Free-Electron Lasers

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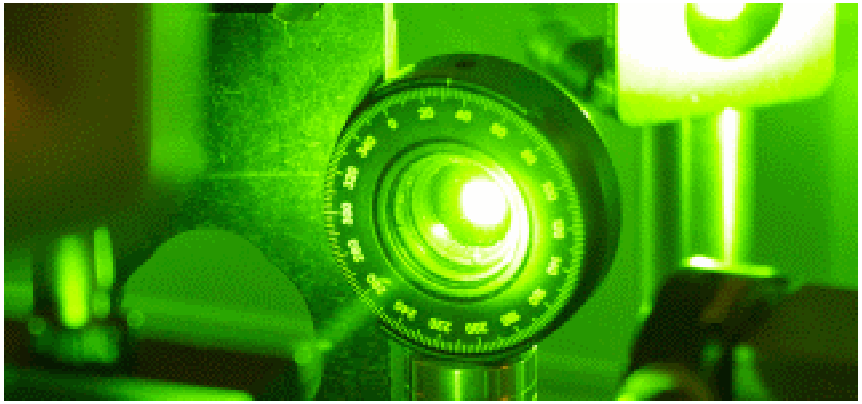
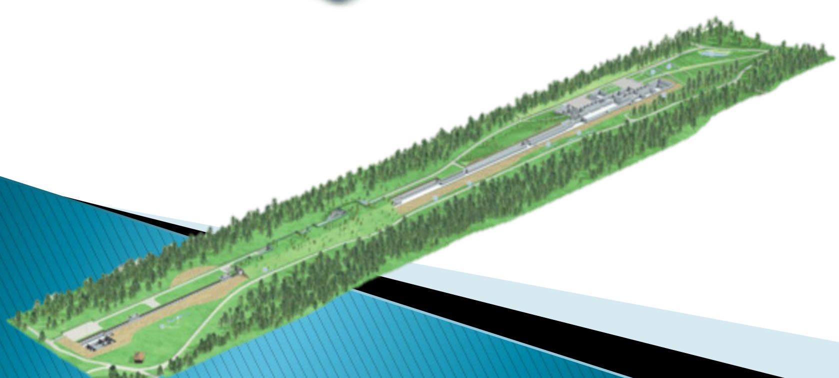


Optical short pulse lasers
Pulse duration: +++ (few fs)
Wavelength: – – – (~800 nm)
→ Fastest processes can be analyzed
→ Spatial resolution limited

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

3 Types of Light Sources

	Optical lasers	Synchrotrons	FELs
Time atomic res.	Yes	No	Yes
Spatial atomic res.	No	Yes	Yes
Pulse energy	few mJ	< nJ	few mJ
Rep rate	< 0.1 MHz	~500 MHz	~0.1 – 1 MHz
Facility cost	Moderate (≥10 MEUR)	High (≥100 MEUR) (but government funded)	Very High (≥300 MEUR) (but government funded)
User accessibility	Poor, normally buy it yourself!	Good: ~50 user facilities worldwide (~10 beamlines each)	Fair: ~5 user facilities worldwide (1-2 beamlines each)

- **FELs are the only source providing atomic resolution in space and time but they are expensive → use them only when high power or ultra-short pulses are required**
- **Synchrotrons are sufficient for most of studies on structural analysis**

All light sources are necessary and complementary

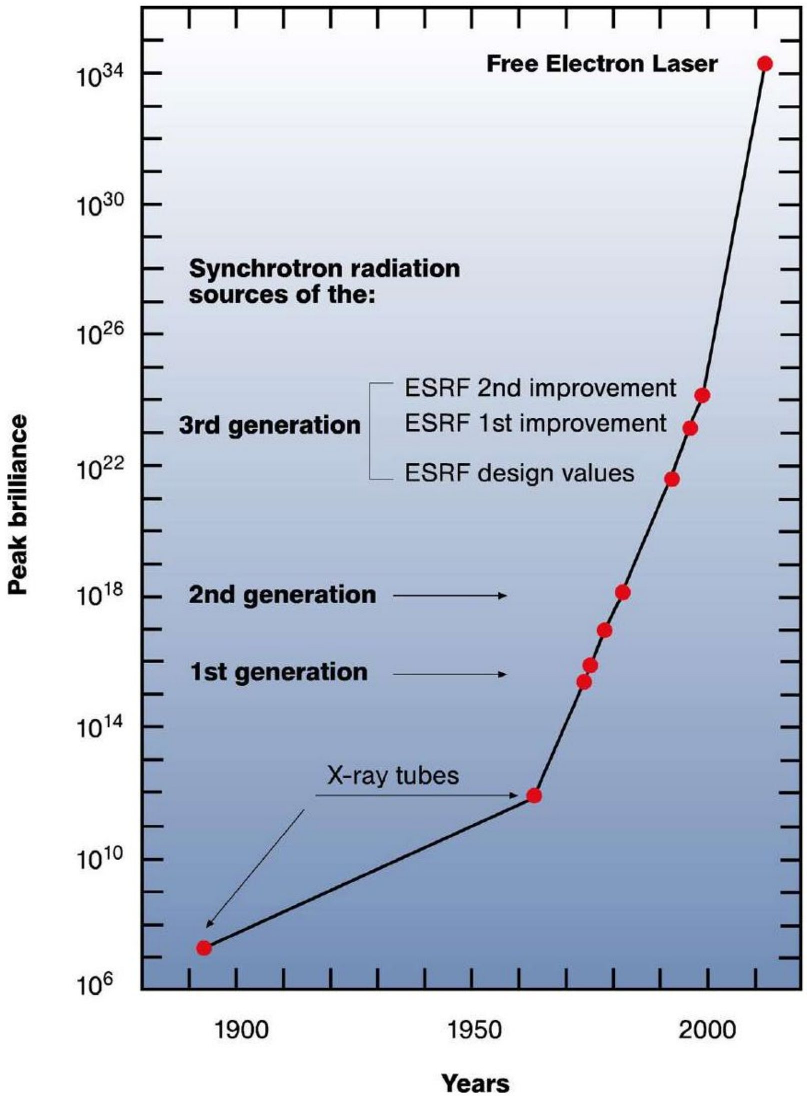
Brilliance

- At the business end, the appropriate figure-of-merit for light sources is the **brilliance.**
- It takes into account:
  - the number of photons produced per time unit (use second)
  - the angular divergence of the photons (in $mrad^2$)
  - the cross-sectional area of the photon beam (use mm^2)
  - the number of photons falling within a certain bandwidth (BW) of the central wavelength (0.1% are customary)
- Therefore the awkward but appropriate unit for brilliance is:

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

- Some other terms are used in the literature
  - *brightness* (should be reserved for the phase-space density of particle beams)
  - *intensity* (should only be used for power per unit area!)
  - *photon flux* (is the number of photons per time and area, it misses divergence and bandwidth)

Historical evolution of peak brilliance



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

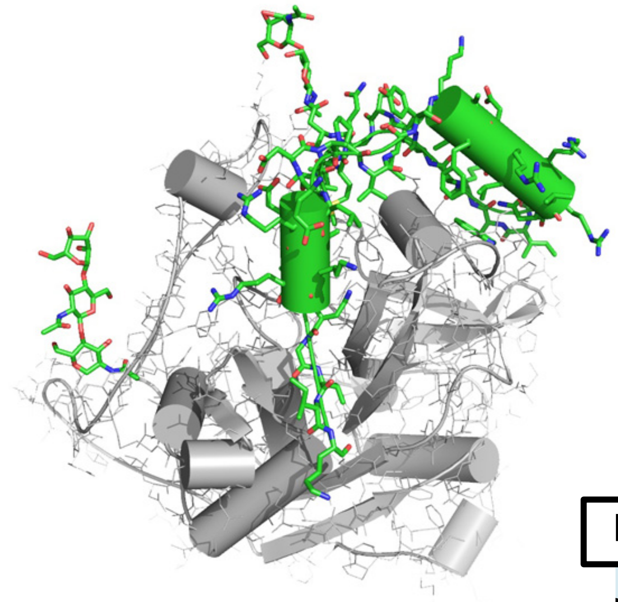
(ESRF is a reference for 3rd generation light sources)

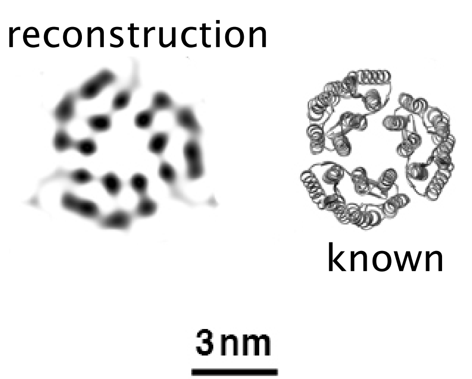
4th generation light sources: FELs

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

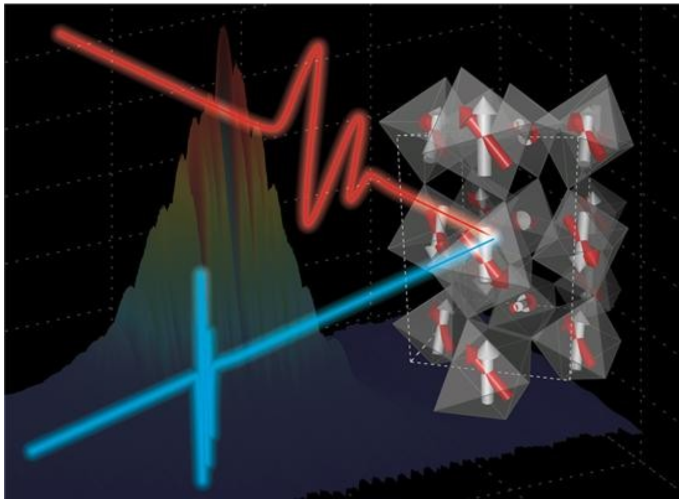
Science with light sources

- 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





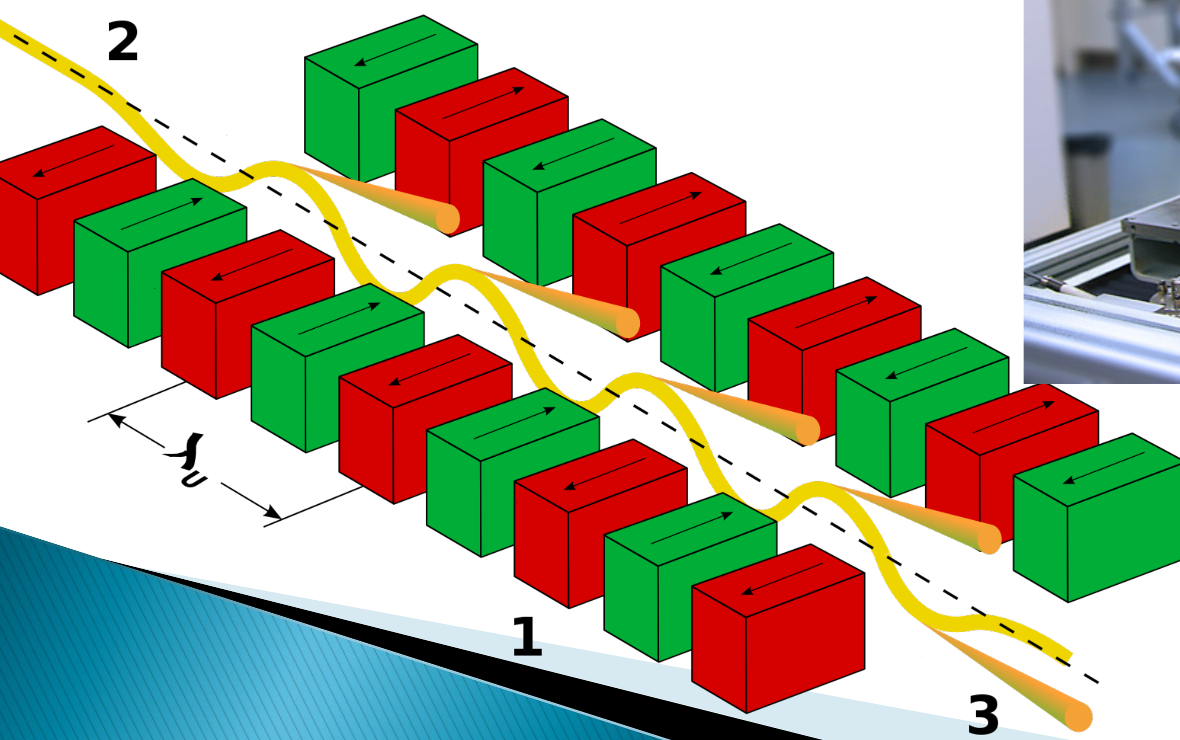
Ref. PNNL and FELs of Europe

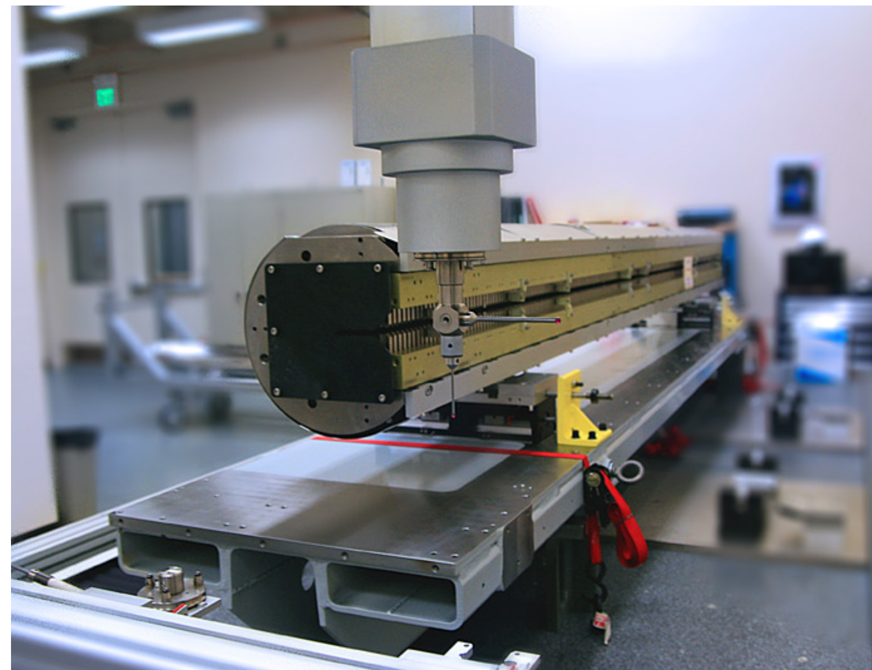


II. Basic physics principles
Electron motion

Forcing the Electrons to Wiggle…

- … by injecting them into a period field of an wiggler magnet (also often called undulator).





Wiggler module from the LCLS XFEL

Wiggler Field

- Defined by a 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

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

Motion in Planar Undulator

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

Dominant field in y

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

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

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

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

Undulator parameter

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

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

Transverse

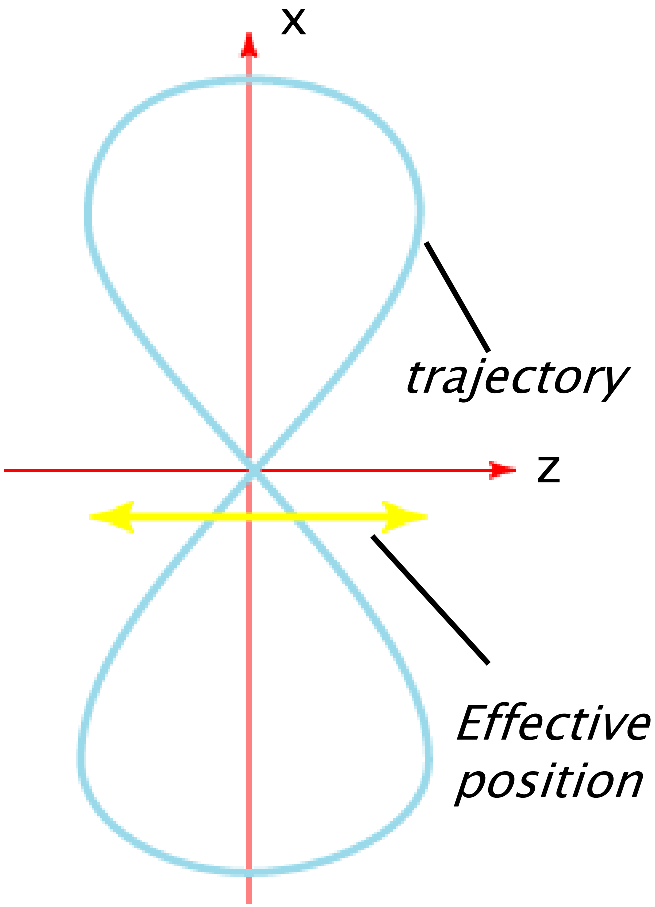
$$\beta_x = -\frac{K}{\gamma} \sin(k_u z)$$

Longitudinal

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

Average over one period

In the Co-moving frame



- Longitudinal wiggle has twice the period.
- Causes a figure "8" motion in the co-moving frame.
- The longitudinal position is effectively smeared out

In a helical wiggle the longitudinal motion is constant

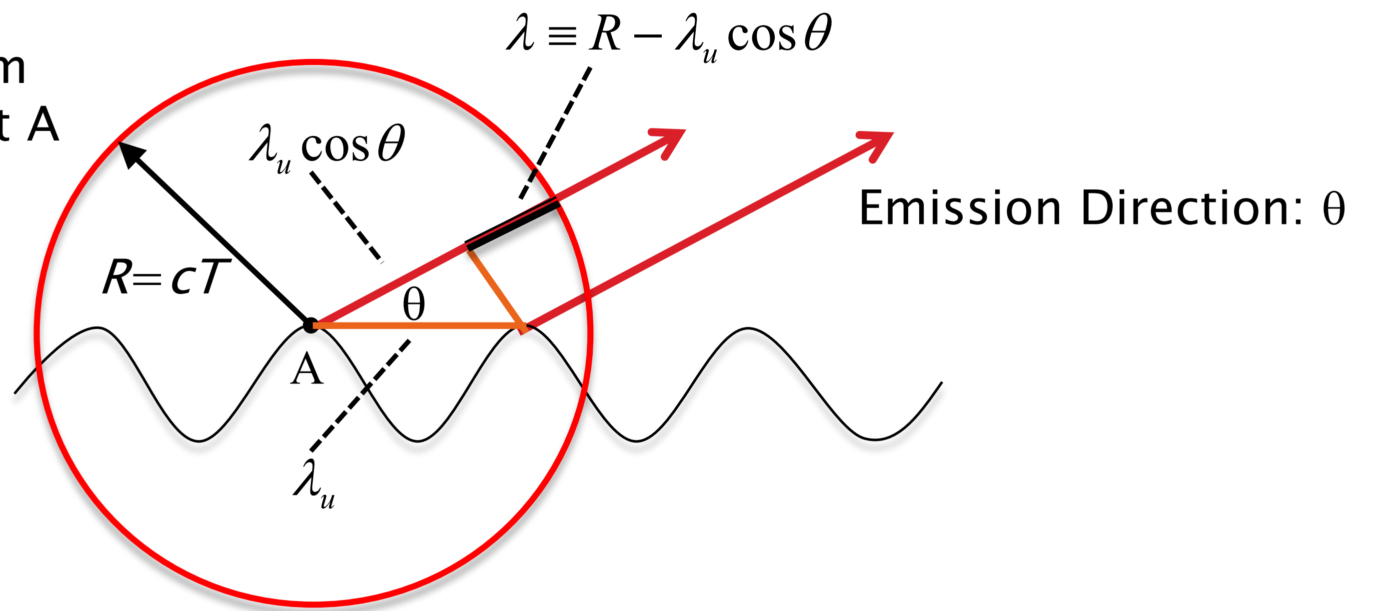
II. Basic physics principles. Undulator radiation

Resonance Condition (I)

Accelerated particles are emitting radiation

Condition to have a constructive interference between electrons and photons

Wavefront from emission point A when electron has moved by one period



Resonance Condition (II)

$$\lambda = R - \lambda_u \cos\theta$$

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

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

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

For small angles

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

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

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

The FEL Resonant Wavelength

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

- Example: 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. Interaction with radiation field

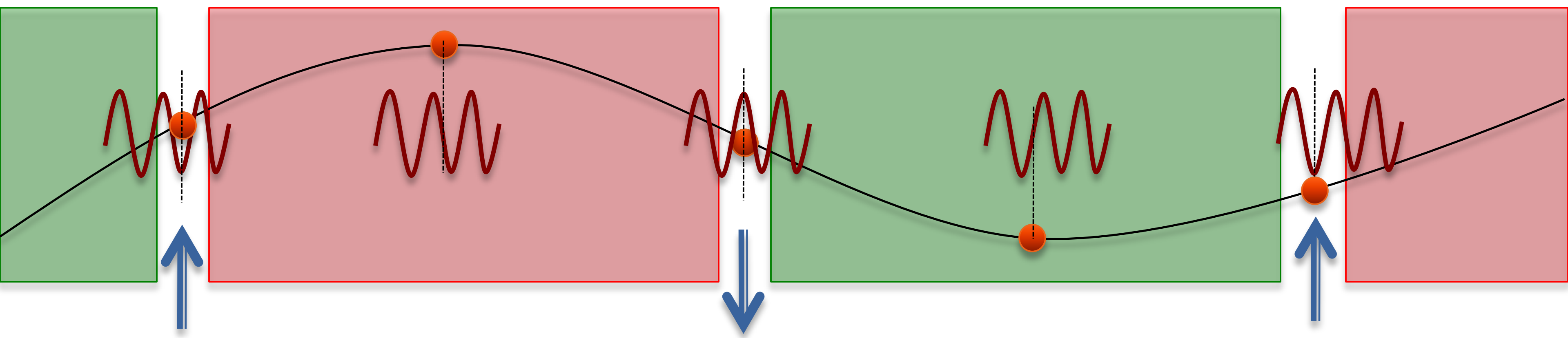
Basic ideas

- The wiggling electrons emit radiation. Some of it co-propagates along the undulator.
- The transverse oscillation allows the coupling of the electron beam with the radiation field.
- Electrons absorbing more photons than emitting become faster and tend to group with electrons, which are emitting more photons than absorbing.

The FEL exploits a collective process, which ends with an almost fully coherent emission at the resonant wavelength.

Co-Propagation of Electrons and Field

- The transverse oscillation allows to couple with a co-propagating field $\vec{v}_\perp \cdot \vec{E}_\perp$
- The electron moves either with or against the field line
- After half undulator period the radiation field has slipped half wavelength. Both velocity and field, have changed sign and the direction of energy transfer remains.



The net energy change can be accumulated over many periods

Energy Modulation & Longitudinal Motion

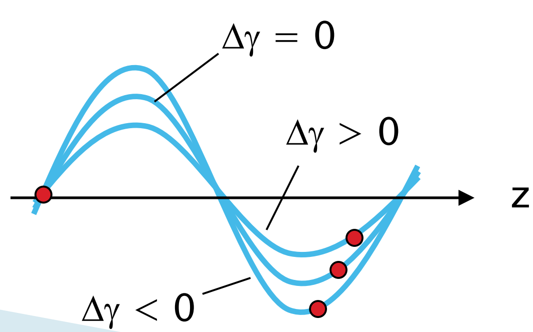
- The energy change of an electron depends on its phase θ

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

f_c: coupling factor (<1)

- For a given wavelength λ there is one energy γ_r, where the electron stays in phase with radiation field.
- It can be proven that the condition that satisfies this is exactly the resonance condition.

- Electrons with energies above the resonant energy, move faster ($d\theta/dz > 0$), while energies below will make the electrons fall back ($d\theta/dz < 0$). For small energy deviations:



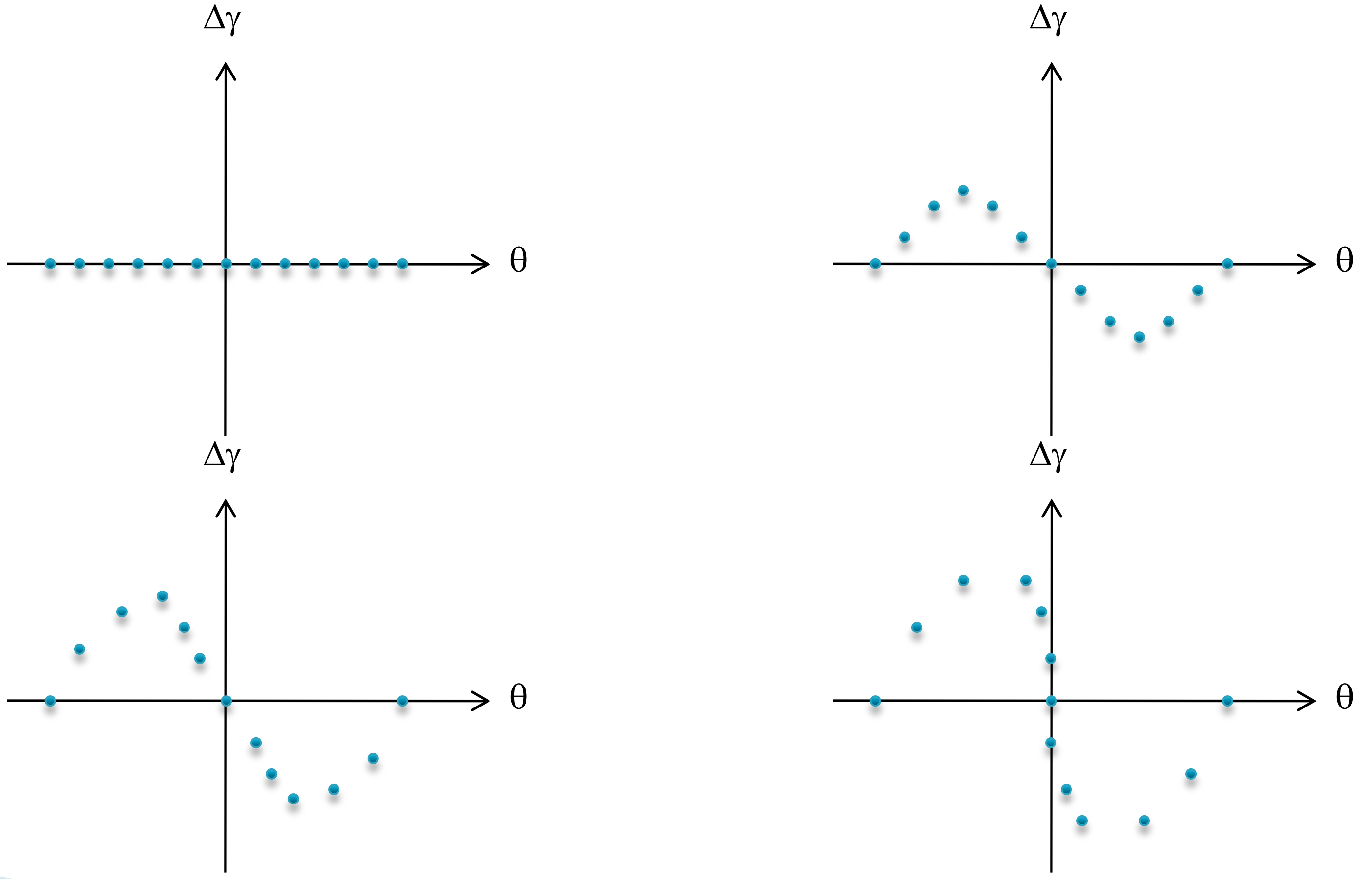
$$\frac{d}{dz}\theta = 2k_u\frac{\Delta\gamma}{\gamma_r}$$

Motion in Phasespace

$$\frac{d}{dz}\gamma = -\frac{ef_cK}{2\gamma}\frac{E_0}{mc^2}\sin(\theta)$$

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

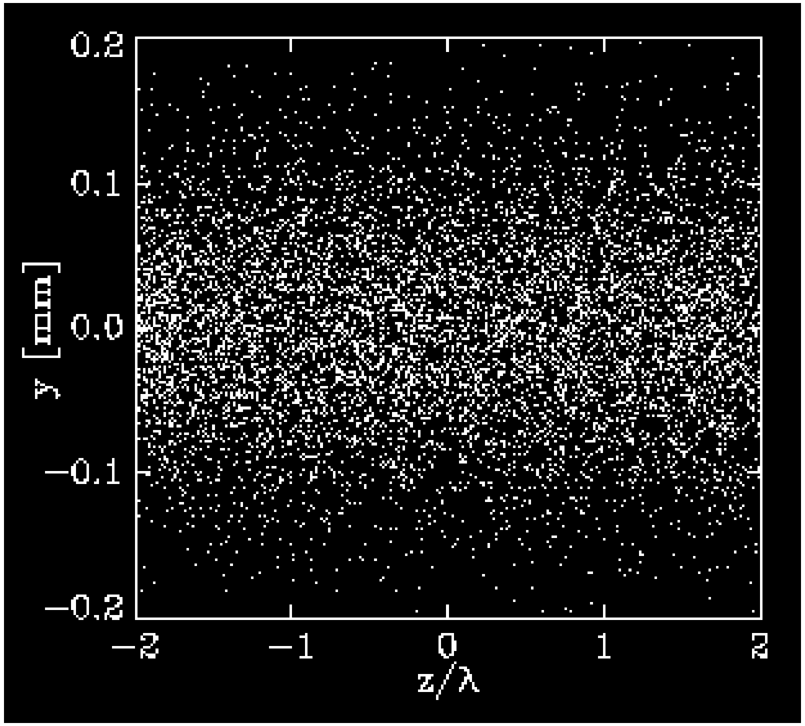
- Wavelength typically much smaller than bunch length.
- Electrons are spread out initially over all phases.



Electrons are bunched on same phase after quarter rotation

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.

II. Basic physics principles. Field Emission

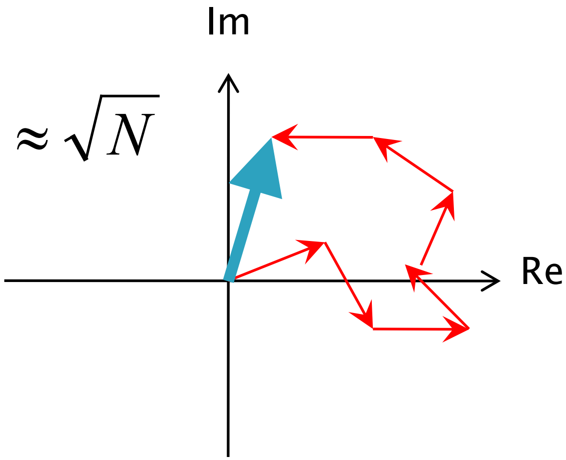
Coherent Emission

- The electrons are spread out over the bunch length with its longitudinal position δz_j. The position adds a phase $\phi_j = k\delta z_j$ to the emission of the photon
- The total field is:

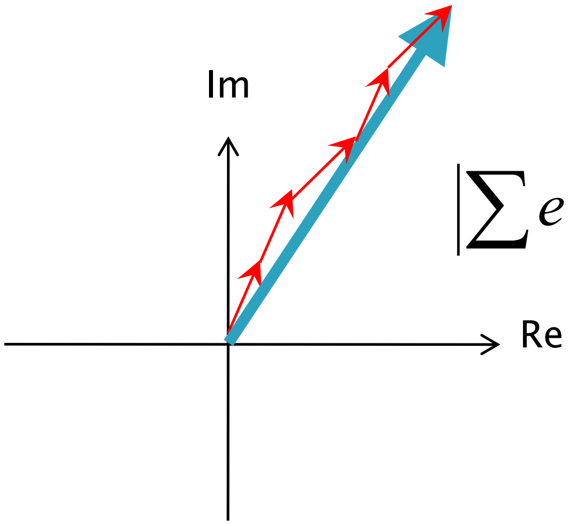
$$E(t) \propto \sum_j e^{i(kz_j - \omega t)} = e^{i(k\langle z\rangle - \omega t)} \cdot \sum_j e^{ik\delta z_j} = e^{i(k\langle z\rangle - \omega t)} \cdot \sum_j e^{i2\pi \frac{\delta z_j}{\lambda}}$$

Case 1: $\delta z_j \geq \lambda$
Electrons spread over wavelength:
Phasor sum = random walk in 2D

$$\left|\sum e^{i\phi}\right| \approx \sqrt{N}$$



Case 2: $\delta z_j << \lambda$
Electrons bunched within wavelength:
Phasor sum = Add up in same direction



$$\left|\sum e^{i\phi}\right| \approx N$$

Power ~ |E|² –> Possible Enhancement: N (N→N²)

Complete Picture: Evolving Radiation Field

- The FEL field *u* (relative to E) depends on the longitudinal position along the undulator (z), the time coordinate (t) and the transverse properties.

$$u = \frac{eE_0}{imc^2 k} e^{i\phi}$$

- The change in the radiation field is given by the following equation:

$$\left[\nabla_\perp^2 + 2ik\left(\frac{\partial}{\partial z} + \frac{\partial}{c\partial t}\right)\right] u = i\frac{\rho_e e^2 \mu_0}{2m} \sum_j \frac{f_c K}{\gamma_j} e^{-i\theta_j}$$

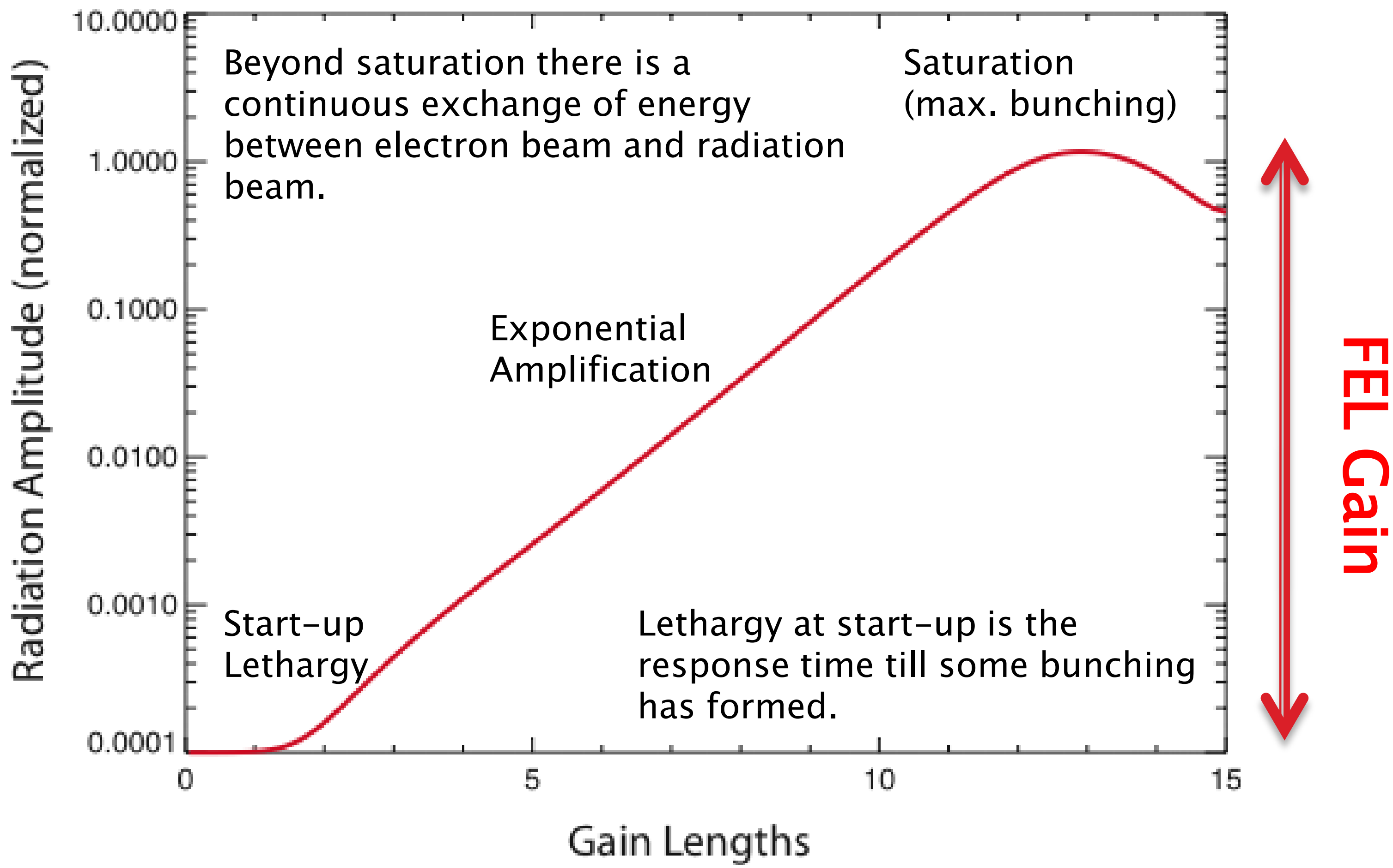
Diffraction

Evolution along Undulator

Evolution along Bunch (Slippage)

Source Term

The Generic Amplification Process



II. Basic physics principles. SASE FELs

FEL Modes

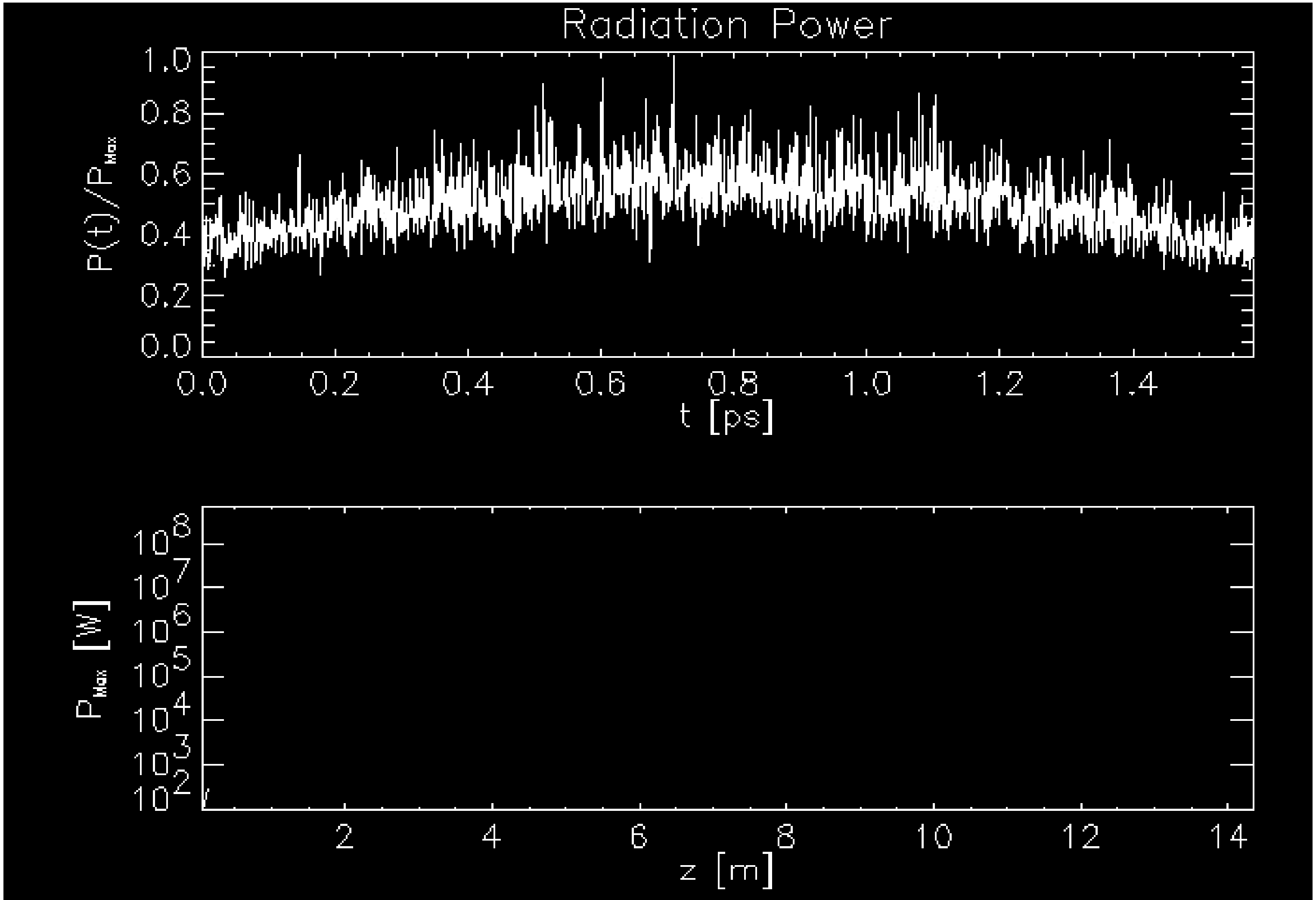
- SASE FEL (Self-Amplified Spontaneous Emission)

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

Typical Growth of SASE Pulse

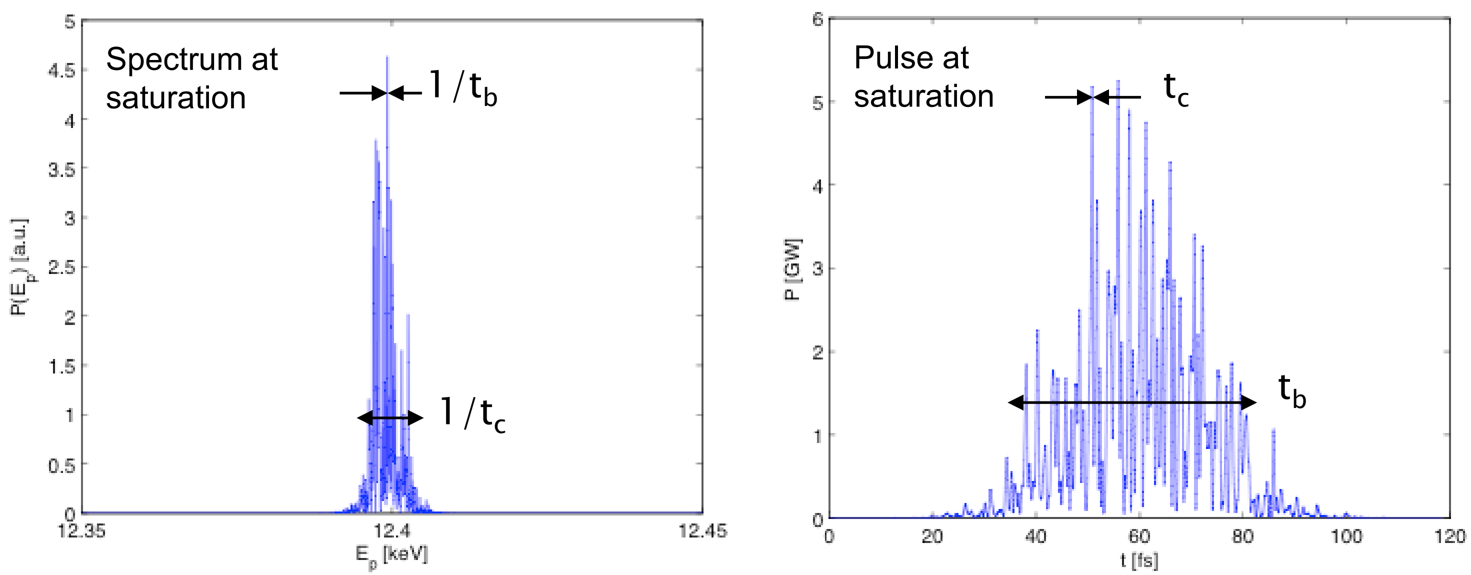


Simulation for FLASH FEL

SASE FELs

- FEL starts with the broadband signal of spontaneous radiation (almost a white noise signal)
- Within the FEL bandwidth $\Delta\omega$ the noise is amplified
- Spikes in spectrum and time profile.

SwissFEL: Simulation for 1 Angstrom radiation



Cooperation Length: $L_c = ct_c$

II. Basic physics principles. The FEL parameter ρ

The Importance of the FEL Parameter ρ

- FEL parameter ρ.   Typical values= $10^{-4} - 10^{-2}$

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

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

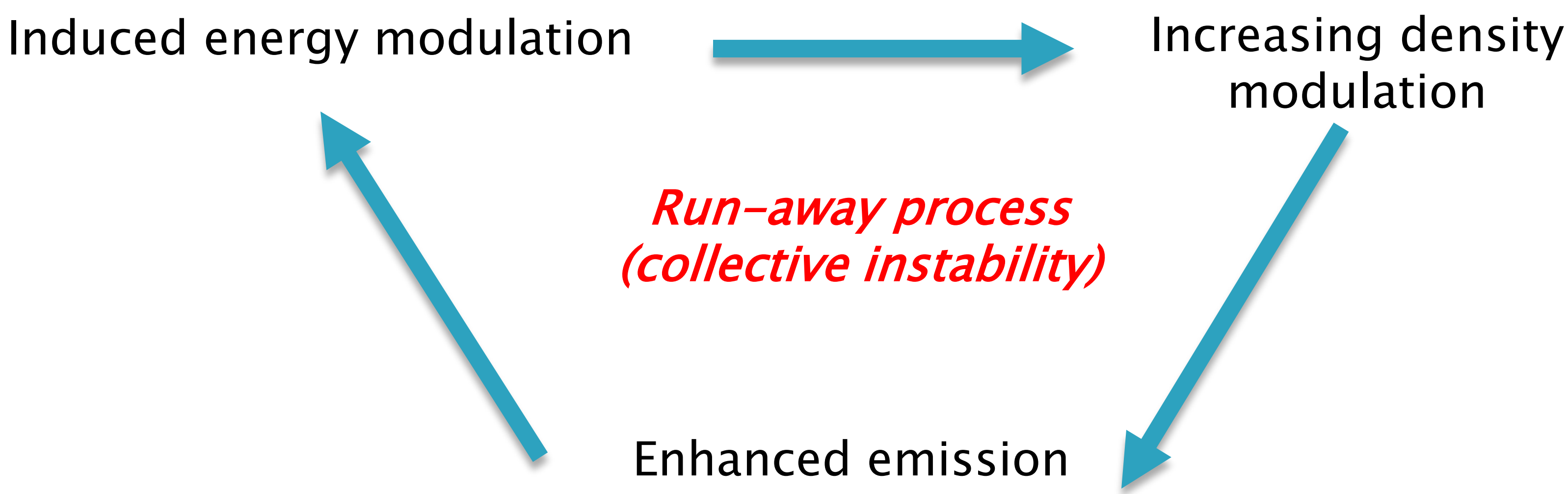
Gain length	*Efficiency*	*SASE Spike Length*	*Bandwidth*
$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\cdot\rho}$	$P_{FEL} \approx \rho P_{beam}$	$L_c = \frac{\lambda}{4\pi\rho}$	$\frac{\Delta\omega}{\omega} = 2\rho$

- Beam Requirements:

Energy Spread	*Emittance*	*Beam Size*
$\frac{\sigma_\gamma}{\gamma} << \rho$	$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$	$\beta_{opt} \approx 3\sqrt{\frac{\varepsilon_n}{\gamma}\frac{4\pi}{\lambda}}L_g$

Summary of basic physics principles

FEL Process

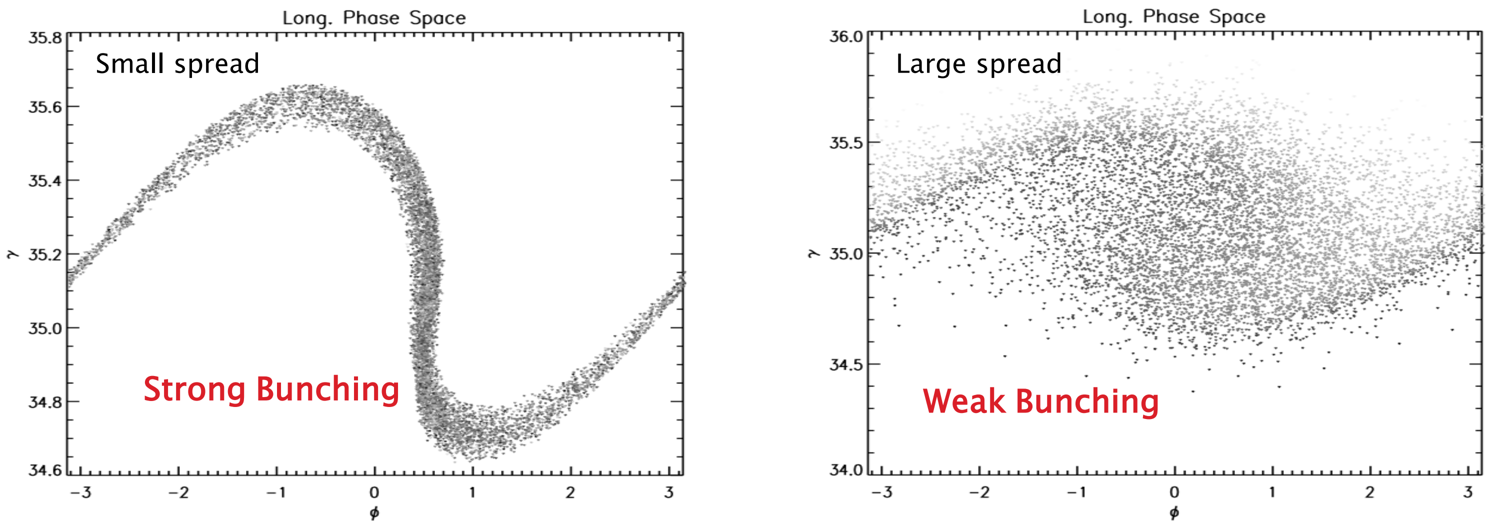


- FEL utilized the strong coherent emission in the collective instability with the tuning ability of the wavelength.
- Instability can only occur with a beam with low energy spread and emittance.

III. Electron beam requirements

Electron Beam Requirements: Energy Spread

- Only electrons within the FEL bandwidth can contribute to FEL gain.
- FEL process is a quarter rotation in the separatrix of the FEL. If separatrix is filled homogeneously, no bunching and thus coherent emission can be achieved.



Energy Spread Constraint:

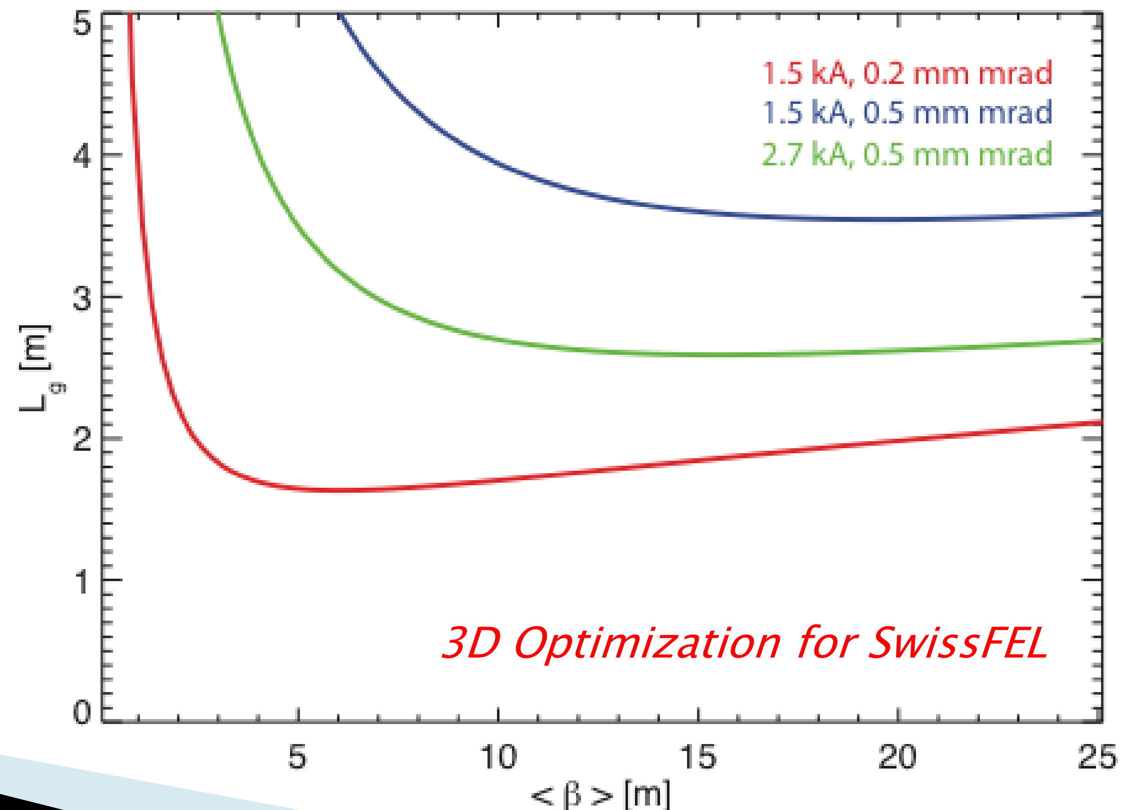
$$\frac{\sigma_\gamma}{\gamma} << \rho$$

Optimizing the Focusing

- Decreasing the β–function (increase focusing), increases the FEL parameter ρ.
- Stronger focusing:
  - Larger kinetic energy of betatron oscillation
  - Less kinetic energy for longitudinal motion
  - Smearing out of growing bunching

From 1D Theory:

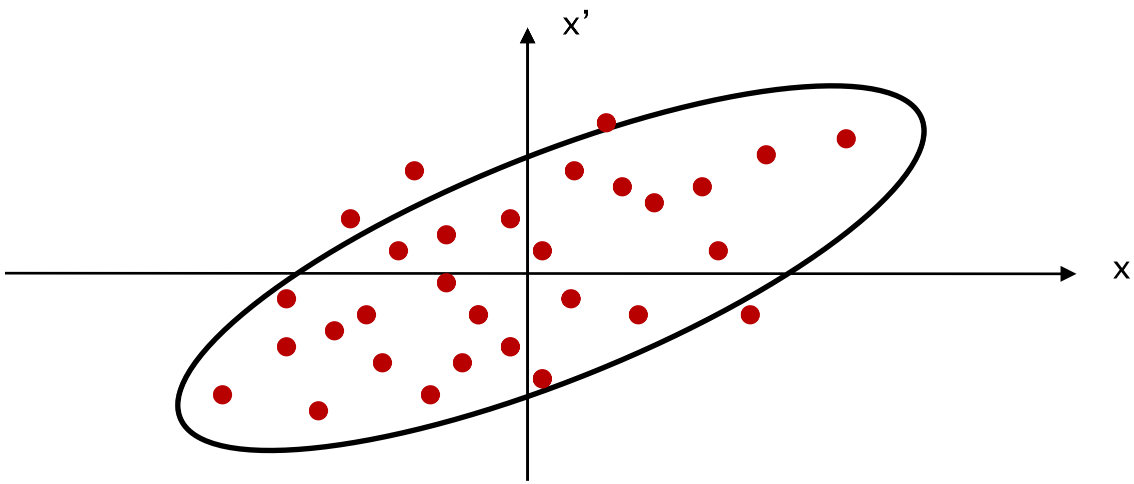
$$\beta_{opt} \approx 3\sqrt{\frac{\varepsilon_n}{\gamma}\frac{4\pi}{\lambda}L_g}$$



3D Effects – Emittance

- The effective "emittance" for the fundamental mode of the radiation field is $\lambda/4\pi$.
- The effective phase space ellipse should enclose all electrons, allowing them to radiate coherently into the fundamental mode.
- Electrons, outside the ellipse, are emitting into higher modes and do not contribute to the amplification of the fundamental mode.

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



IV. FEL driver accelerators

Linac-based FELs

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

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

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

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

- The X-ray FEL requirements on the electron beam quality are so demanding that only linear accelerators can be used to provide the drive beam.
- Low emittance and high peak current beams are required in the undulators, but not available at feasible electron sources.
- Typically long beams are produced with low emittance and then compressed later. Compression should not dilute emittance too much (i.e. space-charge forces).

Electron sources

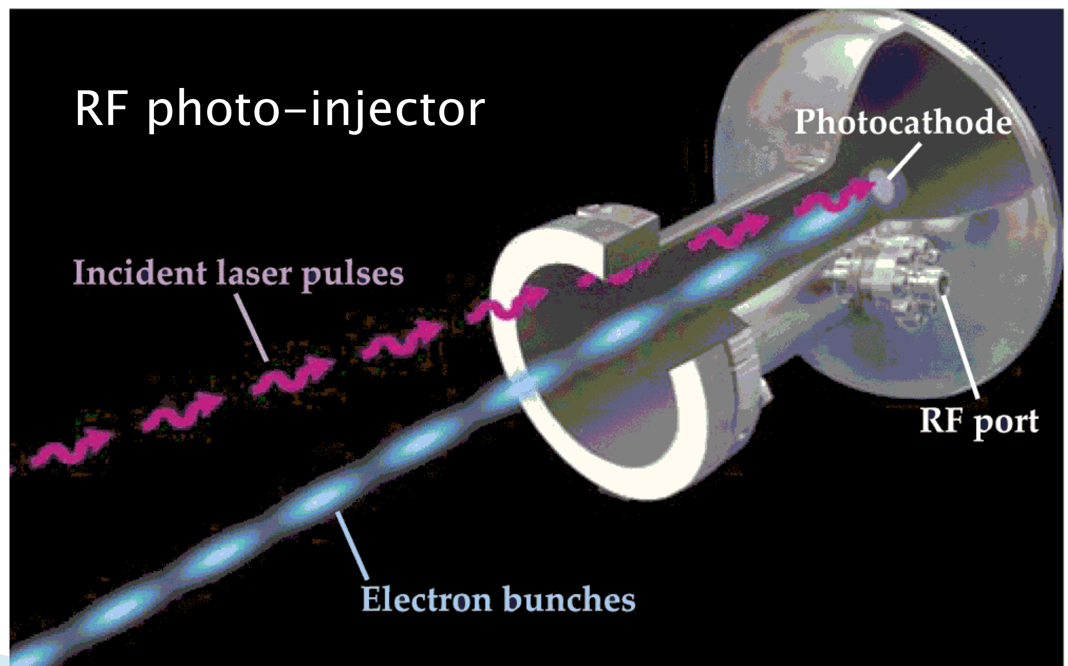
- RF photo-injectors are normally used to generate high-brightness electron beams
- Electrons are produced via the photo-electric effect by a laser of a proper wavelength impinging on a photocathode mounted inside an RF gun.
- Final energy of the electrons is of few-several MeV
- Other (less bright) alternatives: thermionic or DC guns

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

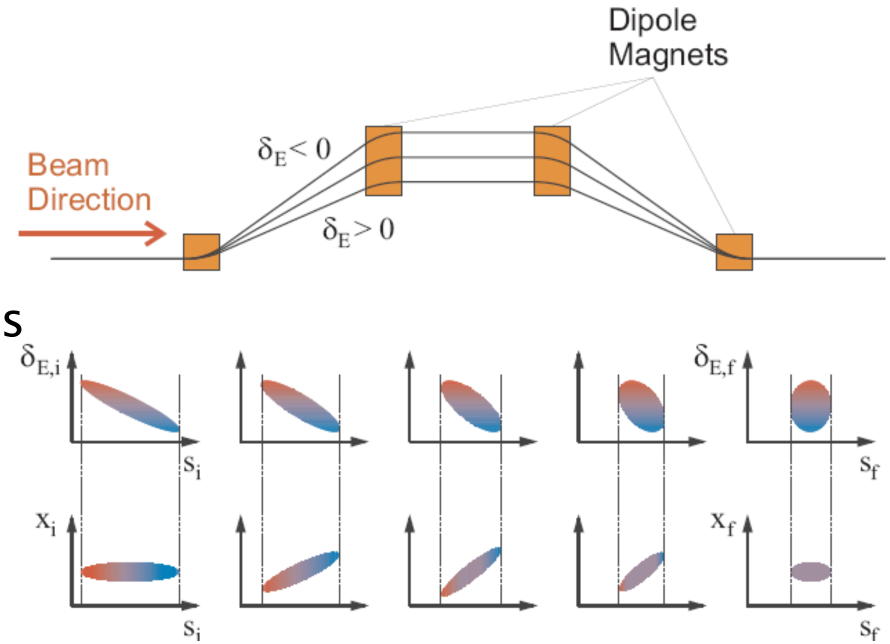
- Emittance goals:

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



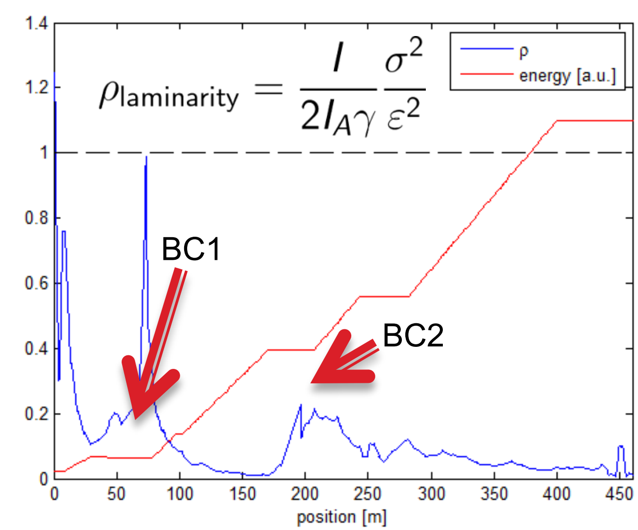
Bunch compression principle

1. Energy chirp generation in rf structures
2. Transport through magnetic chicanes

Where to compress?

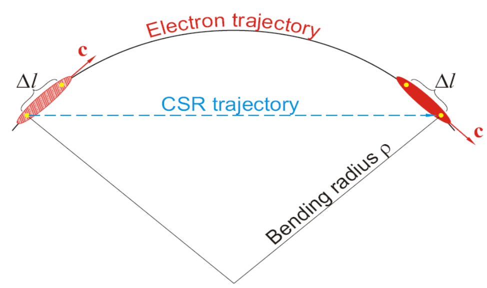
- Early compression would lead to high charge density beams at low energies which would increase the emittance.
- Late compression would require the transport of long bunches trough the linac without emitance dilution, which is difficult (RF-curvature, wake fields, …)

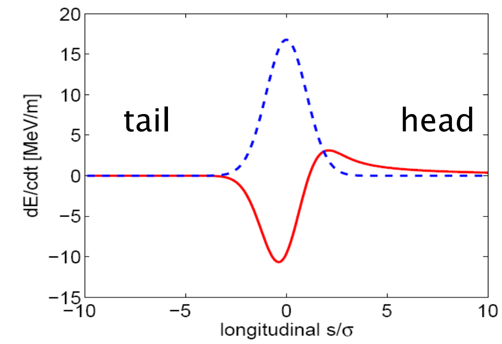
⇒ Multi-stage-compression: 2 stages in case of LCLS, FLASH, and SwissFEL



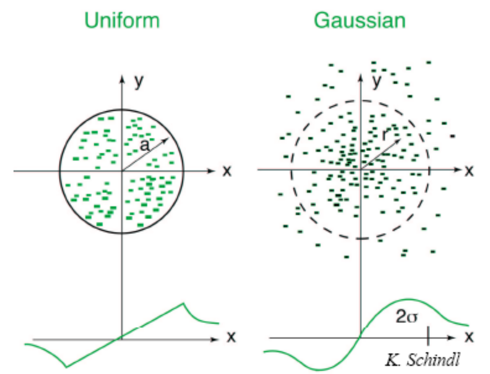
Self Interactions

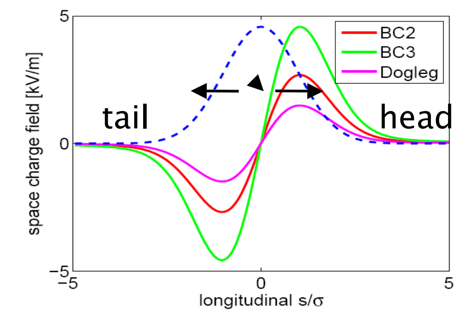
- High charge densities give rise to strong electro-magnetic fields generated by the electron bunches. Electrons within the bunch experience these fields.
- Coherent Synchrotron Radiation



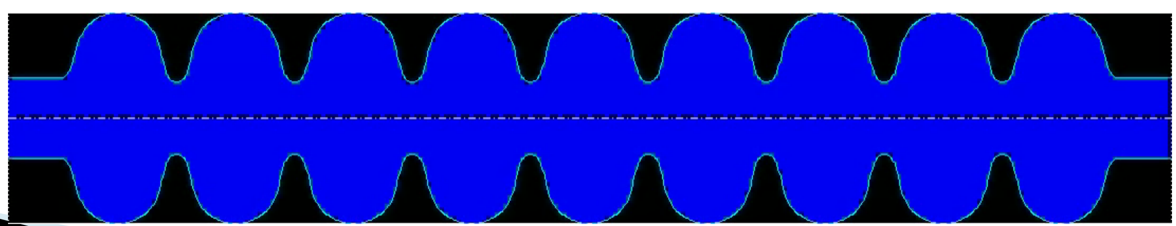


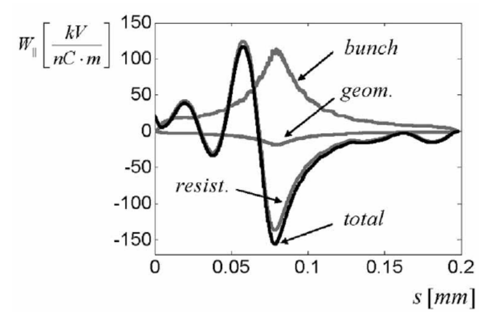
- Space Charge fields





- Wake fields

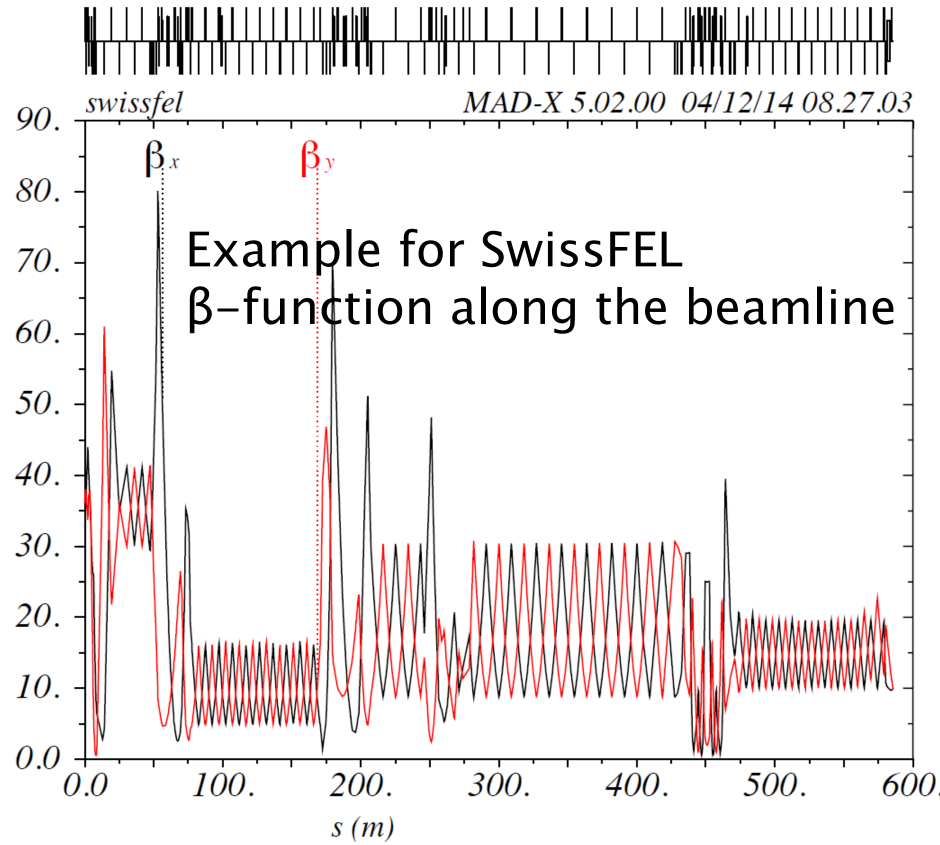


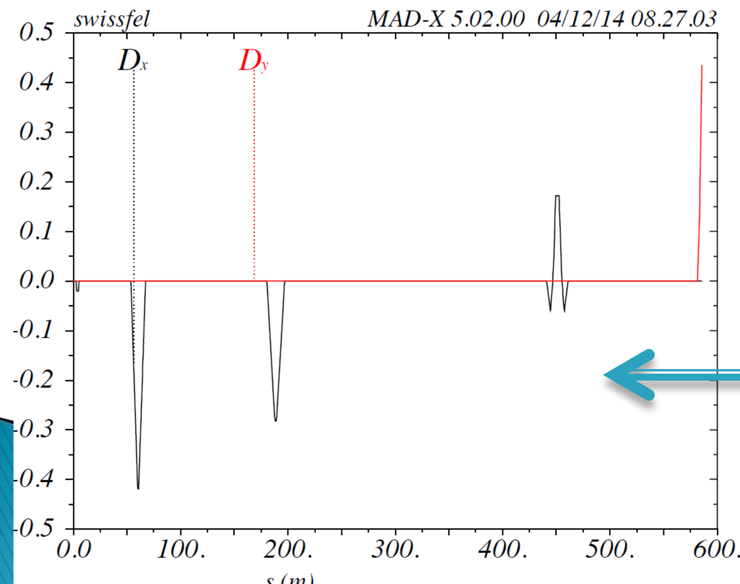


Electron beam optics

Optics design has to consider:

- Maximum/minimum beam size
- Chromaticity
- Sensitivity to quadrupole field errors
- CSR in bunch compressors
- Diagnostics: TDC measurements, emittance measurements
- Optimum beta-function in the undulator
- …





Example for SwissFEL
Dispersion along the beamline

Requirements of an FEL / Diagnostics

Diagnostics are required to characterize, setup and optimize the electron beam

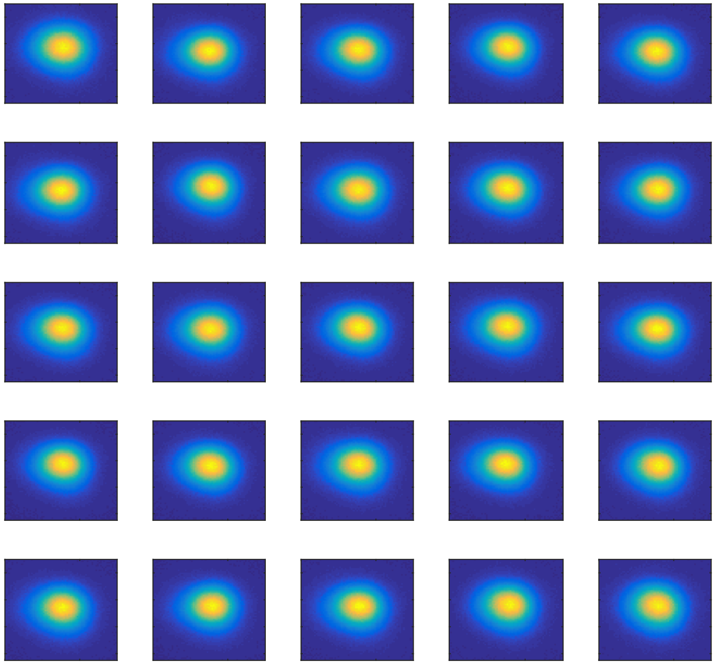
Requirement	Implementation	Measurement/Verification
Electrons	Laser electron gun (photocathode + RF cavity)	e.g. Wall current monitor
Focusing (optics)	Quadrupole magnets	Screen monitor
Localization (orbit)	Steering magnets (dipoles)	Beam position monitor (BPM)
Energy	Radiofrequency cavities (3 GHz = S-band)	Spectrometer (Dipole magnet)
Peak current	• Laser pulse shape • Magnetic chicane (bunch compressor)	Beam profile measurement with RF deflector and screen monitor
Beam size / emittance	• Design electron gun • “emittance compensation”	• “Pepperpot”/slits (low energies) • Beam optical methods (higher energies)

Requirements of an FEL / 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

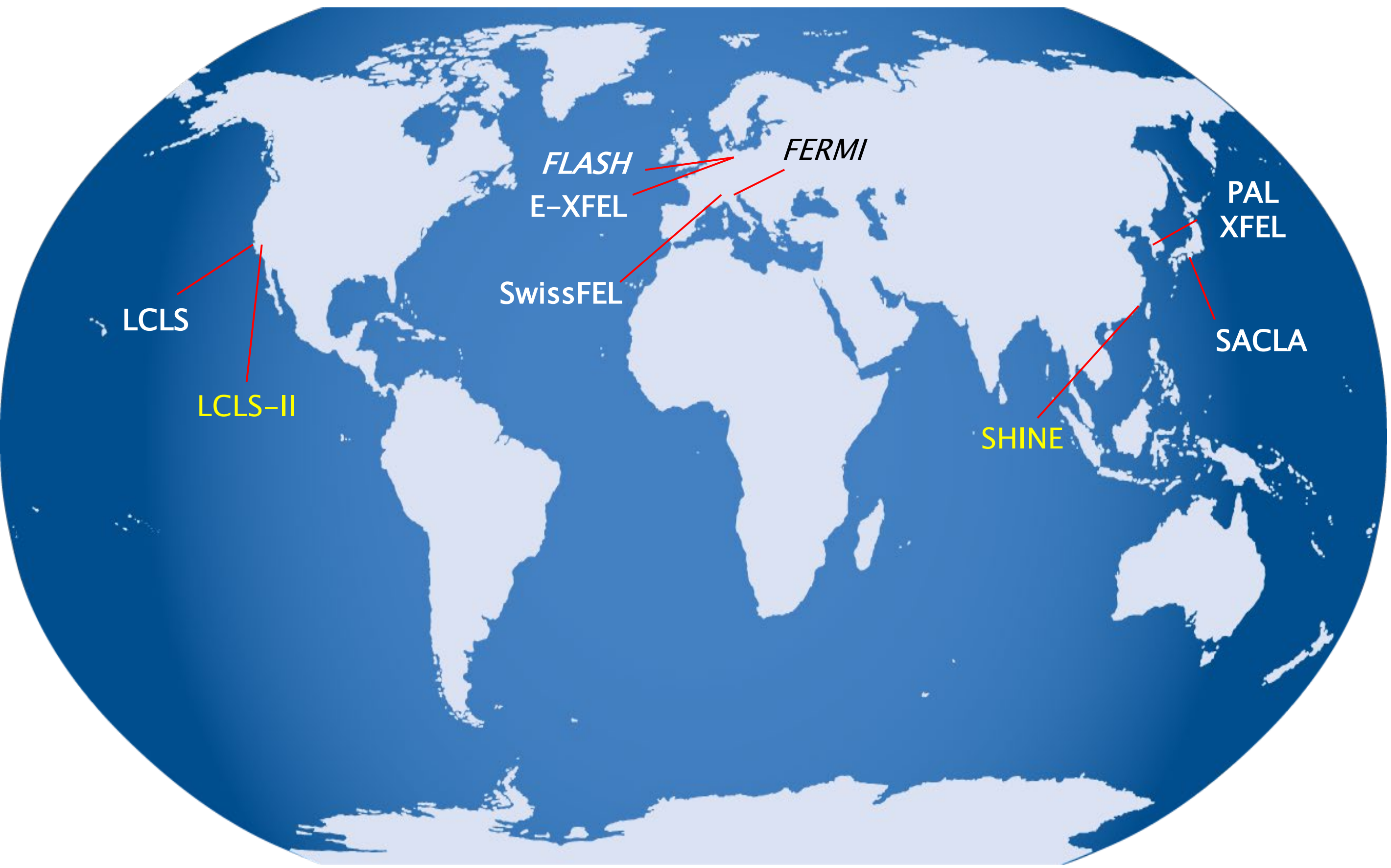
- Need several diagnostics for:
  - Electron beam (BPMs, compression monitors, charge, arrival time, etc.)
  - Photon beam (spectrometer, pulse energy, arrival time, transverse profile…)



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

V. FEL projects around the world

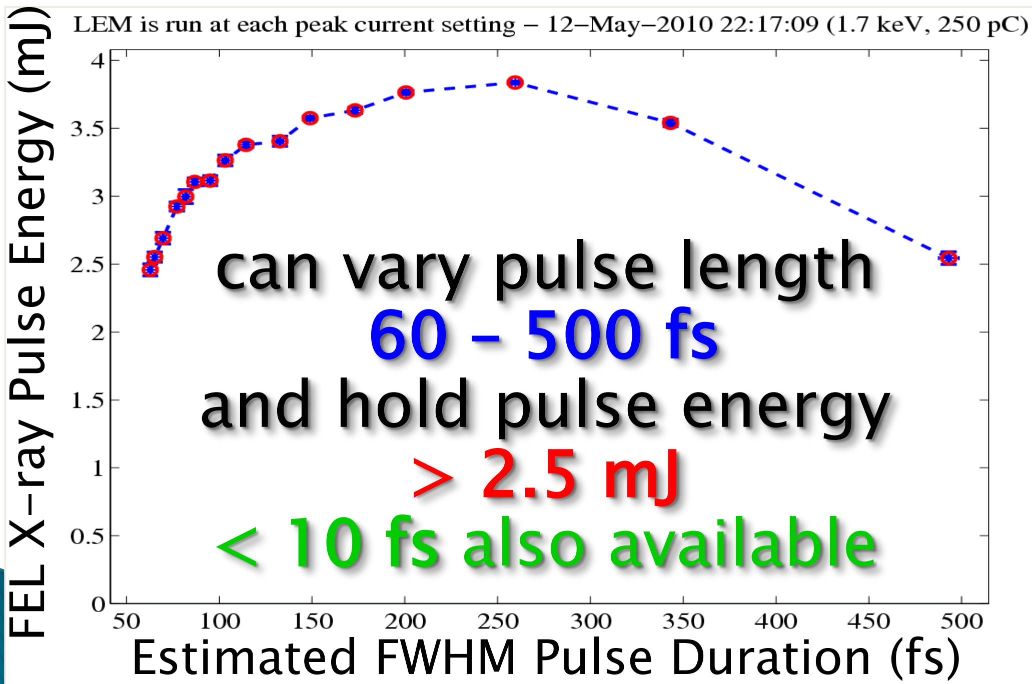
X-ray FEL Projects Around the World

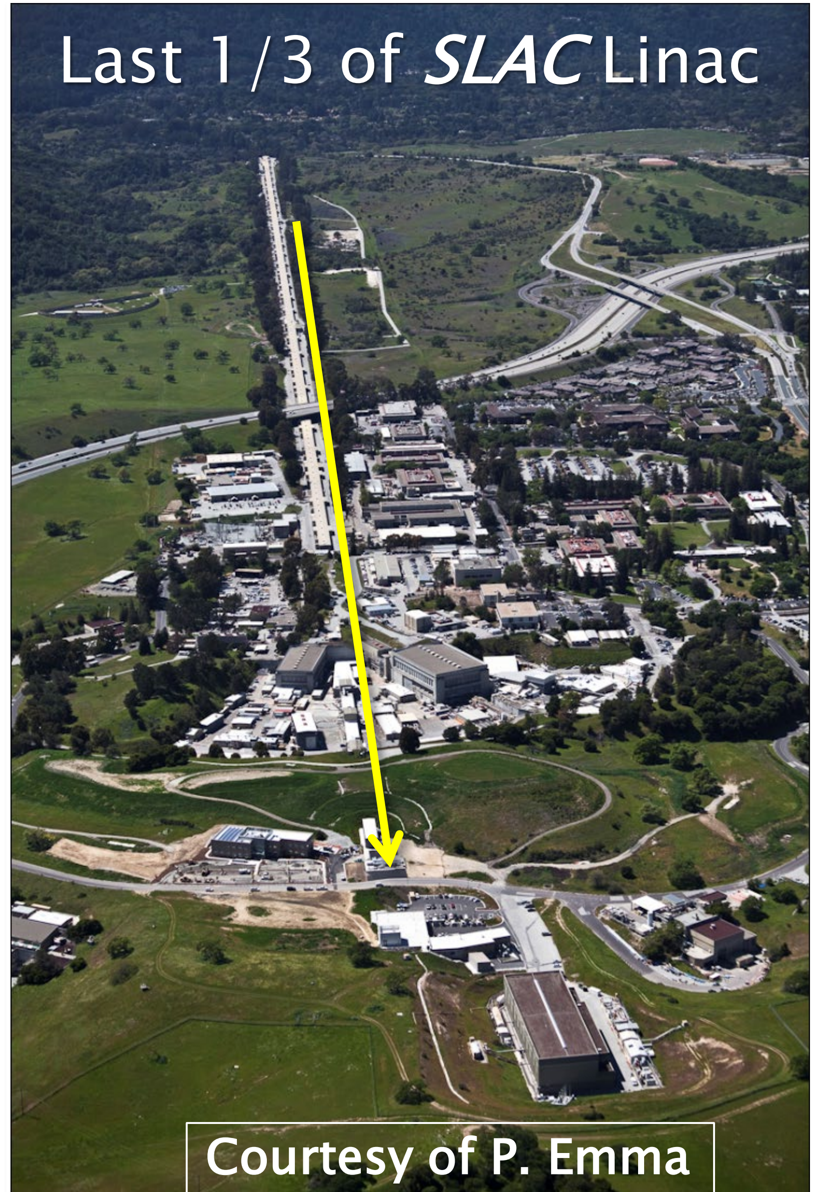


- FLASH: first soft X-ray with high repetition rate (MHz), 2007
- LCLS: first hard X-ray, 2009
- SACLA: compact hard X-ray, 2011
- FERMI: first soft X-ray seeded-FEL, 2013
- PAL-XFEL: hard X-ray with low (20 fs) timing jitter, 2016
- E-XFEL: hard X-ray with high repetition rate, 2017
- SwissFEL: compact hard X-ray driven by low emittance beam, 2017
- Future facilities: LCLS2 and SHINE (high repetition rate)

LCLS (Linac Coherent Light Source)

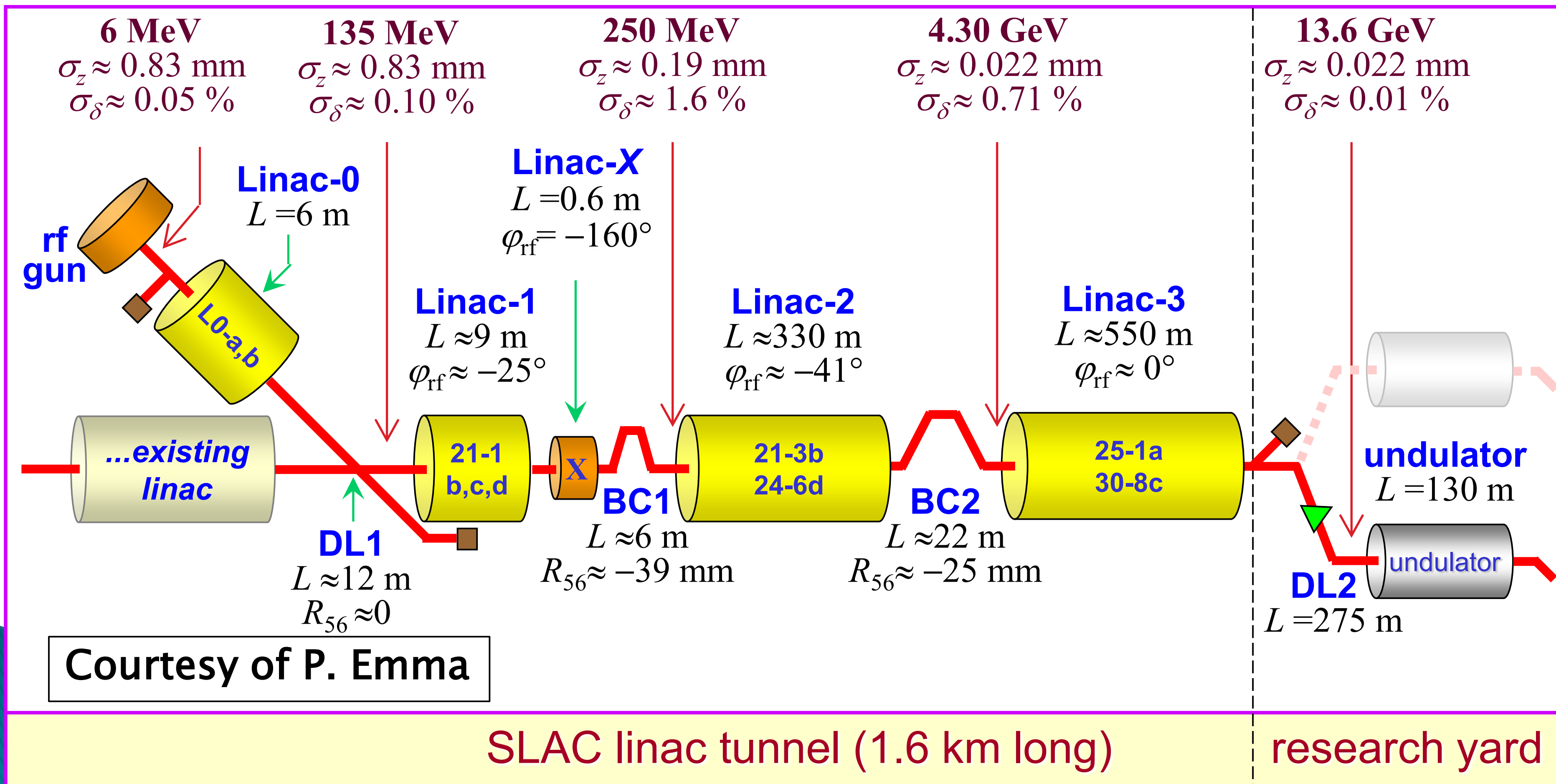
Electron energy	= 3 – 15 GeV
Photon energy	= 0.3 – 11 keV
X-ray pulse length	= 5 – 500 fsec
Bandwidth	= 0.005 – 2 %
Repetition rate	= ≤ 120 Hz
Machine length	≈ 2 km





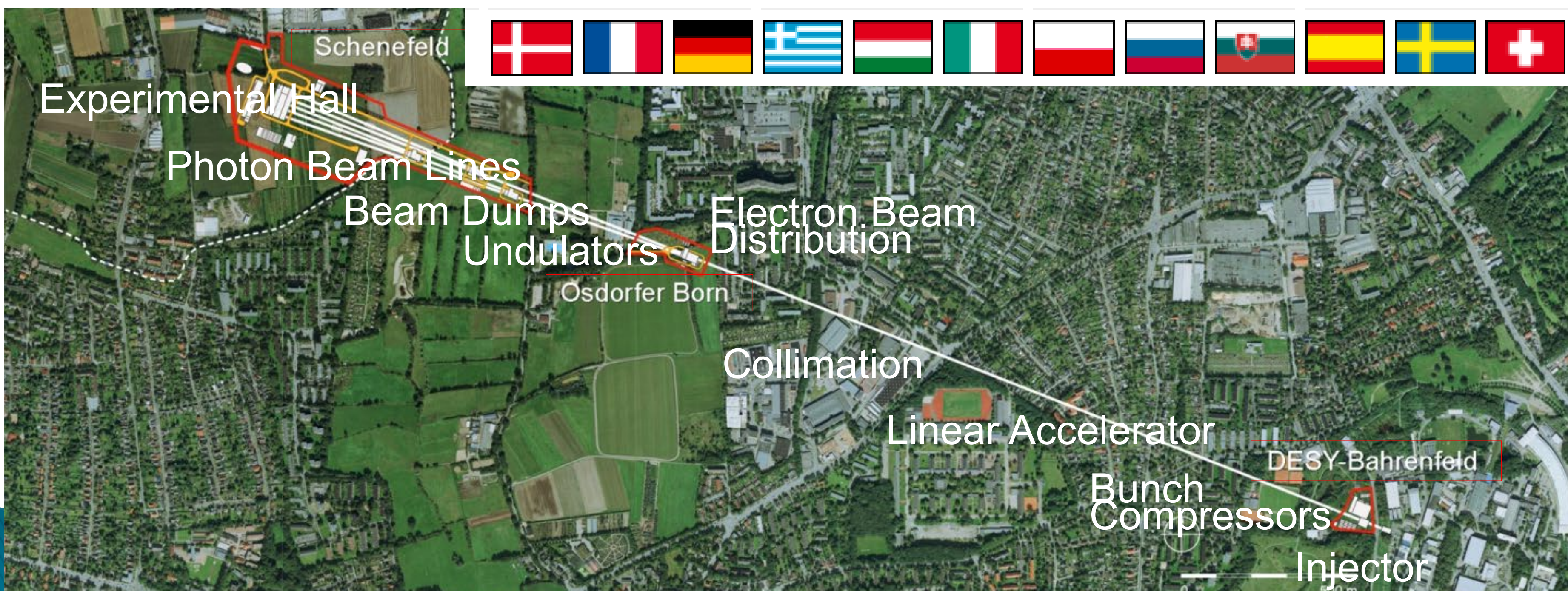
LCLS Layout

- RF electron gun
- Two bunch compressors
- Laser heater system
- S-band linac (2.856 GHz) to 14 GeV
- RF harmonic linearizer (11.424 GHz)
- Permanent magnet undulator



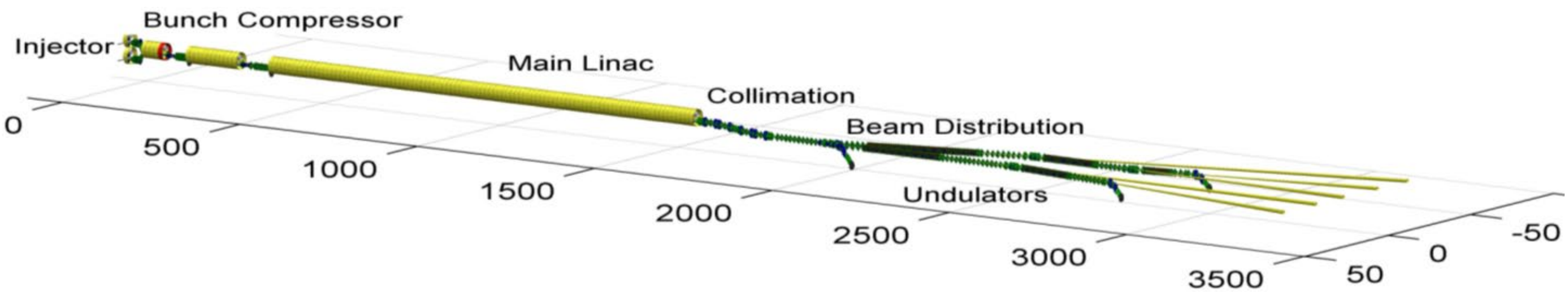
European-XFEL

- 17.5 GeV superconducting linac, almost 1 MW beam power
- 27000 pulses per second in 10 Hz burst mode
- Three moveable gap undulators for hard and soft X-rays (0.25 to 25 keV)
- Initially 6 equipped experiments
- Total length around 3 km
- Commissioning started in December 2015 / First FEL light in 2017



Courtesy of W. Decking

European-XFEL Layout



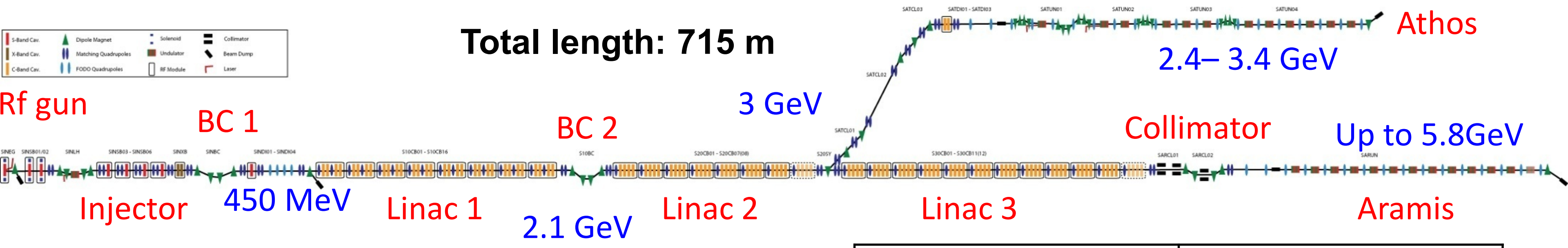
Courtesy of W. Decking

Quantity	Value
pulse repetition rate	10 Hz
beam pulse length	600 μs
bunch repetition frequency within pulse	4.5 MHz
electron bunch length after compression	2 – 180 fs (FWHM)
bunch charge	0.02 – 1 nC
slice emittance	0.4 – 1.0 mm mrad
slice energy spread	4 – 2 MeV

SwissFEL

- 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) and ultra-low emittance.
- Budget ~300 MCHF
- First ideas more than 10 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 users from 2021.

SwissFEL Layout



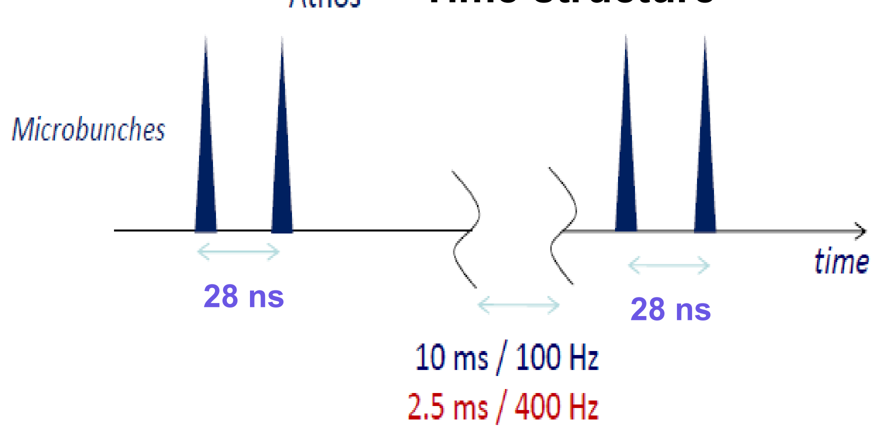
Electron source
RF gun with laser driven Cu-photocathode

RF structures
- Gun and Injector: S-band
- Linac: C-band
- X-band for phase-space linearization

Undulator beamlines:
1. Aramis: hard X-ray FEL (1-7 Å)
Undulators with variable gap, period = 15mm
2. Athos: soft X-ray FEL (7-70 Å)
Undulators with variable gap , period = 40mm

Wavelength	1 Å - 70 Å
Pulse duration	1 – 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10 – 200 pC
Repetition rate	100 Hz

Time structure



2 bunch operation: serve 2 undulator lines simultaneously at full repetition rate

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Open positions at SwissFEL

Open positions at SwissFEL

Summer-student positions for 2020 (for students that have not finished their master degree yet):

- *Improvement of beam optics and emittance measurements at SwissFEL*: https://www.psi.ch/en/pa/job-opportunities/32394-trainee
- *Online pulse duration reconstruction from spectra analysis at SwissFEL*: https://www.psi.ch/en/pa/job-opportunities/32388-trainee
- *Virtual longitudinal diagnostics at SwissFEL*: soon online at https://www.psi.ch/en/pa/job-opportunities

Two post-doctoral positions on "Single-particle imaging experiments at the soft X-ray beamline of SwissFEL":

- Postdoc 1 on *generation and measurement of short and high-power XFEL pulses* (starting Q3/Q4 2020)
- Postdoc 2 on *photon pulse-duration measurements and imaging experiments* (starting 2021)

Soon online at https://www.psi.ch/en/pa/job-opportunities