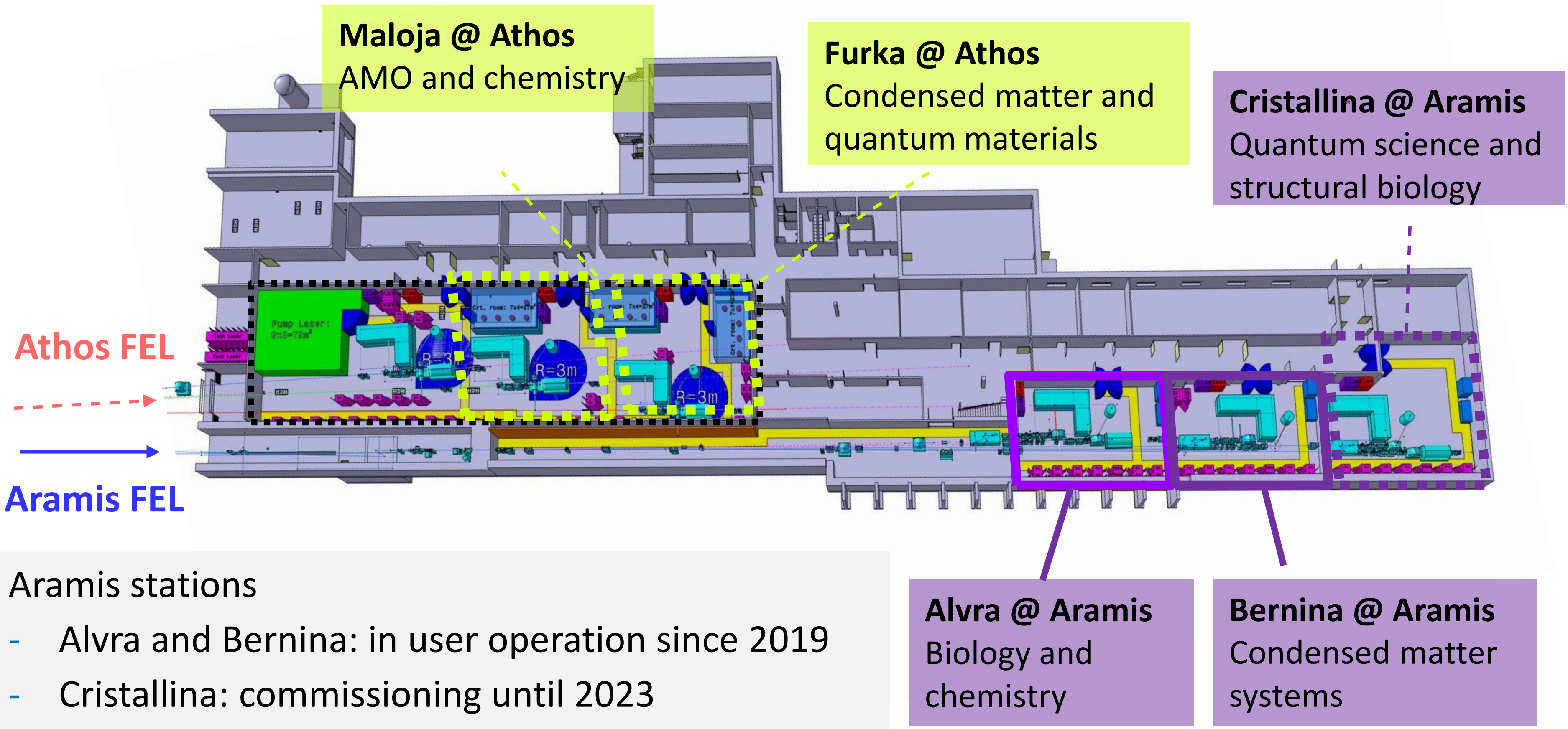
Porthos: (possible configuration)

Hard X-ray FEL, λ=0.05–0.3 nm

Variable polarization, in-vacuum, cryogenic APPLE-X undulators

Start of construction: 2025+

Experimental beamlines



Aramis stations
- Alvra and Bernina: in user operation since 2019
- Cristallina: commissioning until 2023

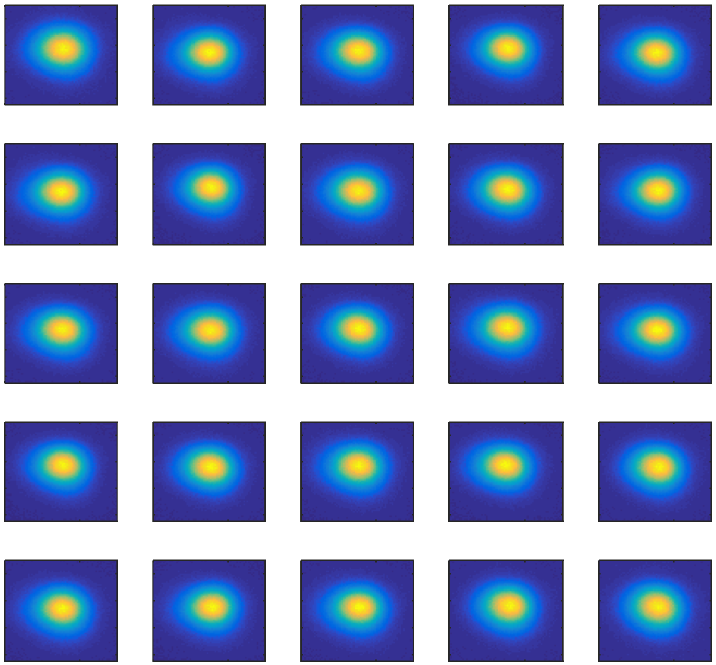
Athos stations:
- Maloja: first light in 2020, pilot experiments in 2021, first users in 2022
- Furka: first light in 2021, pilot experiments in 2022, first users in 2023

Diavolezza@Athos
Scientific concept and design phase

X-ray FEL machines
Stability

Stability

- Scientific users require extremely stable FEL radiation output in terms of:
  - pulse energy (~% level)
  - arrival time (~10 fs)
  - wavelength (~0.1%)
  - pointing (~10% of beam size).
- Several feedbacks are used for that:
  - Charge feedback (gun laser)
  - Trajectory feedbacks along the machine
  - Compression (current) feedbacks after each bunch compressor
  - Arrival time feedbacks
  - Electron beam energy feedbacks
- Need several diagnostics for:
  - Electron beam (BPMs, compression monitors, charge, arrival time, etc.)
  - Photon beam (spectrometer, pulse energy, arrival time, transverse profile…)



Example: shot to shot FEL spots at SwissFEL. Intensity stability of few %, pointing stability around 10% of the rms beam size

Comparison and conclusion

Synchrotrons vs X-ray FELs. Electron beam properties

	Synchrotrons	X-ray FELs
Emittance	≥ 300 pm in X ≥ 1 pm in Y Asymmetric beam	≥ 10 pm in X ≥ 10 pm in Y Round beam
Energy spread	$\sim 10^{-3}$	$\sim 10^{-4}$
Peak current	~10 A	**≥ 1 kA**
Pulse durations	~10 ps	**≤50 fs**

Synchrotrons vs X-ray FELs. Photon beam properties

	Synchrotrons	X-ray FELs
Pulse energy	~nJ	~mJ
Relative bandwidth	$\gg 10^{-4}$	$\sim 10^{-4}$
Peak brilliance	$10^{25} – 10^{27}$	$10^{35} – 10^{37}$
Repetition rate	~500 MHz	0.1 kHz – 1 MHz
User accessibility	Good >50 facilities, up to 50 beamlines per facility	Worse 5–10 facilities, up to 10 beamlines per facility

Conclusion

- Both synchrotrons and X-ray FELs are invaluable research tools capable of observing matter with spatial resolution at the atomic level.

- X-ray FELs offer higher peak brilliance, higher pulse energies and a better time resolution suitable to study the dynamics of processes occurring at the atomic level

- But synchrotrons have a higher repetition rate and provide easier access to the scientific community.

- Both tools are necessary and complementary

Thanks for your attention!