Free-Electron Lasers

Eduard Prat, Paul Scherrer Institut
JUAS, 30 January 2023

Contents

i. Introduction

ii. Basic physics principles:
   a) Electron motion
   b) Undulator radiation
   c) FEL radiation
   d) FEL modes
   e) FEL performance and requirements

iii. FEL driver accelerators

iv. FEL projects around the world

I. Introduction

3 Types of Light Sources

Optical short pulse lasers

Pulse duration: +++ (few fs)

Wavelength: - - - (~800 nm)

→ Fastest processes can be analyzed

→ Spatial resolution limited

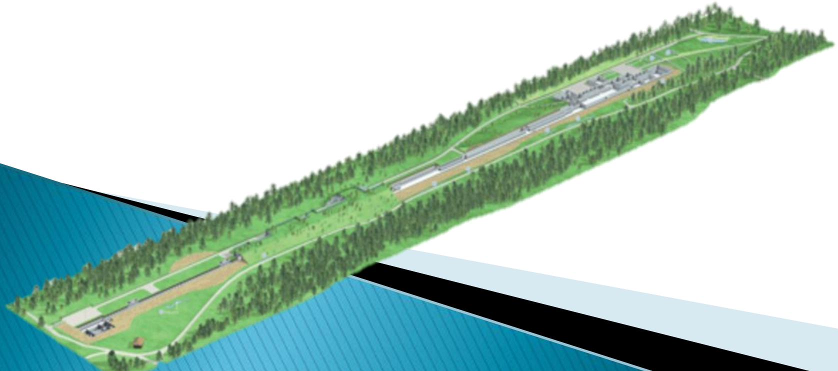
Synchrotrons

Pulse duration: o (few ps)

Wavelength: +++ (~ 0.1 nm)

→ Temporal resolution limited

→ Wavelength allows for atomic resolution



X-ray free-electron lasers

Pulse duration: +++ (few fs)

Wavelength: +++ (~ 0.1 nm)

→ Fastest processes can be analyzed

→ Wavelength allows for atomic resolution

Historical evolution of peak brilliance

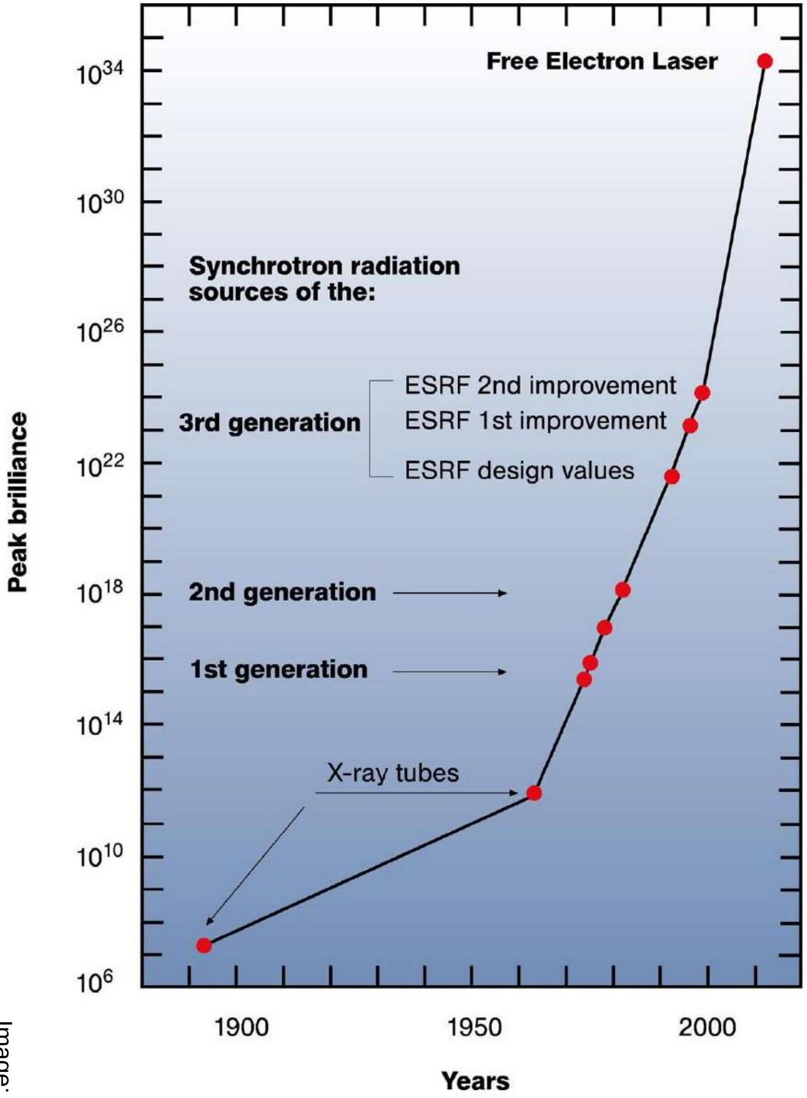


Image: www.xfel

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

Classification of synchrotron light sources:

- **1st generation:** parasitic use of synchrotrons built for particle physics
- **2nd generation:** dedicated synchrotrons / storage rings built for photon science
- **3rd generation:** dedicated storage rings optimized for operation with insertion devices (wigglers and undulators)
- **4th generation**: free electron lasers

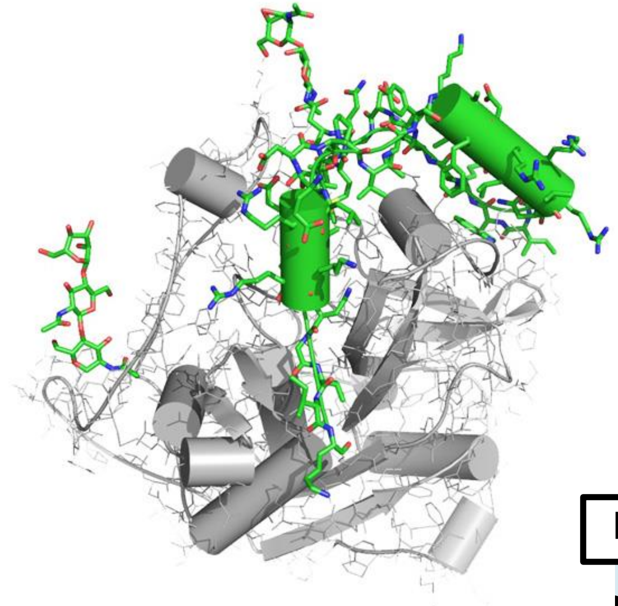
(ESRF is a reference for 3rd generation light sources)

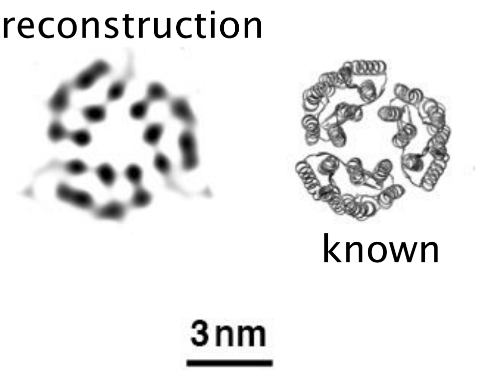
4th generation light sources: FELs

- The most brilliant light sources
- Tunable wavelength, down to 1 Angstrom
- Pulse Length less then 100 fs (sub fs demonstrated)
- High Peak Power well above 1 GW
- Fully Transverse Coherence
- Longitudinal coherence (with “seeding”)

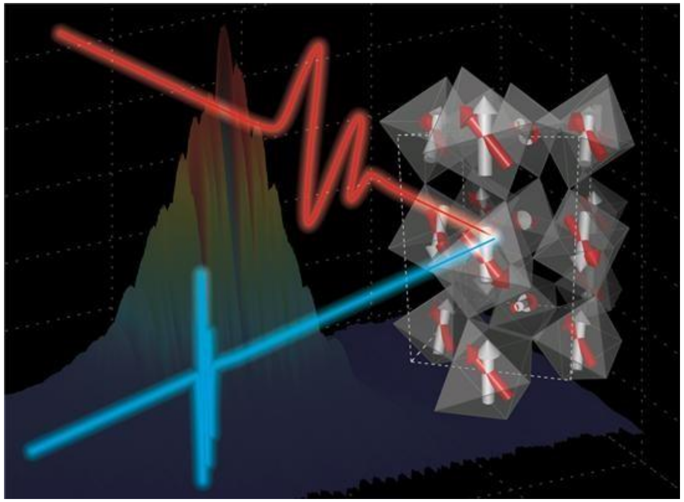
Science with light sources

- FELs are unique light sources to observe matter on **spatial AND time** scales of atomic processes
- They can address fundamental research questions across the disciplines of physics, chemistry, materials and life sciences.
- Examples:
  - Crystallography to determine structure and dynamics of biomolecules → discovery of new drugs for challenging diseases
  - Observation of transitions in quantum materials → development of new materials for multiple applications





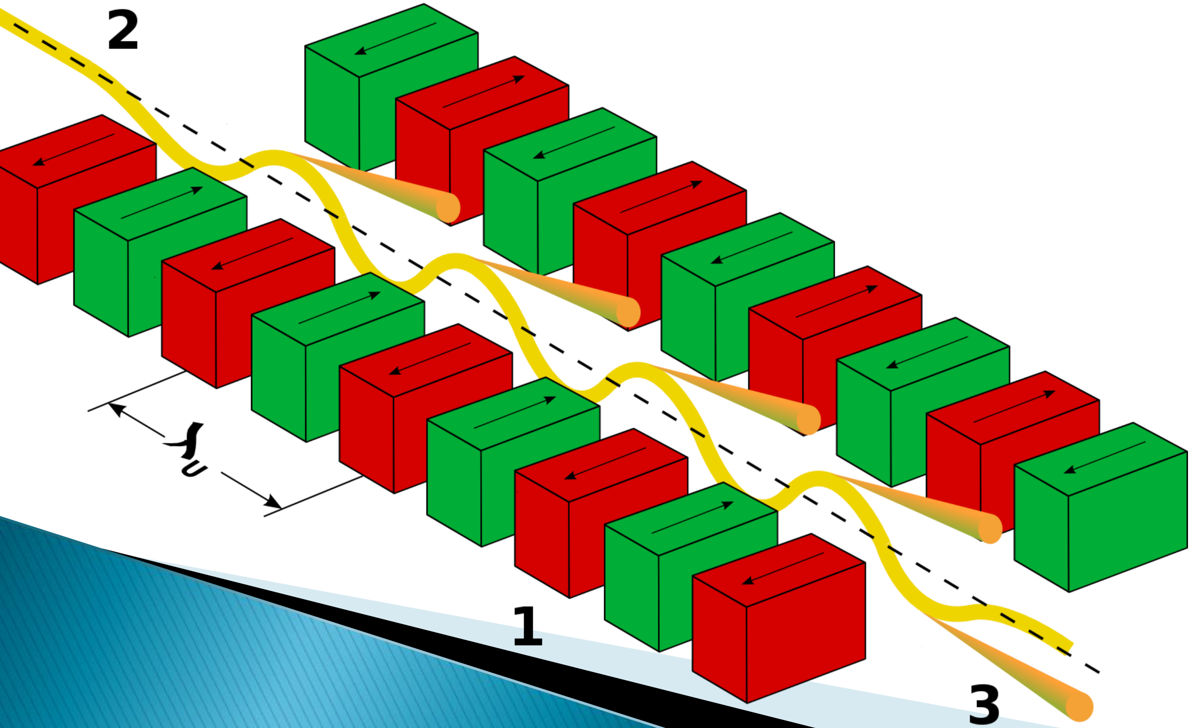
Ref. PNNL and FELs of Europe

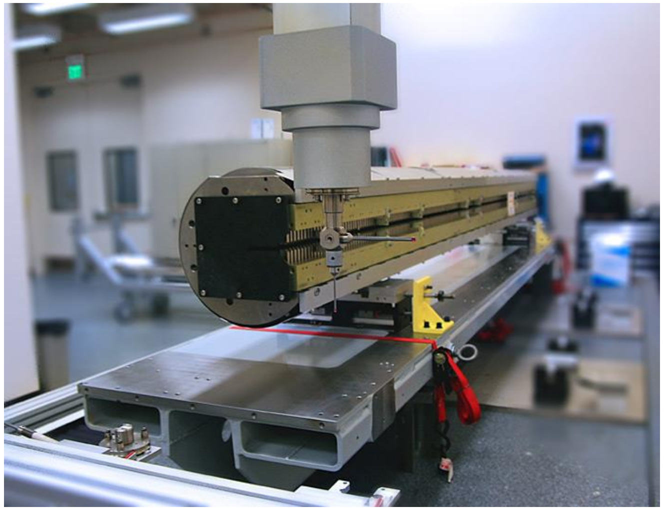


II. Basic physics principles
Electron motion

Forcing the Electrons to Wiggle…

- … by injecting them into an **undulator** i.e. a periodic structure of dipole magnets with alternating polarity, defined by the number of bending magnets N and the period λ_u (few cm)





Undulator from the LCLS-XFEL

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 a planar undulator

Transverse

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

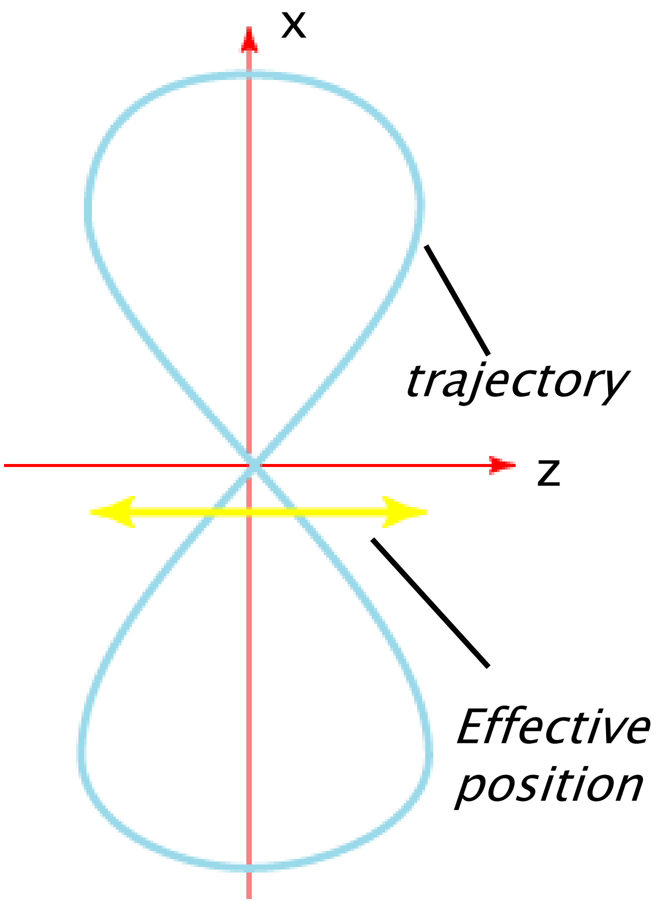
Longitudinal

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

Average over one period

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

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



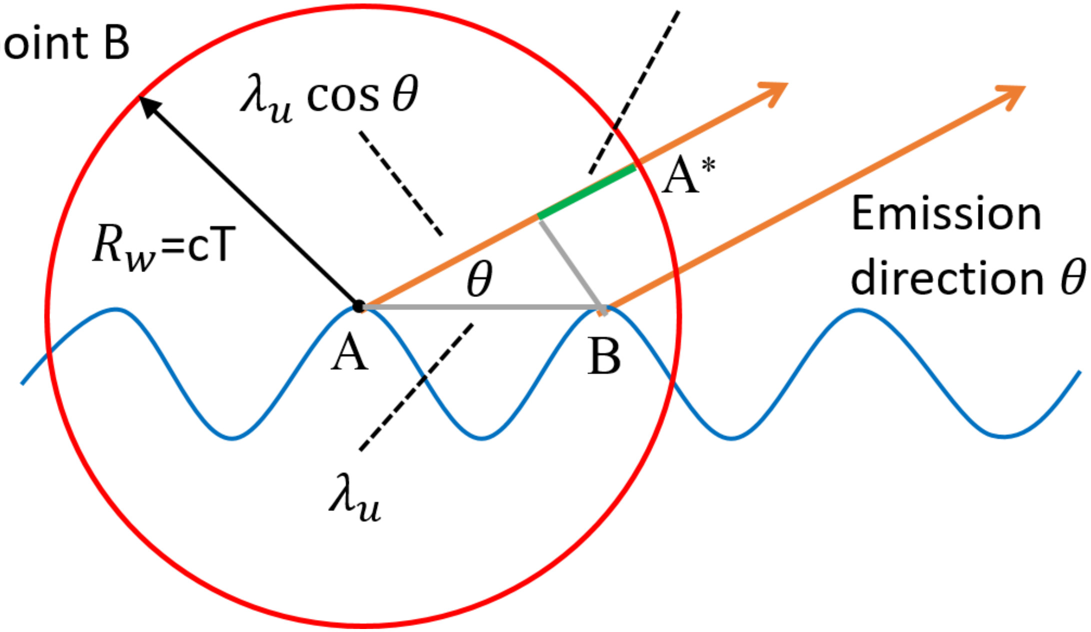
II. Basic physics principles. Undulator radiation

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 wavelength (or a multiple n) over one undulator period

$$\lambda \equiv R_w - \lambda_u \cos\theta$$

Wavefront from emission point A when electron is at point B



Emission direction θ

Resonance Condition (II)

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

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

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

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

For small angles

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

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

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

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 FEL Resonant Wavelength

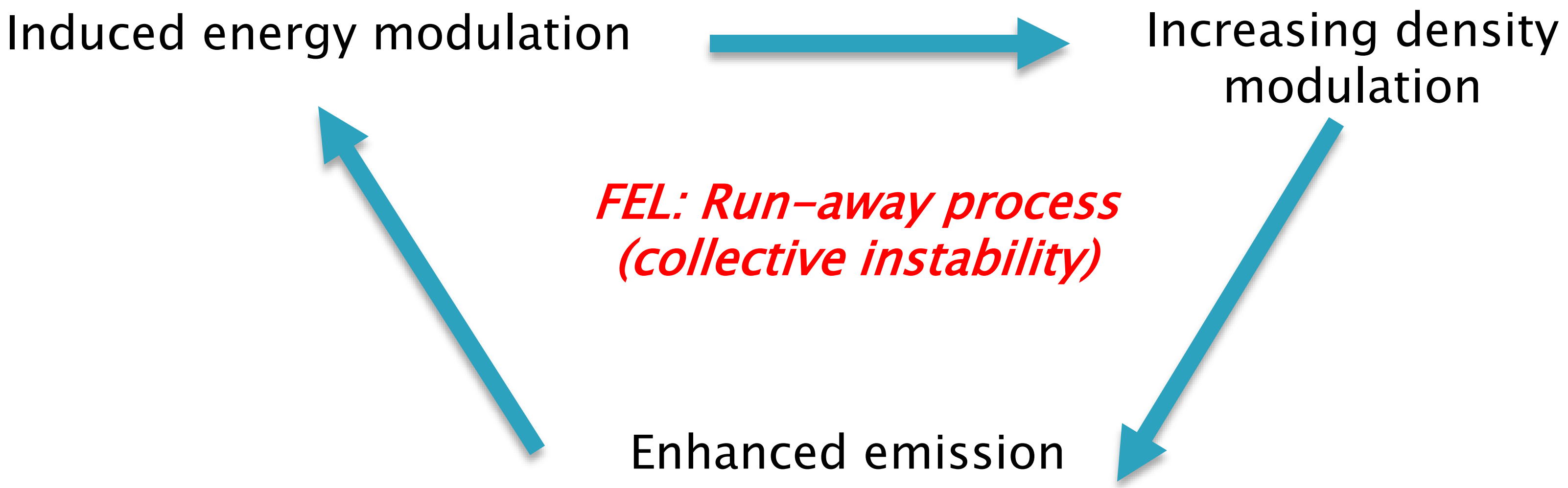
- Radiation wavelength much shorter than undulator wavelength (γ^2 factor)
- The wavelength can be controlled by
  - **Changing the electron beam energy,**
  - **Varying the magnetic field** (requires K significantly larger than 1)
- Example (SwissFEL): an undulator period of 15 mm, a K-value of 1.2 and an energy of 5.8 GeV (γ=11000) would give 1 Å radiation

The Free-Electron Lasers are based on undulator radiation in the forward direction with the resonant wavelength:

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

II. Basic physics principles. FEL radiation

Overview



Induced energy modulation

Increasing density modulation

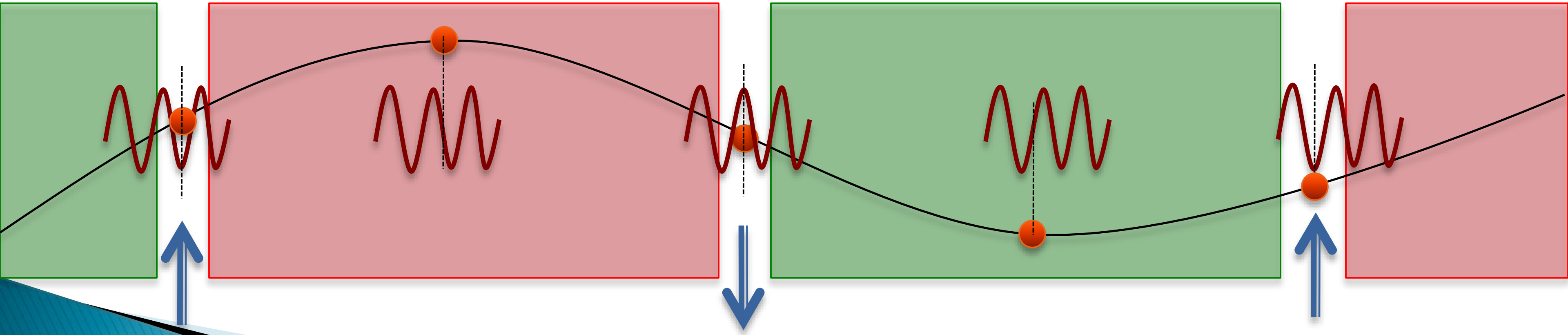
Enhanced emission

FEL: Run-away process (collective instability)

- The FEL process starts with an initial radiation field E_0 (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.



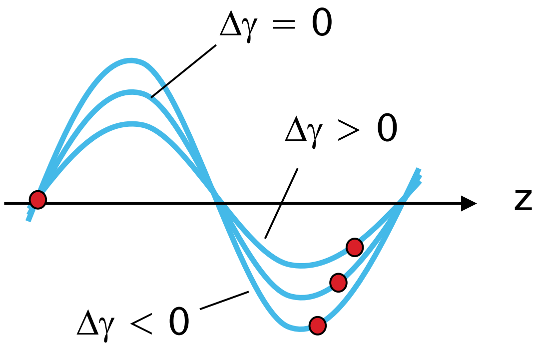
Energy modulation & microbunching

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

$$\boxed{\frac{d}{dz}\gamma = -\frac{e f_c K E_0}{2\gamma m c^2}\sin\phi}$$

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:



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

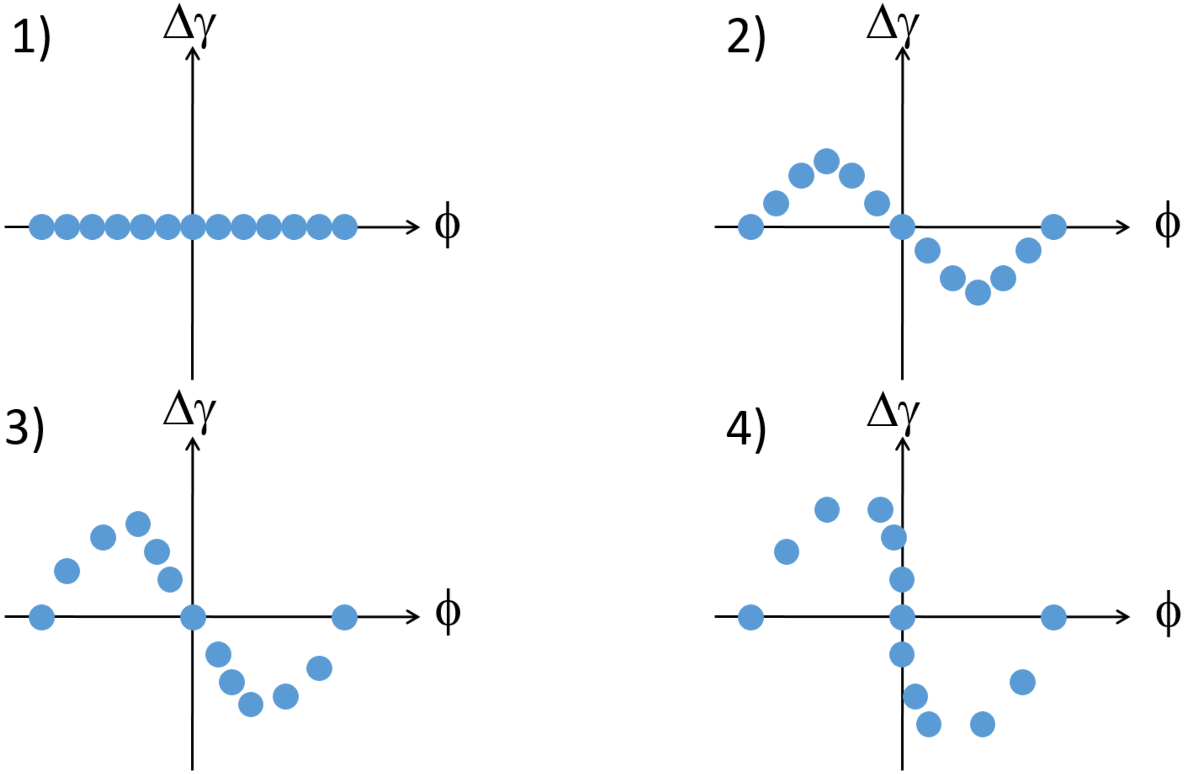
- Because of this effect the electrons move together → density modulation or microbunching

Motion in Phasespace

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

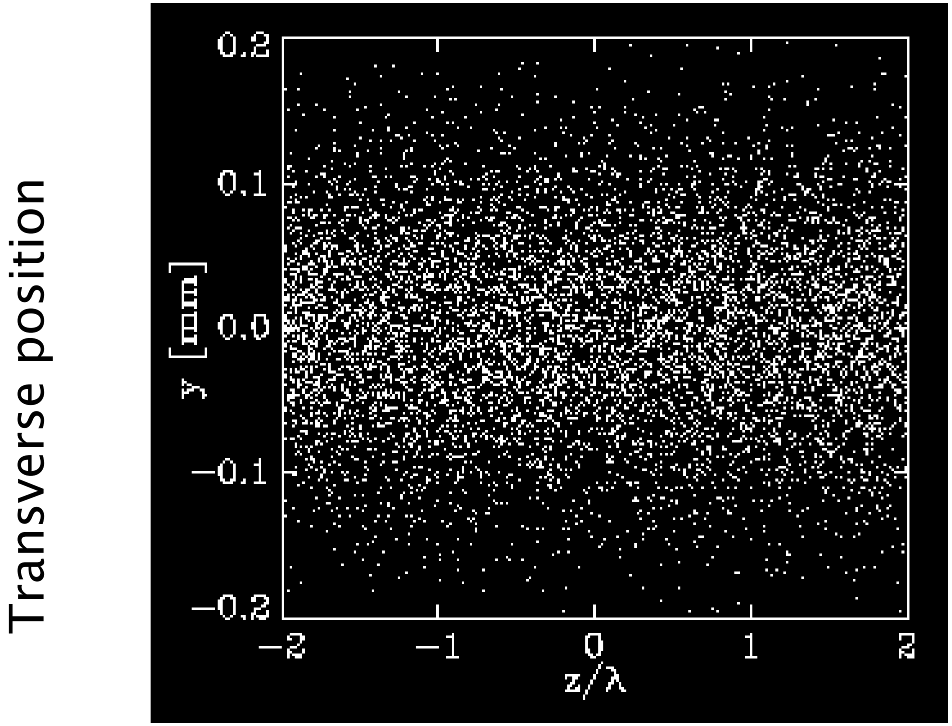
$$\frac{d}{dz}\phi = 2k_u\frac{\Delta\gamma}{\gamma}$$

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



Thanks to microbunching all electrons emit coherently.

Microbunching



Slice of electron bunch (4 wavelengths)

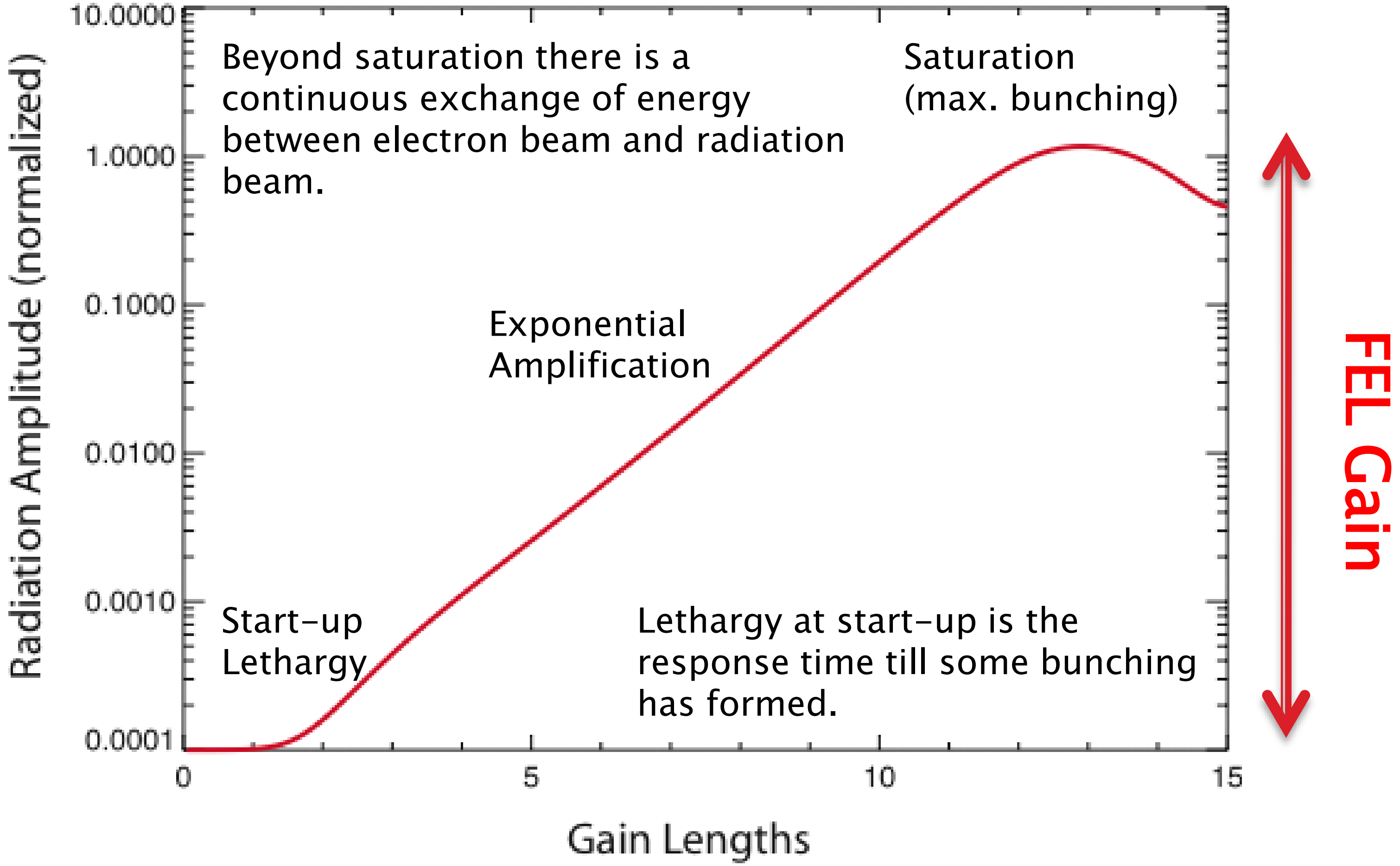
3D Simulation for FLASH FEL over 4 wavelengths

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



Beyond saturation there is a continuous exchange of energy between electron beam and radiation beam.

Saturation (max. bunching)

Exponential Amplification

Start-up Lethargy

Lethargy at start-up is the response time till some bunching has formed.

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

II. Basic physics principles. FEL modes

FEL Modes

- SASE FEL (Self-Amplified Spontaneous Emission)

Output

Electrons

Undulators

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

- FEL Amplifier (starts with an input signal)

Seed

Output

Electrons

Undulators

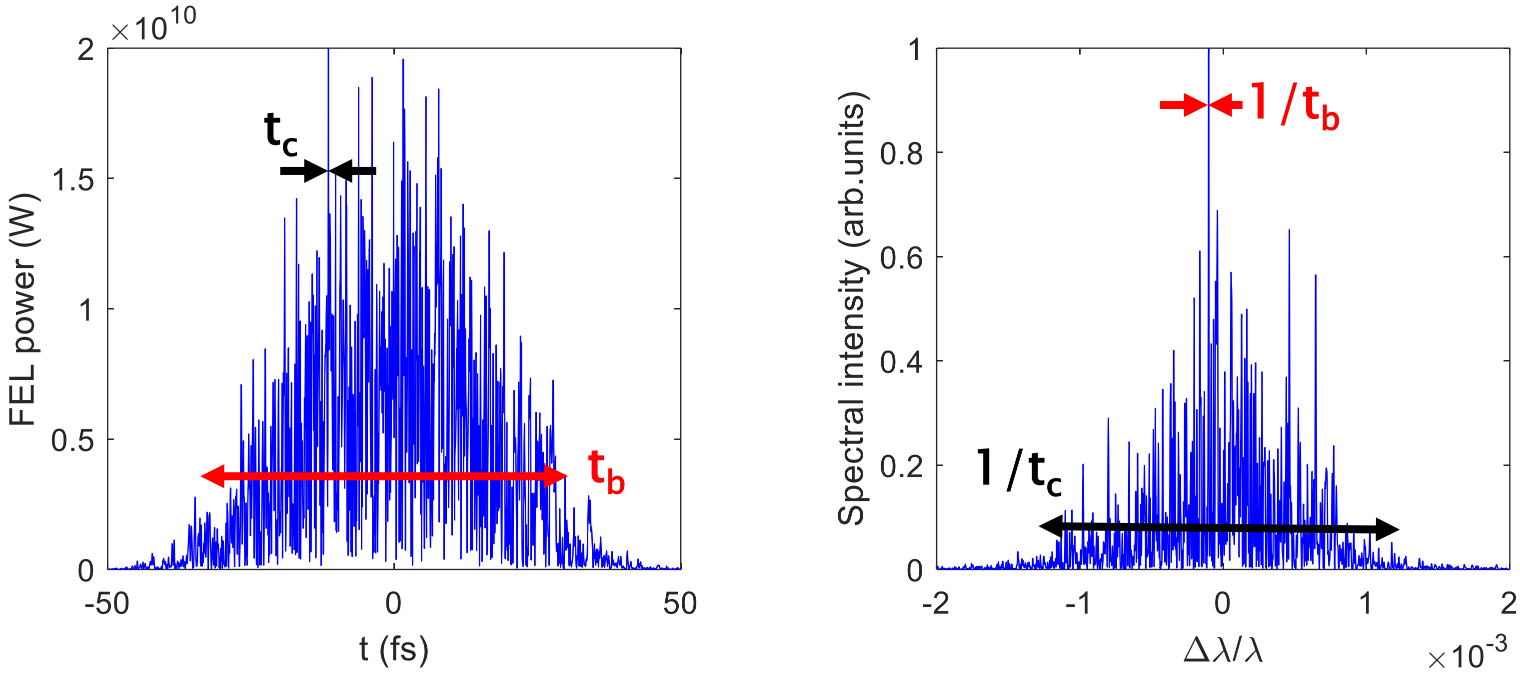
Seed must be above shot noise power (~kW for X-rays).
Output resembles the characteristics of the seed

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

SASE FELs

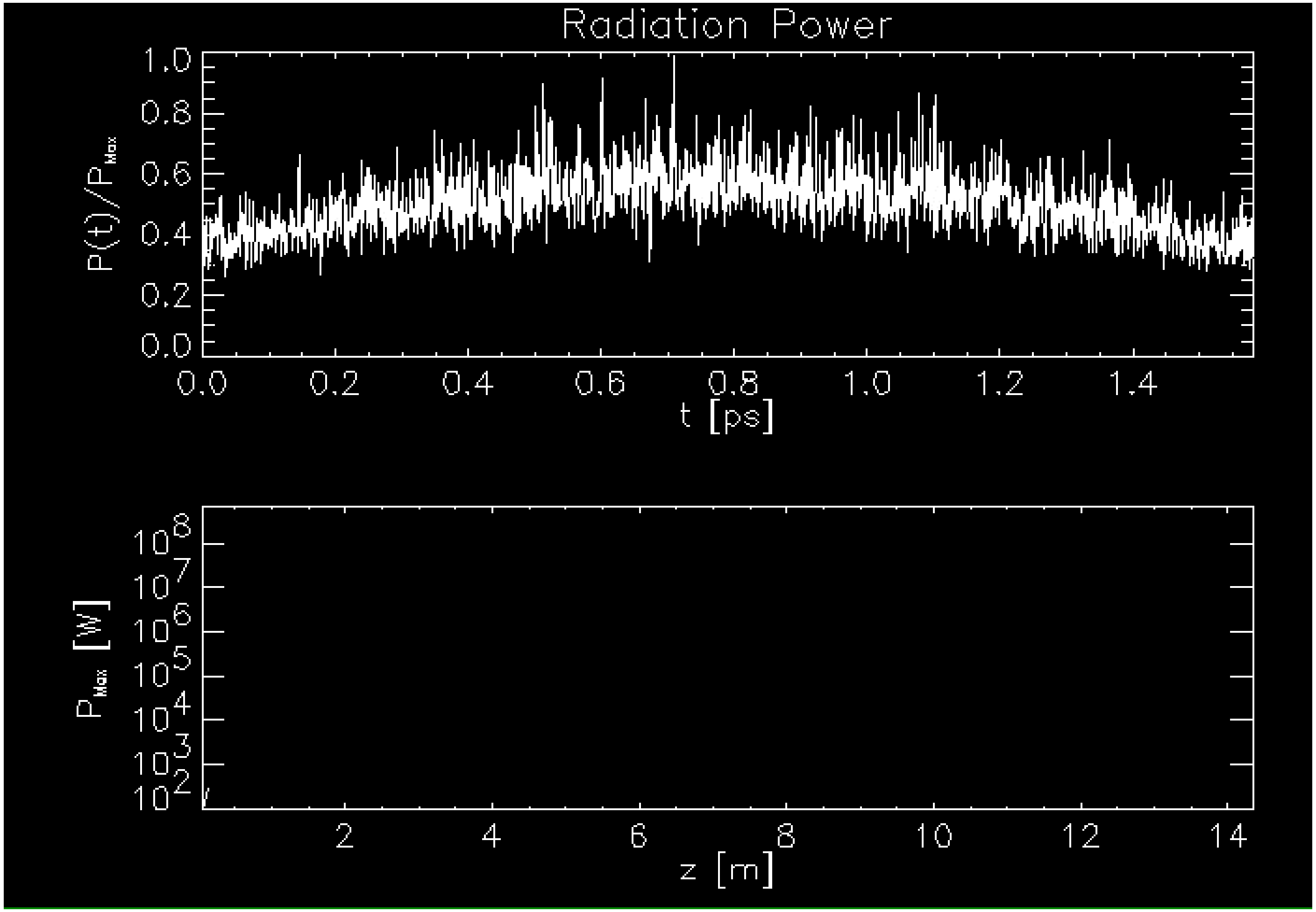
- FEL starts with the broadband signal of spontaneous radiation (almost a white noise signal)
- SASE-FEL radiation is coherent in the transverse direction but not in the longitudinal one → spikes in spectrum and time profile.
- The FEL bandwidth is of the order of the FEL parameter (see later)

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

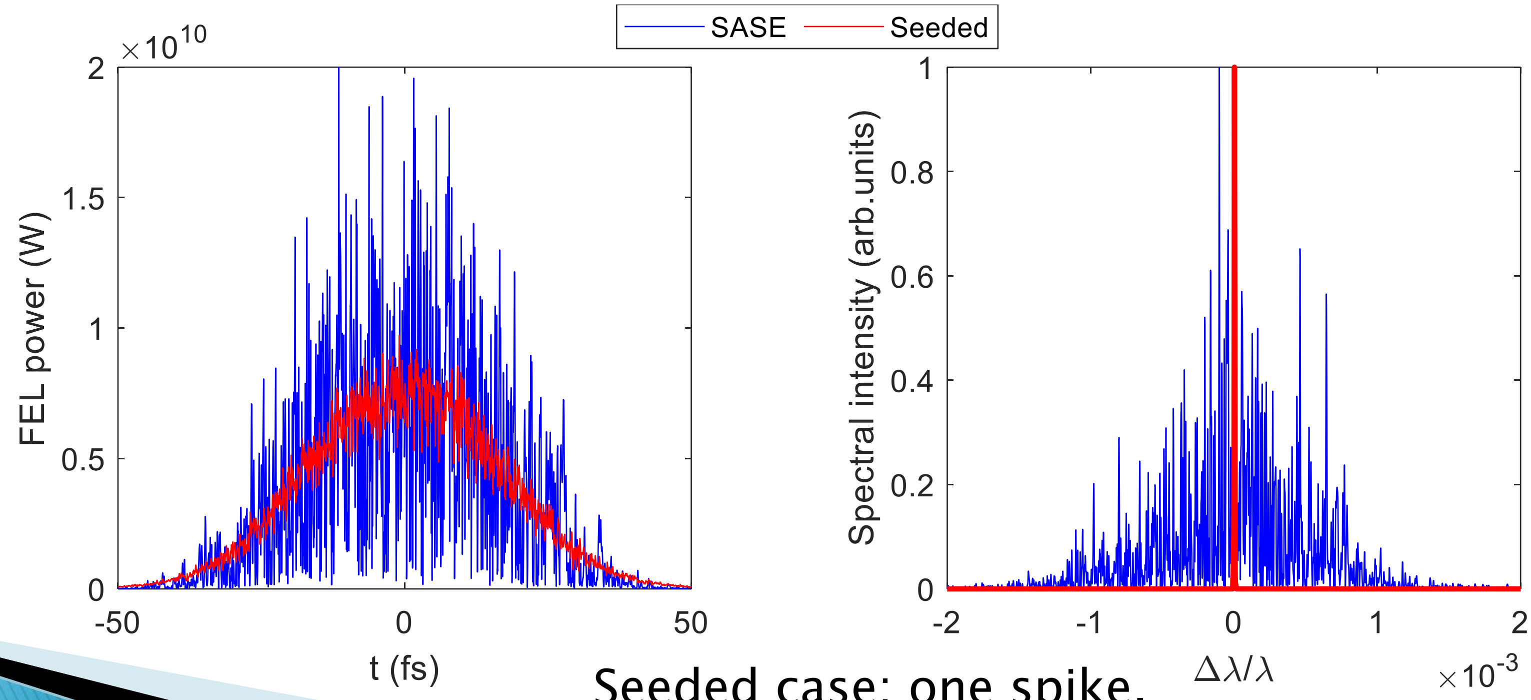


Simulation for FLASH FEL

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

II. Basic physics principles. FEL performance and requirements

FEL performance

- 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)

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

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

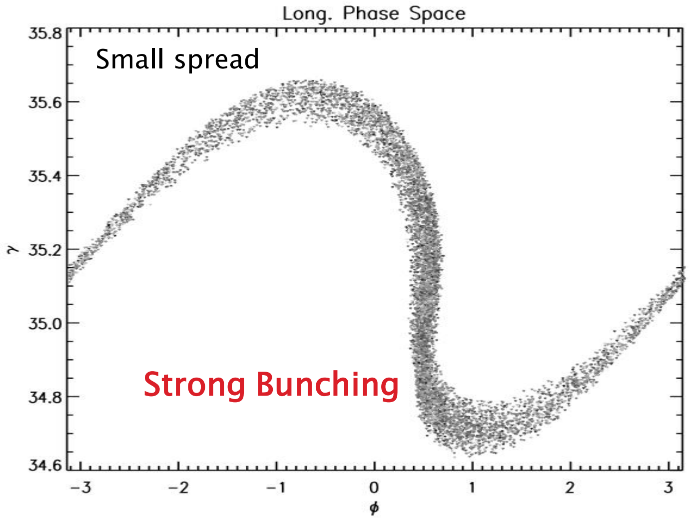
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\rho}$$

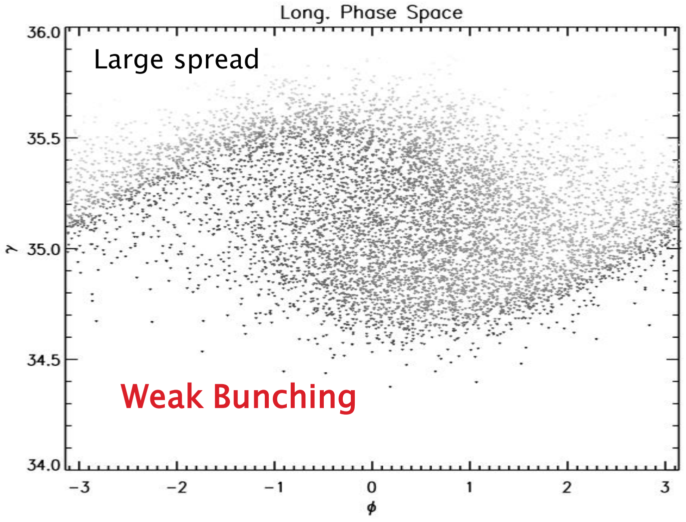
$$P_{FEL} \approx \rho P_{beam}$$

- 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:

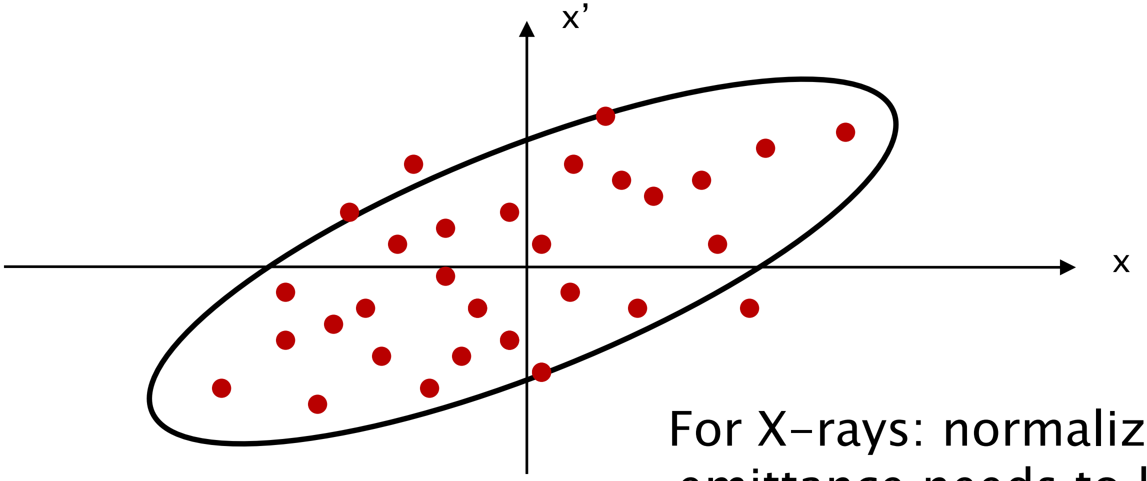
$$\frac{\sigma_\gamma}{\gamma} << \rho$$

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

IV. FEL driver accelerators

Linac-based FELs

- 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.

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

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

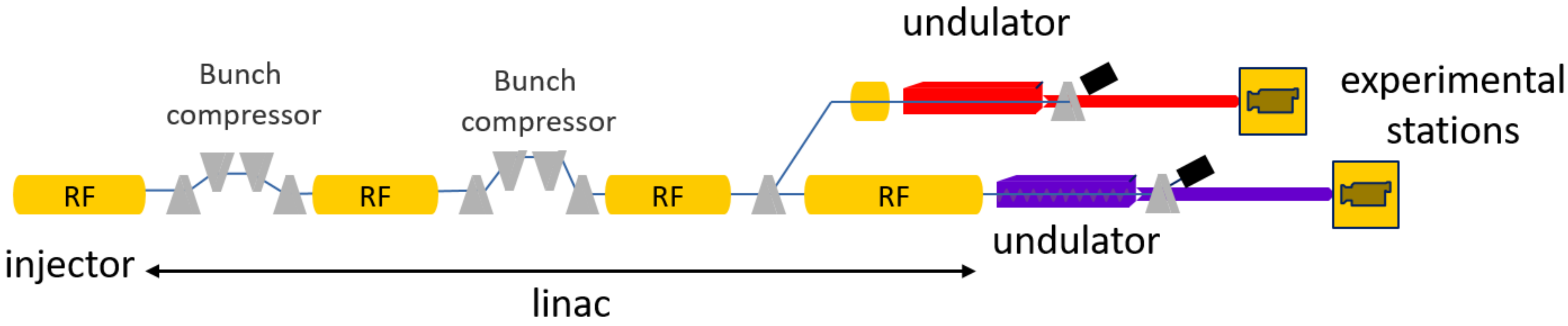
$$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$$

- For X-rays, the electron beam needs to have:
  ~GeV energies ~kA peak currents 0.01-0.1% energy spreads
  $\leq$ 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.
- Circular accelerators are not capable of delivering the required electron beam properties (in particular not the high peak current).

FEL machine layout

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 durations)
3. Undulator
4. Experimental stations



Electron sources

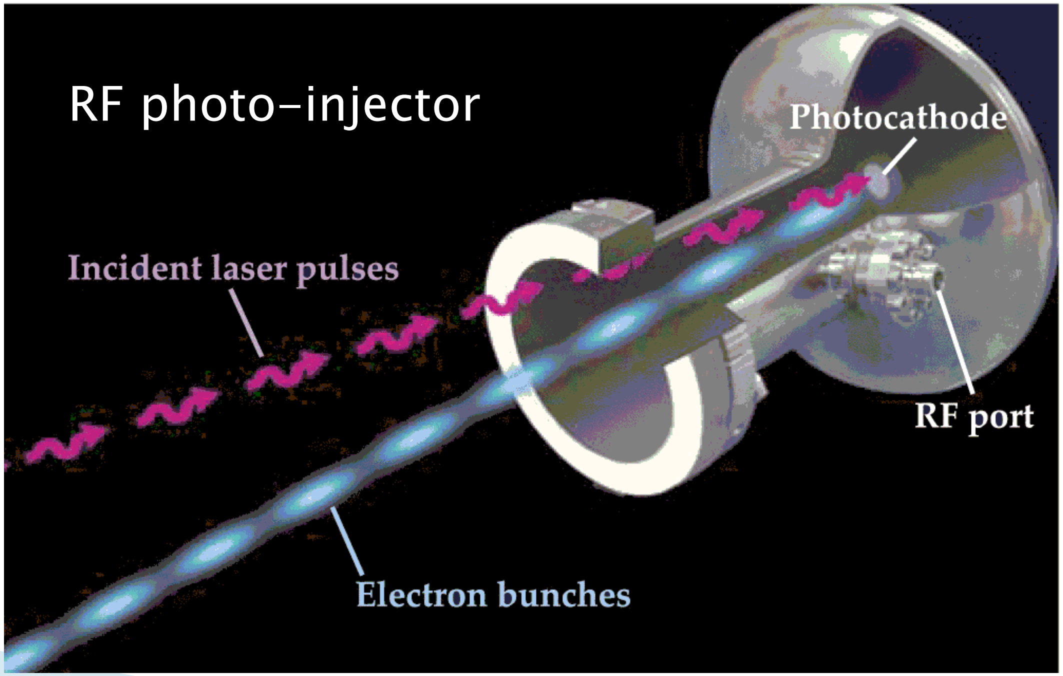
- RF photo-injectors are normally used to generate high-brightness electron beams
- Electrons are produced via the photo-electric effect by a laser of a proper wavelength impinging on a photocathode mounted inside an RF gun.
- Final energy of the electrons is of few-several MeV

- Emittance of the source is determined by: intrinsic emittance of the cathode, space-charge and RF effects.

- Emittance goals:

1. Optimize the source emittance
2. Preserve emittance along the linac

C. Hernandez-Garcia, P. G. O' Shea, and M. L. Stutzman, Phys. Today 61(2), 44 (2008).

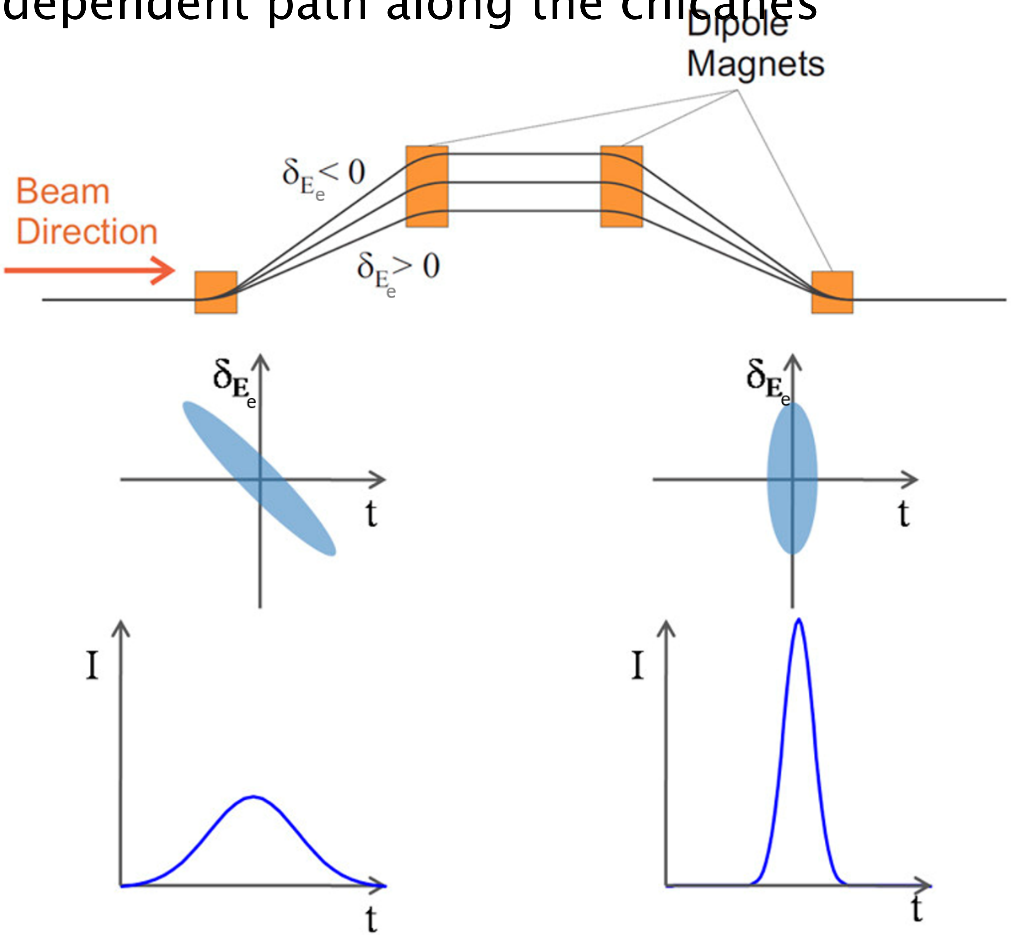


Bunch compression

Principle

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

Compression thanks to the energy-dependent path along the chicanes



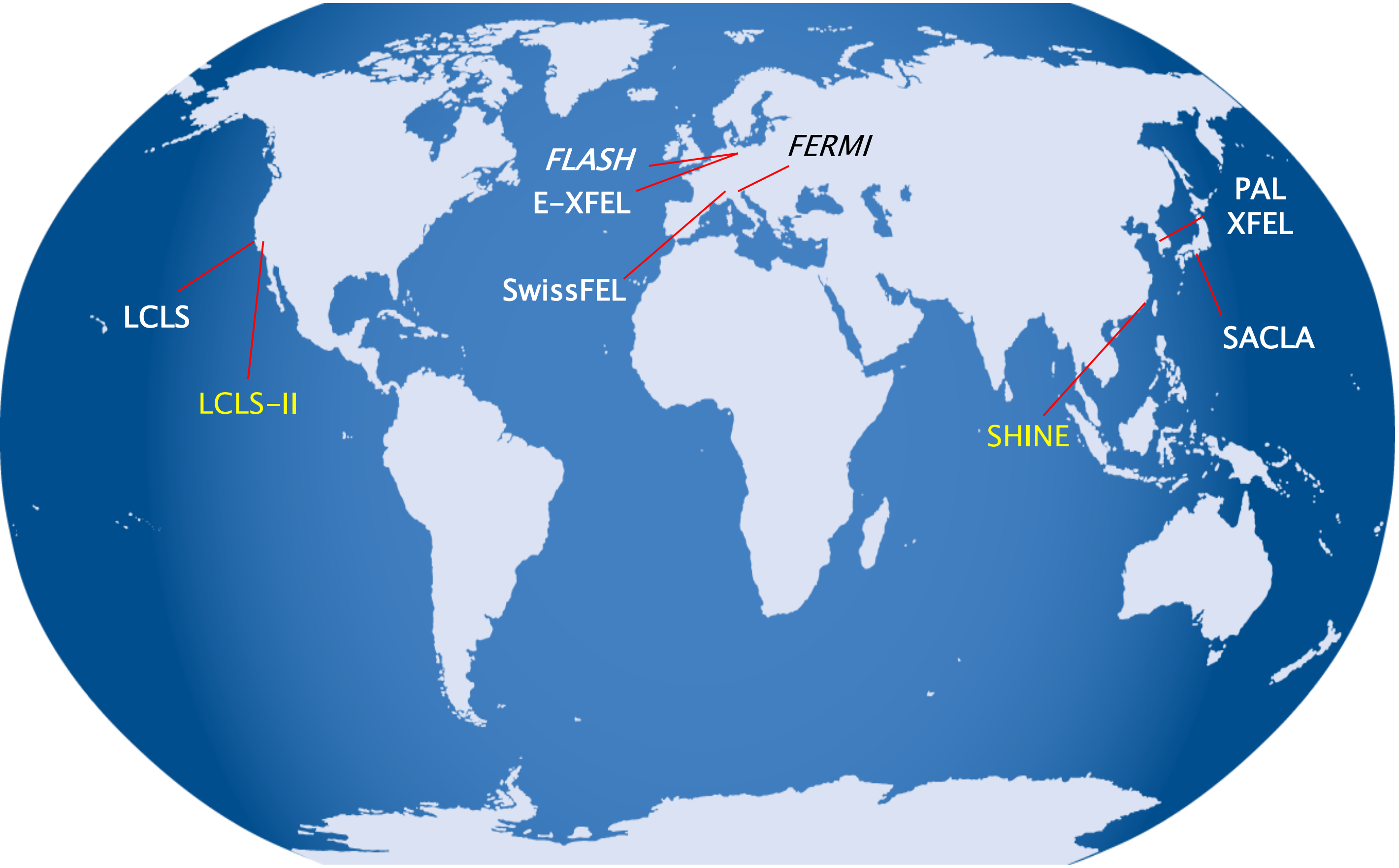
Where to compress?

- 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

V. FEL projects around the world

X-ray FEL Projects Around the World



- FLASH: first soft X-ray with high repetition rate (MHz), 2007
- LCLS: first hard X-ray, 2009
- 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 with high repetition rate, 2017
- SwissFEL: compact hard X-ray driven by low emittance beam, 2017

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

Future facilities: LCLS2 and SHINE (high repetition rate)

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]*

SwissFEL: overview

- X-ray FEL project in Switzerland (Villigen) with 2 beamlines
  - Aramis (hard X-ray)
  - Athos (soft X-ray)
- Compact (~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
- First ideas more than 15 years ago.
- Construction started in 2013.
- Commissioning started in 2016.
- 2018: pilot experiments in Aramis. 2019: first user experiments.
- Athos: first FEL light by end of 2019, first pilot experiments from 2021.

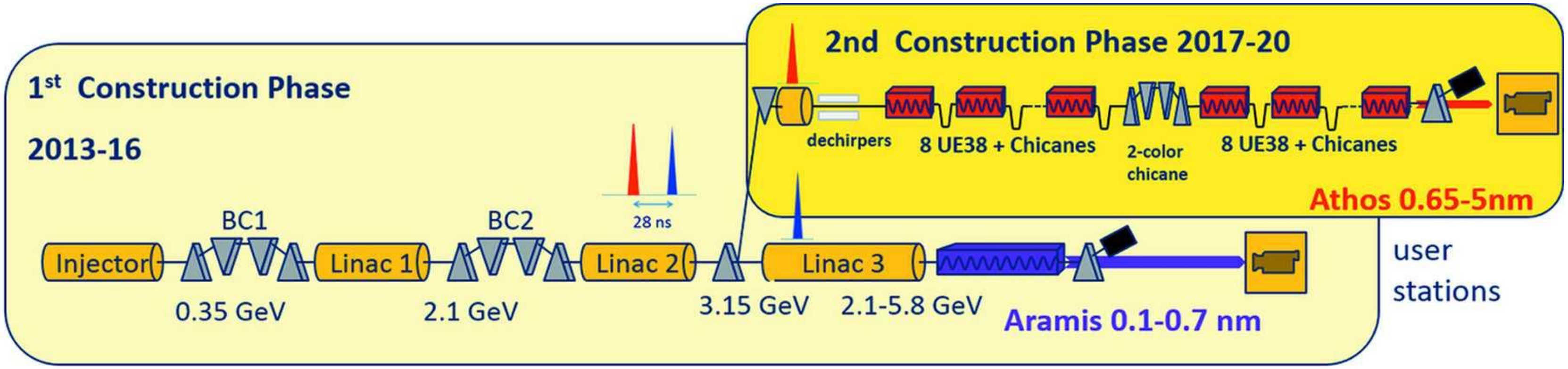
SwissFEL: layout and parameters

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, in-vacuum undulators

First users 2018

Main parameters:

Photon wavelength: 0.1–5 nm

Photon energy : 0.2–12 keV

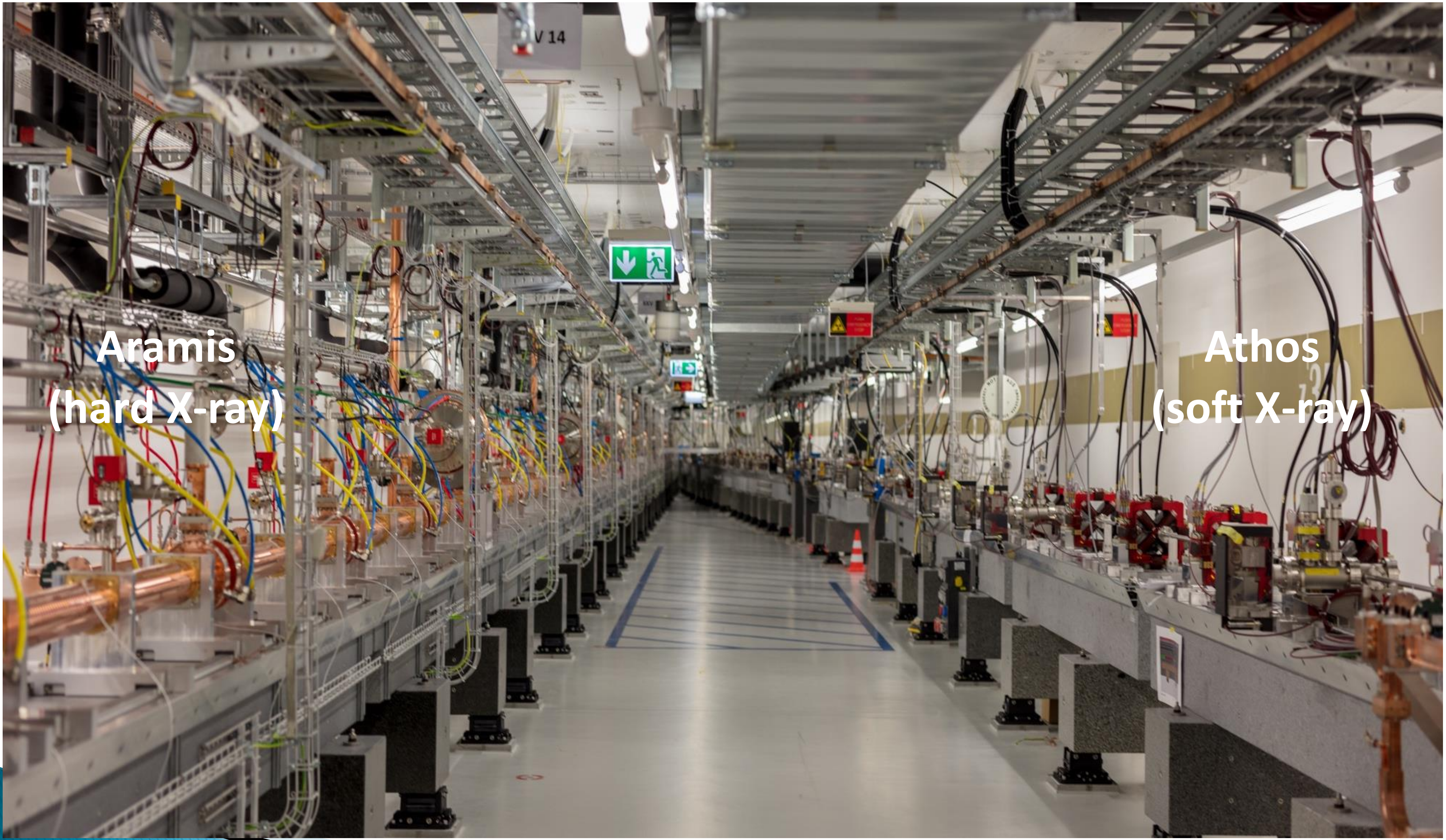
Pulse duration : 1–20 fs

Electron energy : up to 5.8 GeV

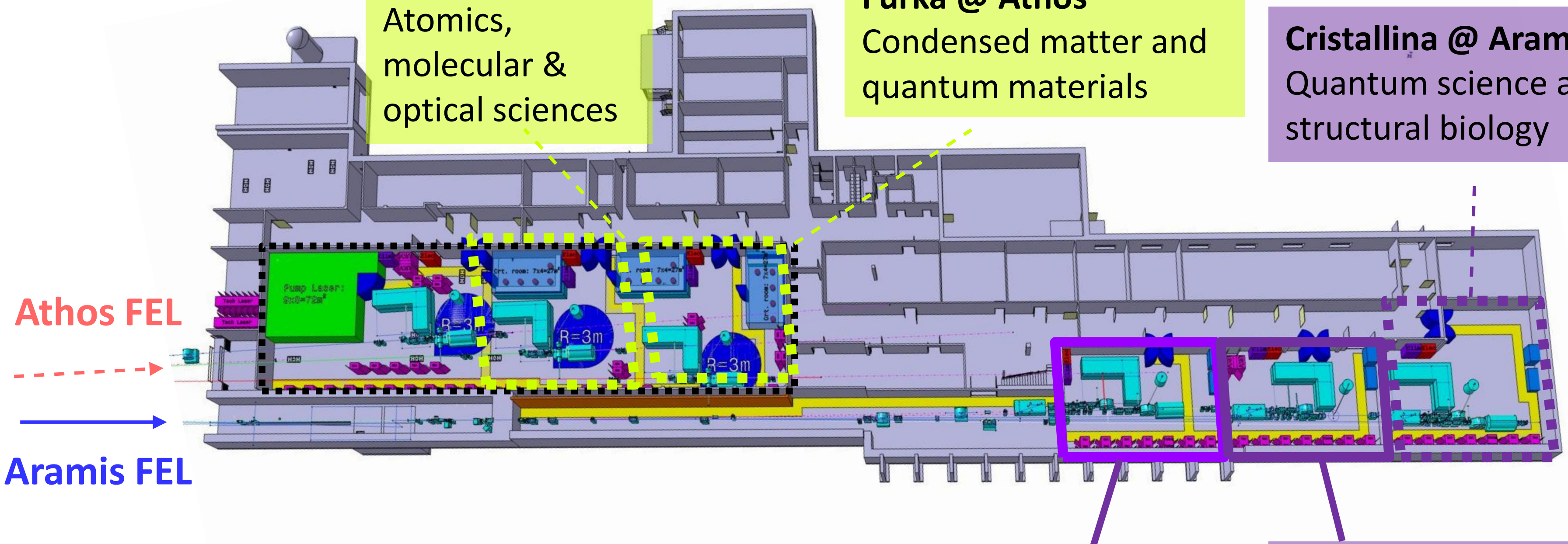
Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

SwissFEL



SwissFEL: experimental beamlines



Maloja @ Athos
Atomics, molecular & optical sciences

Furka @ Athos
Condensed matter and quantum materials

Cristallina @ Aramis
Quantum science and structural biology

Alvra @ Aramis
Ultrafast biology and chemistry

Bernina @ Aramis
Ultrafast phenomena in condensed matter systems

Aramis stations

- Alvra and Bernina: in user operation since 2019
- Cristallina: first users in 2023

Athos stations:

- Maloja: in user operation since 2022
- Furka: first users in 2023
- (Diavolezza: after 2023)

References

References

Z. Huang and K. J. Kim, “Review of X-ray Free-Electron Laser Theory”. *Physical Review Special Topics – Accelerator and Beams 10*, 0.4801/1-034801/38, 2007.

K. J. Kim, Z. Huang, and R. Lindberg, *Synchrotron Radiation and Free-Electron Lasers*. Cambridge University Press, 2017.

C. Pellegrini, A. Marinelli, and S. Reiche, “The physics of x-ray free-electron lasers”. *Reviews of Modern Physics 88*, 015006, 2016.

E. L. Saldin, E. A. Schneidmiller and M. V. Yurkov, *The Physics of Free-Electron Lasers*. Springer, 1999.

P. Schmüser, M. Dohlus and J. Rossbach, *Ultraviolet and Soft X-Ray Free-Electron Lasers. Introduction to Physical Principles, Experimental Results, Technological Challenges*. Springer, 2009.

P. Willmott, *An Introduction to Synchrotron Radiation. Techniques and Applications*. Wiley, 2019.