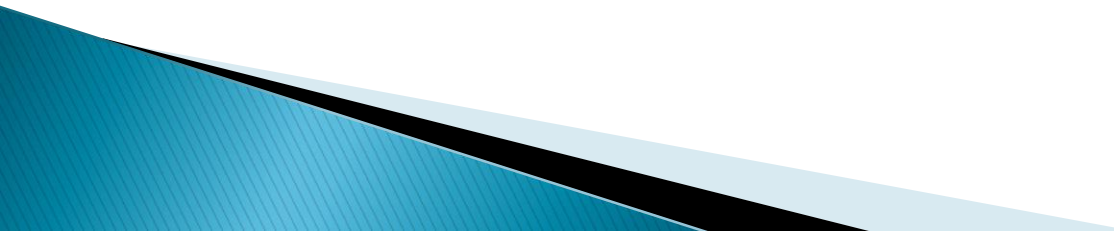


Free-Electron Lasers

Eduard Prat, Sven Reiche, PSI
JUAS, 23 January 2018

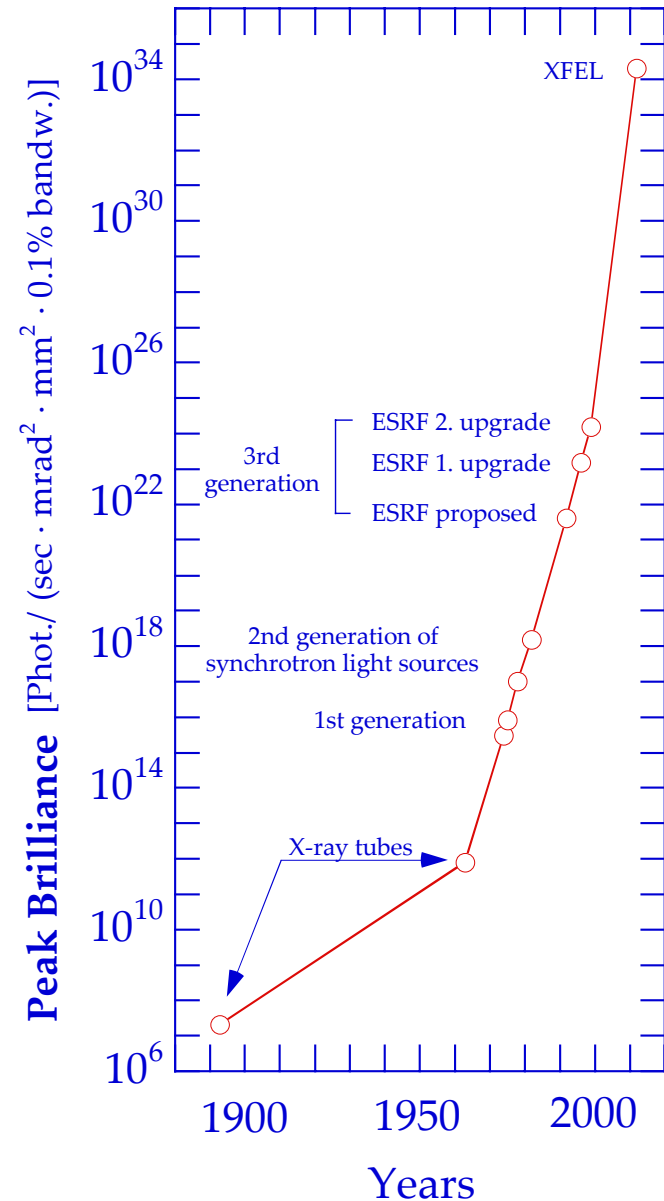
Contents

- i. Introduction
 - ii. Basic physics principles:
 - a) Electron motion
 - b) Undulator radiation
 - c) Interaction with radiation field
 - d) Field emission
 - e) SASE FELs
 - f) The FEL parameter ρ
 - iii. Electron beam requirements
 - iv. FEL driver accelerators
 - v. FEL projects around the world
- 

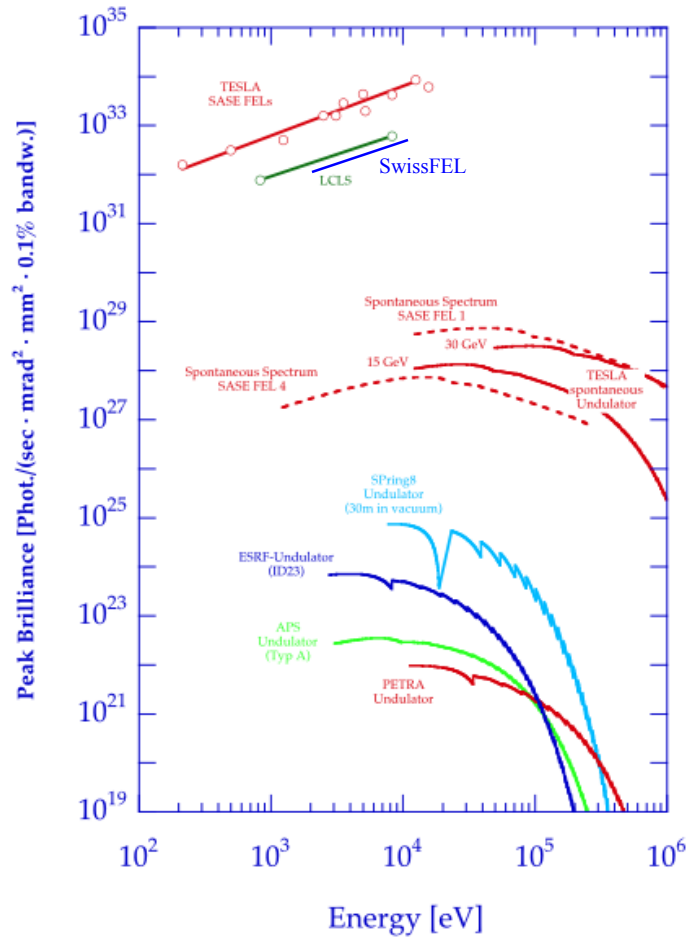
I. Introduction

Accelerator-based Light Sources

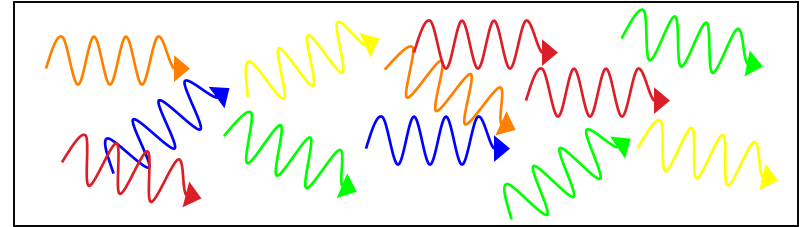
- ▶ **1st Generation:** Synchrotron radiation from bending magnets in high energy physics storage rings
- ▶ **2nd Generation:** Dedicated storage rings for synchrotron radiation
- ▶ **3rd Generation:** Dedicated storage rings with insertion devices (wigglers/undulators)
- ▶ **4th Generation:** Free-Electron Lasers



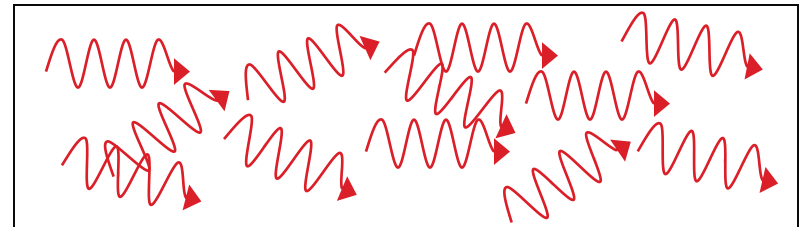
FEL as a Brilliant Light Source



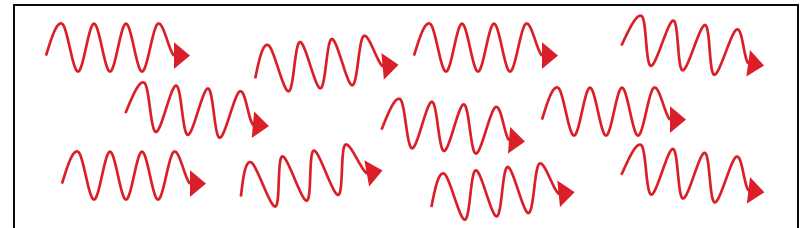
High photon flux



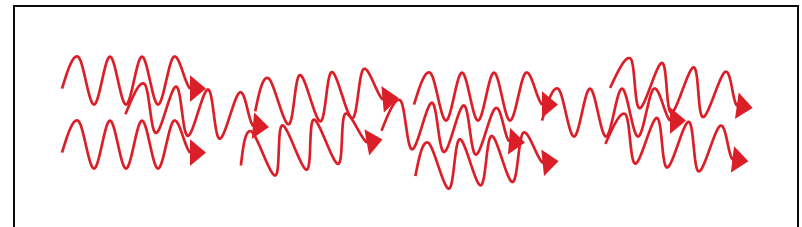
Small freq. bandwidth



Low divergence



Small source size



4th Generation Light Sources

- ▶ Tunable wavelength, down to 1 Angstrom
- ▶ Pulse Length less than 100 fs
- ▶ High Peak Power above 1 GW
- ▶ Fully Transverse Coherence
- ▶ Transform limited Pulses (longitudinal coherence)

**XFELs fulfill all criteria except for the longitudinal coherence
(but we are working on it ☺)**

X-Ray FEL as 4th Generation Light Source

- ▶ Angstrom wavelength range
 - Spatial resolution to resolve individual atoms in molecules, clusters and lattices.
- ▶ Tens to hundreds of femtosecond pulse duration.
 - Temporal resolution. Most dynamic process (change in the molecular structures or transition).
- ▶ High Brightness
 - To focus the radiation beam down to a small spot size and thus increasing the photon flux on a small target.
- ▶ High Photon Flux (10^{12} photons per pulse)
 - To increase the number of scattered photons even at small targets.
- ▶ Transverse Coherence
 - To allow diffraction experiments and to reconstruct 3D model of target sample.

X-ray FEL vs Other Light Sources



Optical short pulse lasers

Pulse duration: +++ (few fs)

Pulse energy: +++ (many mJ)

Wavelength: --- (~800 nm)

→ Fastest processes can be analyzed

→ Spatial resolution very limited



Synchrotrons

Pulse duration: o (few ps)

Pulse energy: o (< nJ)

Wavelength: +++ (~ 0.1 nm)

→ Temporal resolution limited

→ Wavelength allows for atomic resolution

Courtesy of F. Löh

X-ray free-electron lasers

Pulse duration: +++ (few fs)

Pulse energy: ++ (few mJ)

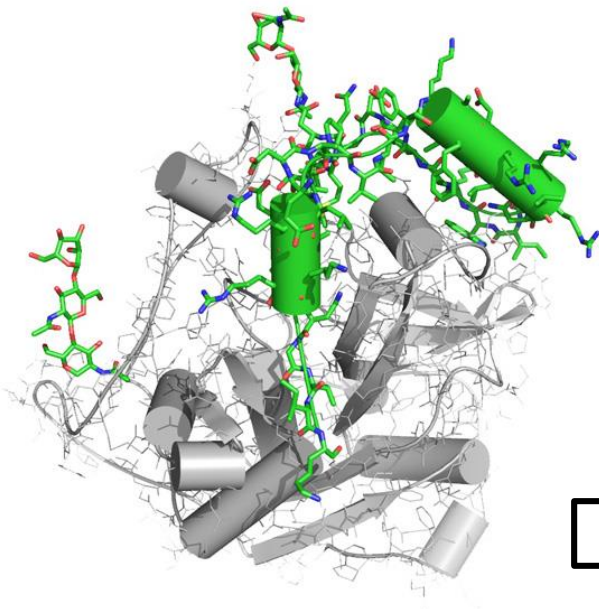
Wavelength: +++ (~ 0.1 nm)

→ Fastest processes can be analyzed

→ Wavelength allows for atomic resolution

Science with FELs

- ▶ FELs are unique light sources to probe any kind of matter at atomic length and time scales
- ▶ FELs 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
 - Observation of transitions in quantum materials → development of new materials for multiple applications



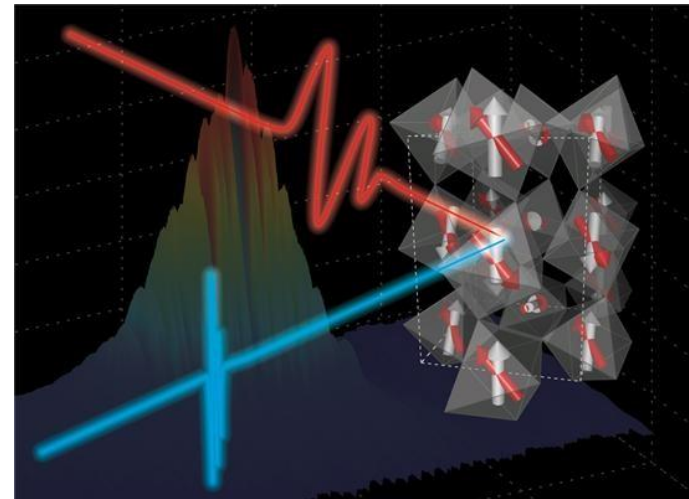
reconstruction



known

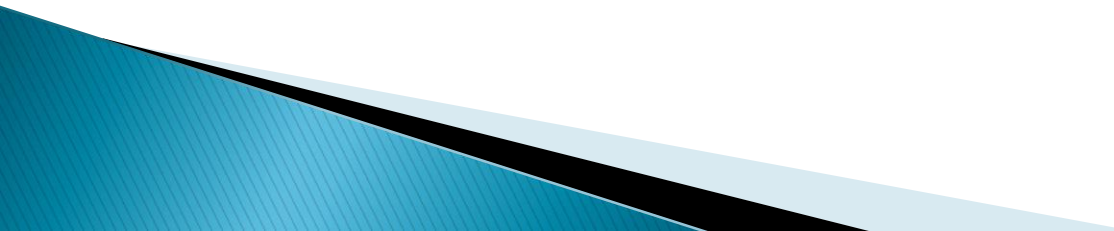
3nm

Ref. PNNL and FELs of Europe



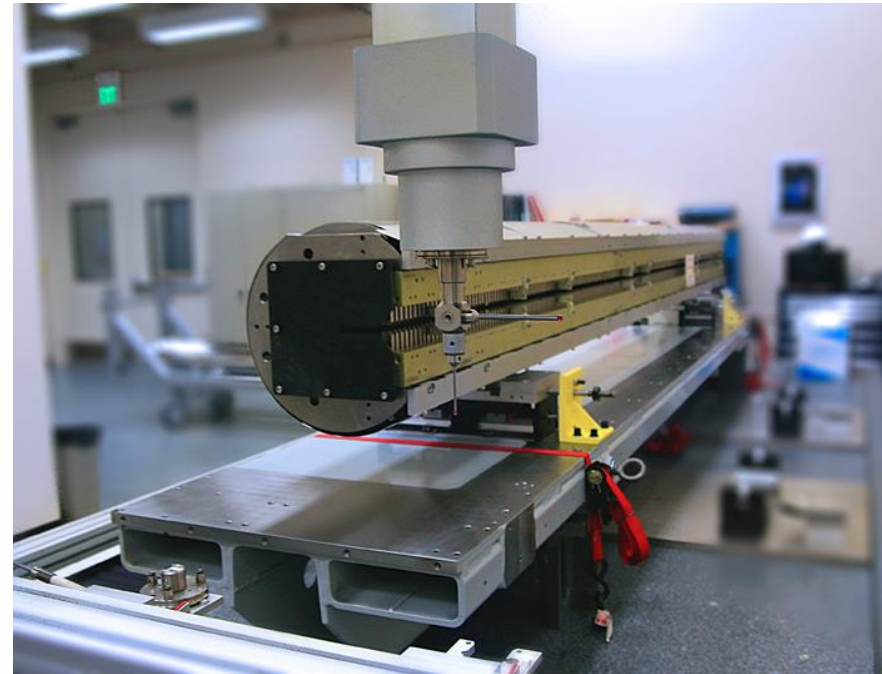
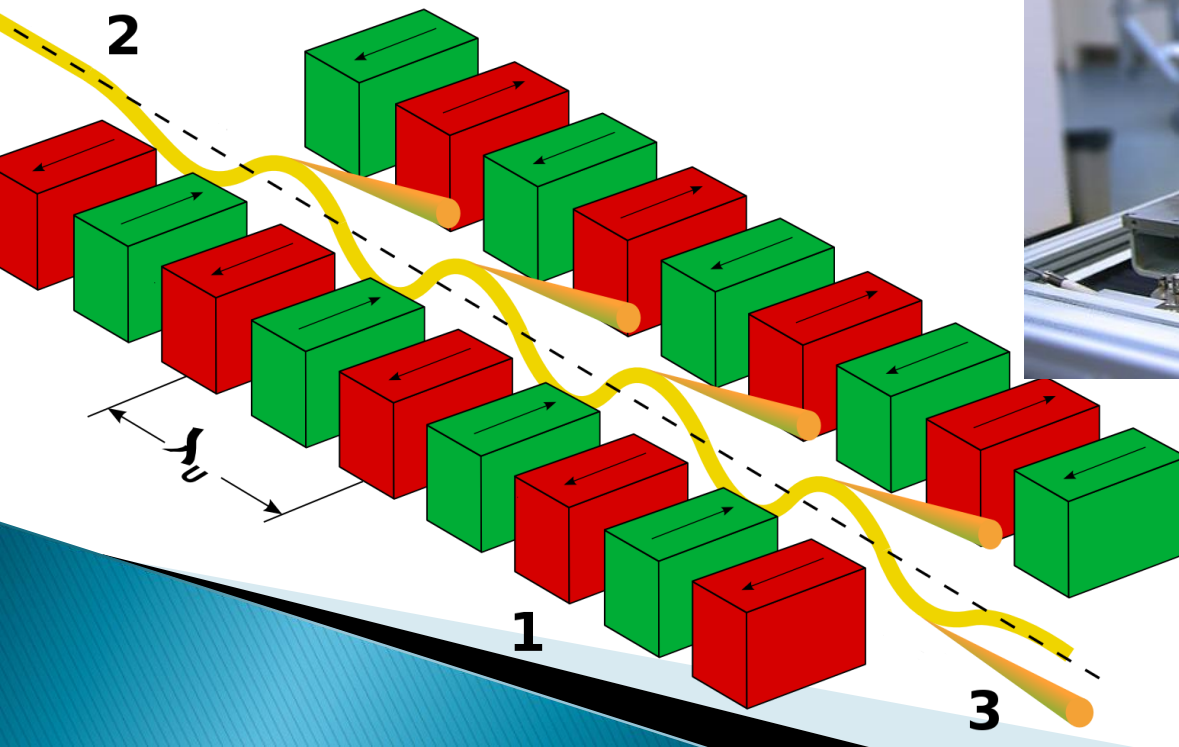
II. Basic physics principles

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

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

**Note that field is only valid on-axis.
4th Maxwell Equation requires other
field component off-axis.**

$$\nabla \times B = 0 \Rightarrow \frac{dB_z}{dy} - \frac{dB_y}{dz} = 0$$

For a planar undulator

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

Motion in Planar Undulator

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

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

Dominant field in y

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

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

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

Undulator parameter

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

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

Transverse

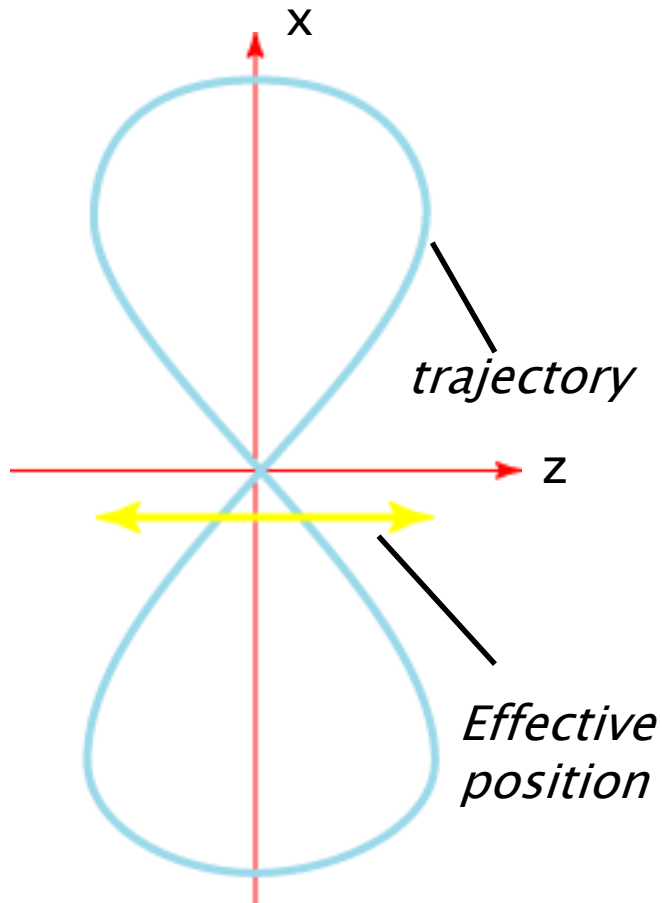
$$\beta_x = -\frac{K}{\gamma} \sin(k_u z)$$

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

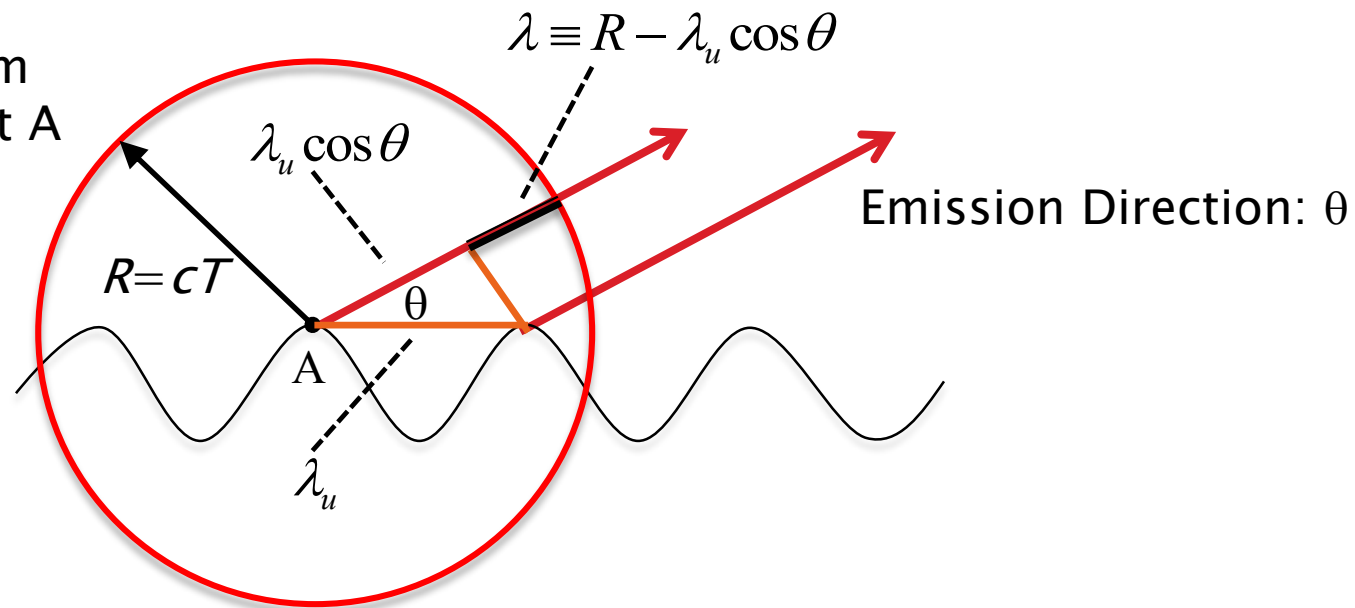
II. Basic physics principles. Undulator radiation

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 ($\gamma=11000$) 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

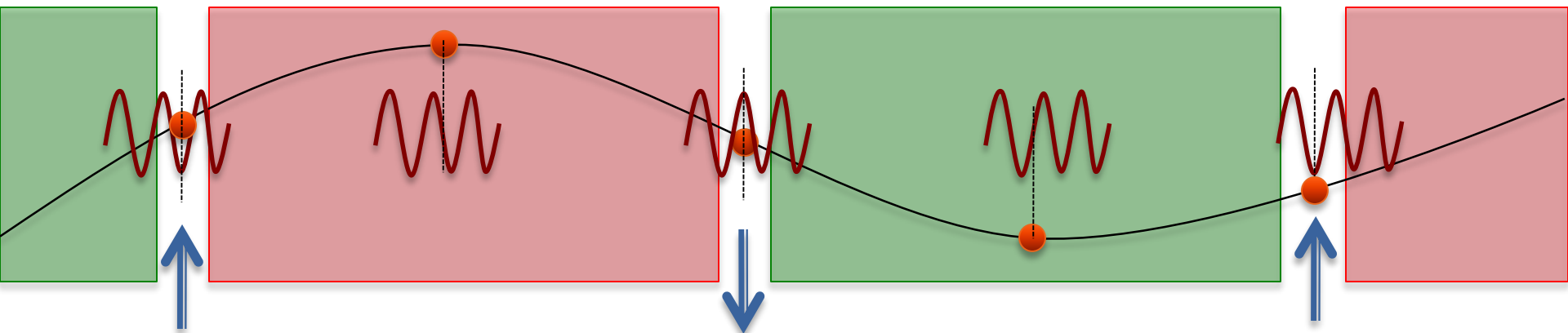
Basic ideas

- ▶ 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.



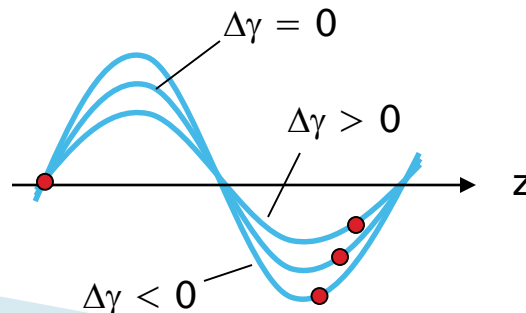
The net energy change can be accumulated over many periods

Energy Modulation & Longitudinal Motion

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

$$\frac{d}{dz} \gamma = - \frac{ef_c K}{2\gamma} \frac{E_0}{mc^2} \sin(\theta) \quad f_c: \text{coupling factor } (<1)$$

- ▶ 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:



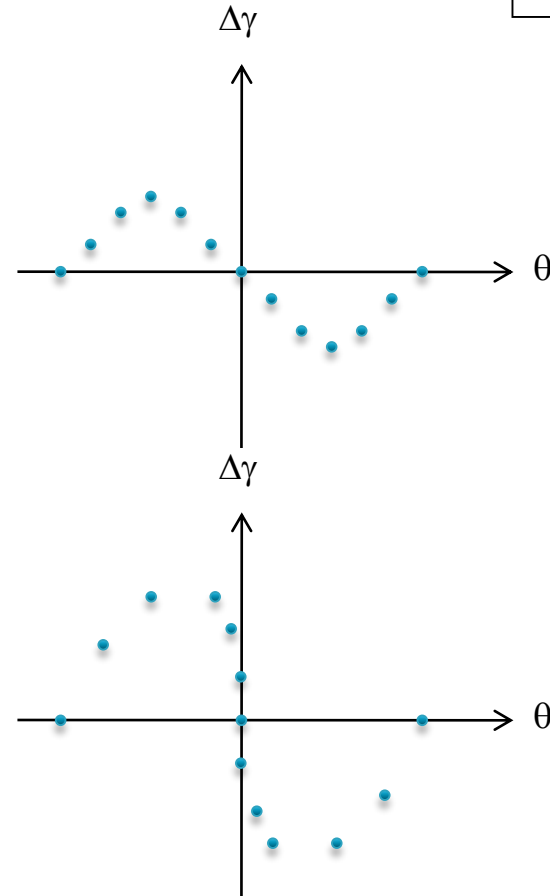
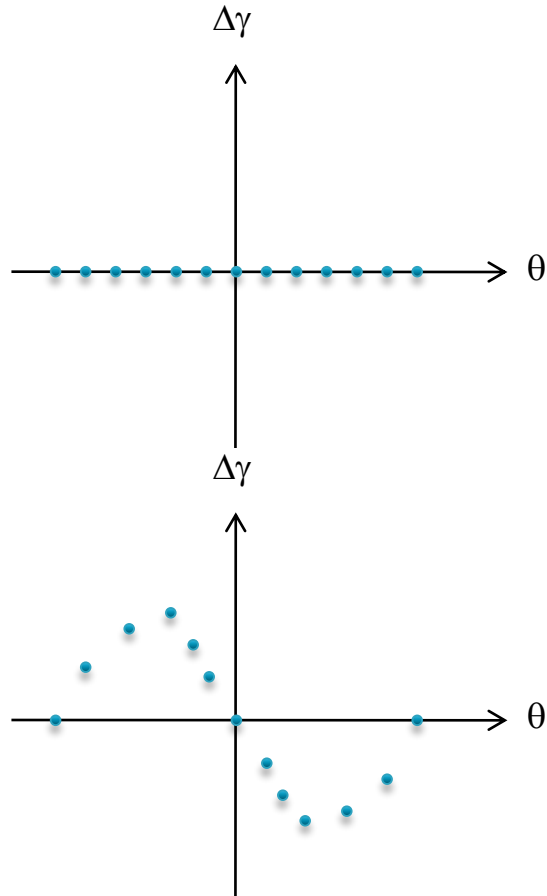
$$\frac{d}{dz} \theta = 2k_u \frac{\Delta\gamma}{\gamma_r}$$

Motion in Phasespace

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

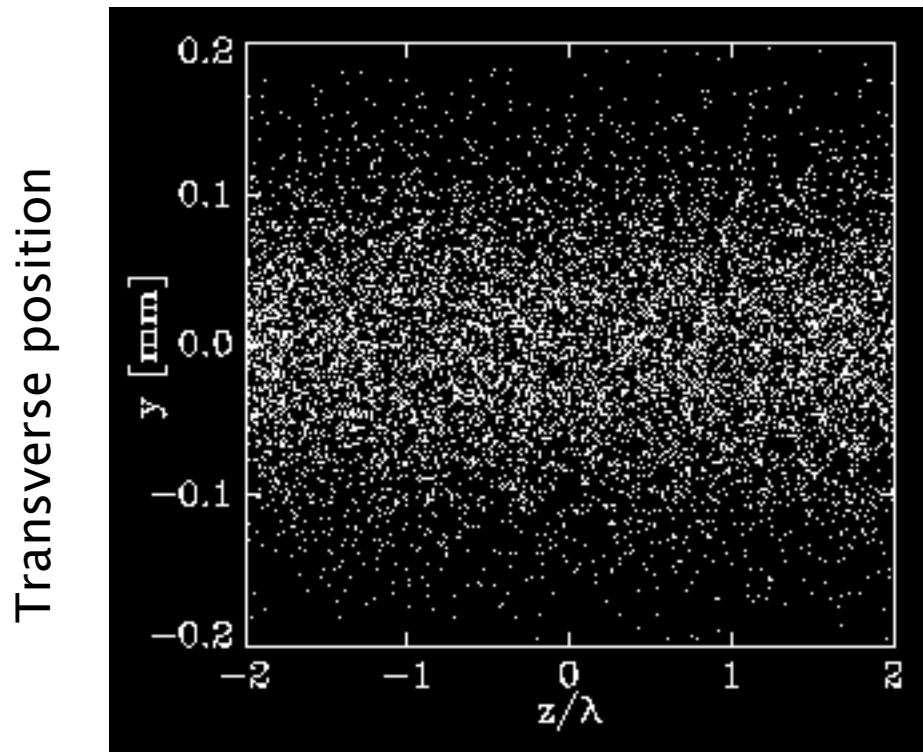
- ▶ Wavelength typically much smaller than bunch length.
- ▶ Electrons are spread out initially over all phases.

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



Electrons are bunched on same phase after quarter rotation

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.

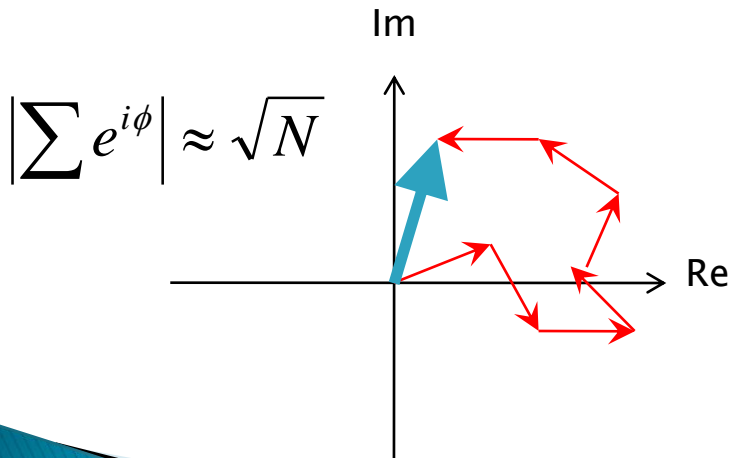
II. Basic physics principles. Field Emission

Coherent Emission

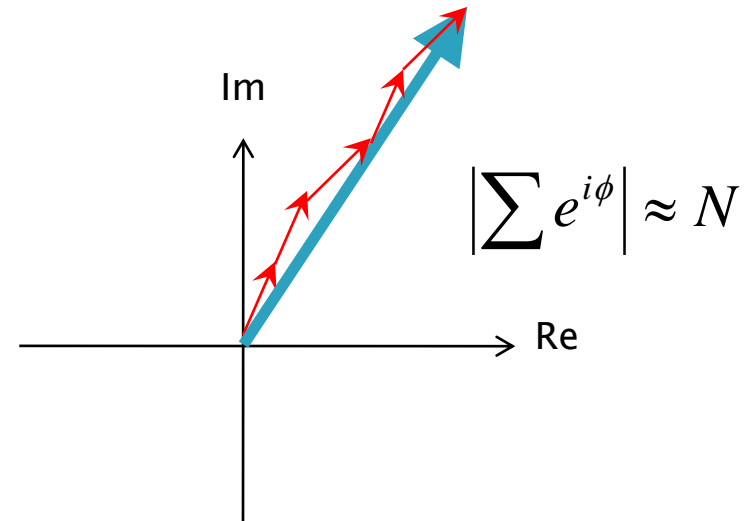
- ▶ The electrons are spread out over the bunch length with its longitudinal position δz_j . The position adds a phase $\phi_j = k\delta z_j$ to the emission of the photon
- ▶ The total field for an electron is:

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

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



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



Power $\sim |E|^2 \rightarrow$ Possible Enhancement: $N (N \rightarrow N^2)$

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.

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

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

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

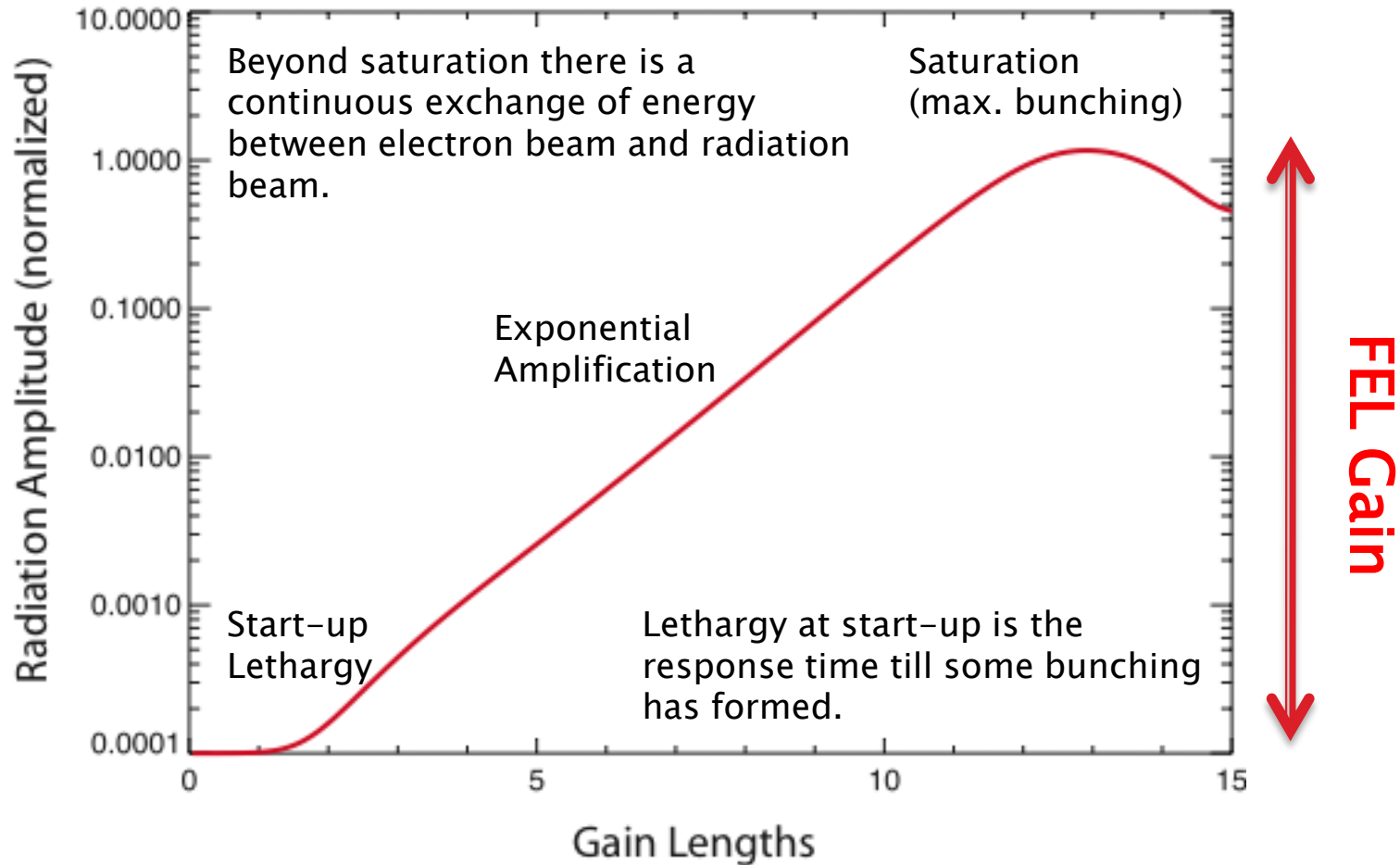
↓
Diffraction

↓
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)



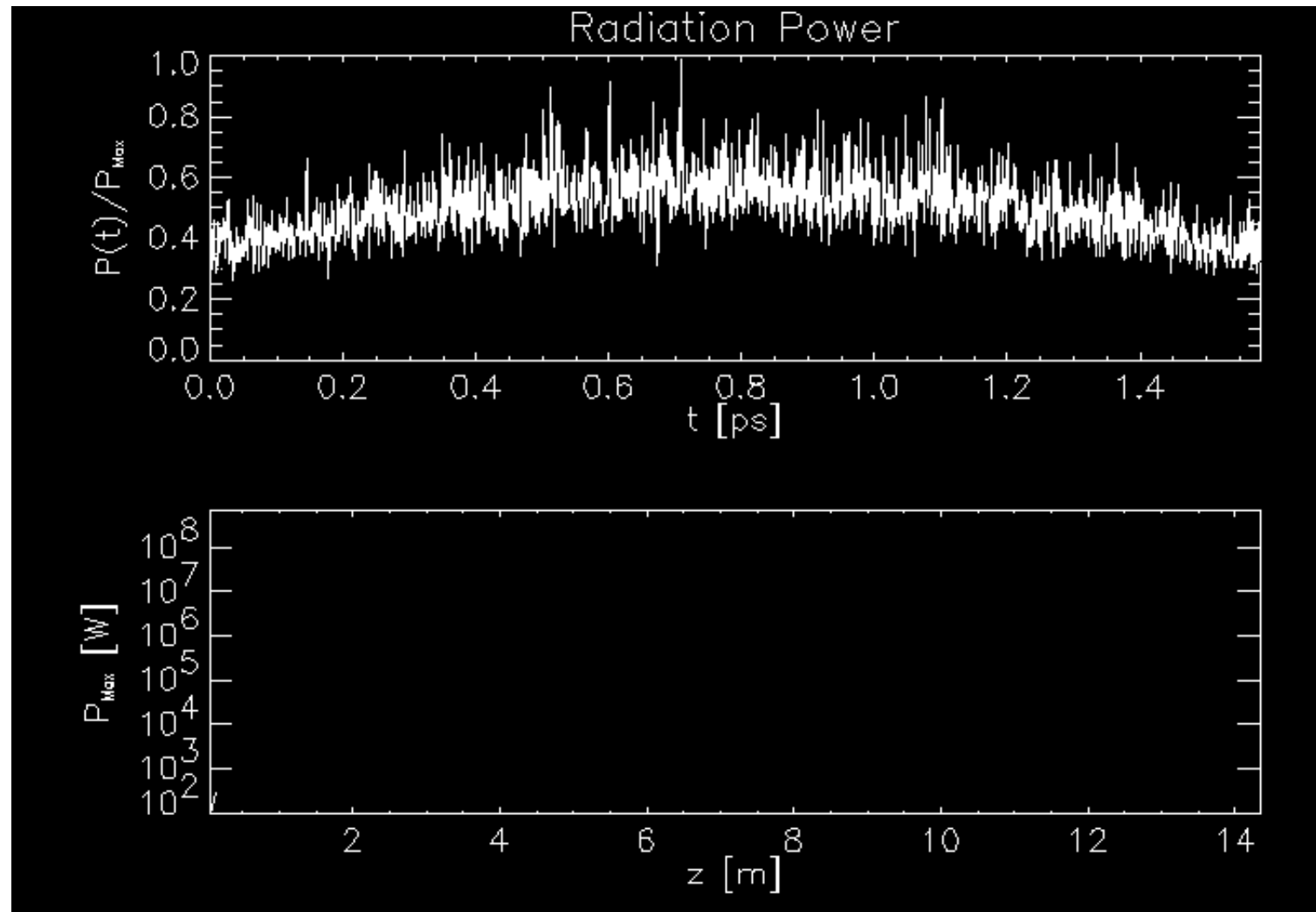
Spontaneous emission (shot noise)
is a broadband seed of "white noise"

- ▶ FEL Amplifier (starts with an input signal)



Seed must be above shot noise power

Typical Growth of SASE Pulse

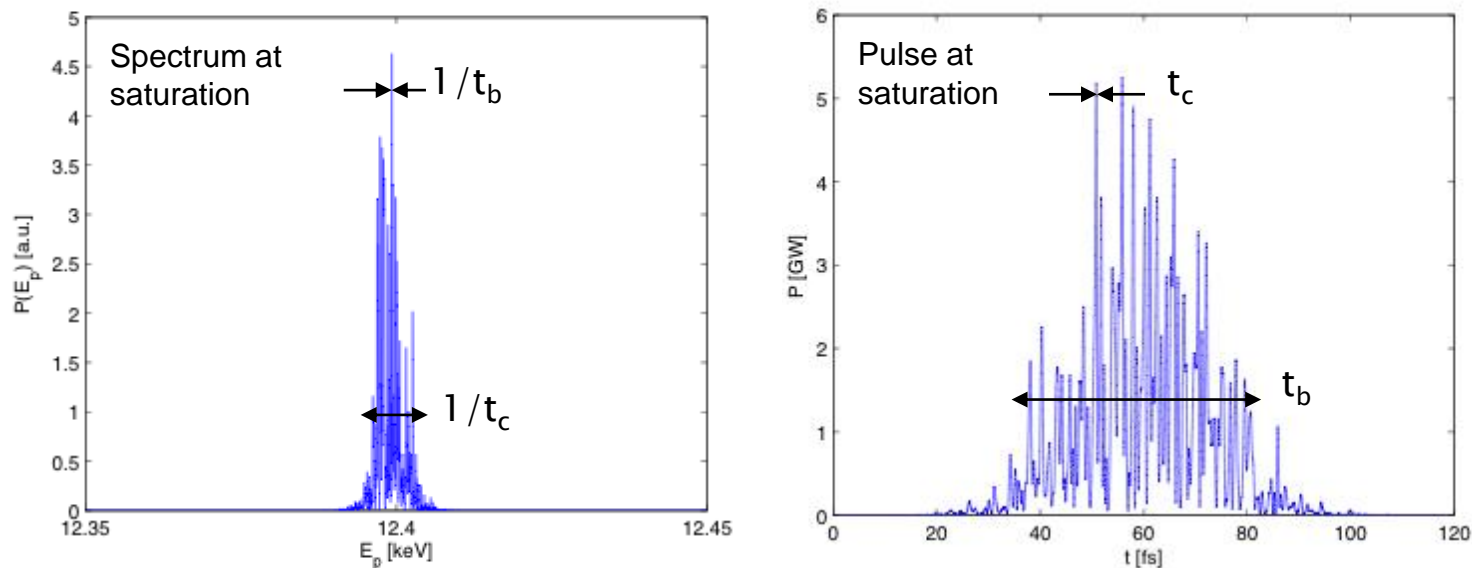


Simulation for FLASH FEL

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 : Alfvén 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

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

- ▶ Beam Requirements:

Energy Spread

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

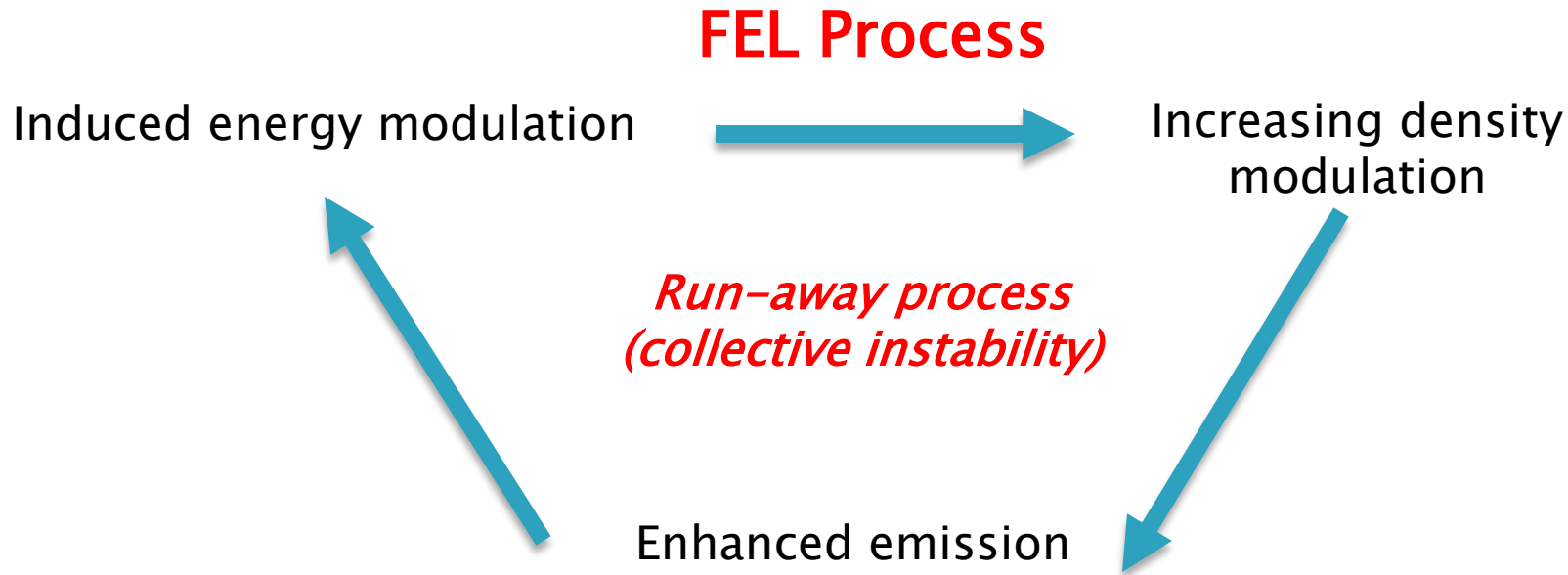
Emittance

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

Beam Size

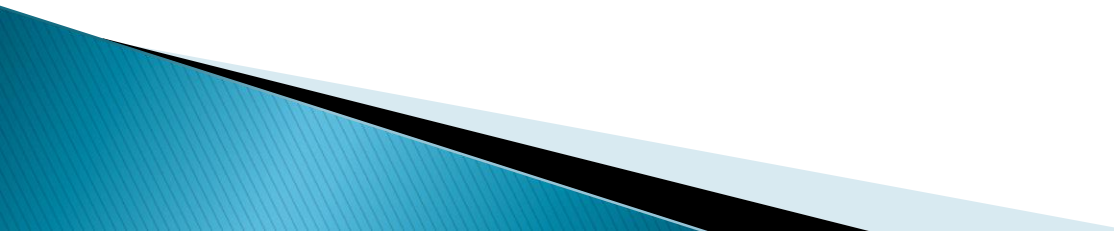
$$\beta_{opt} \approx 3 \sqrt{\frac{\varepsilon_n}{\gamma} \frac{4\pi}{\lambda}} L_g$$

Summary of basic physics principles



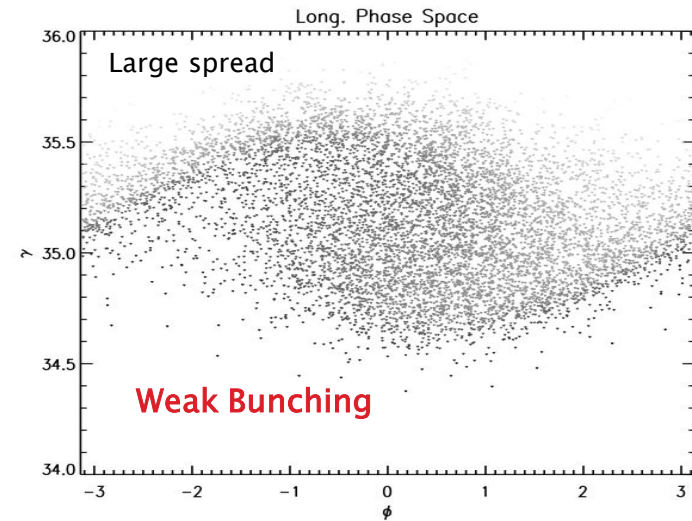
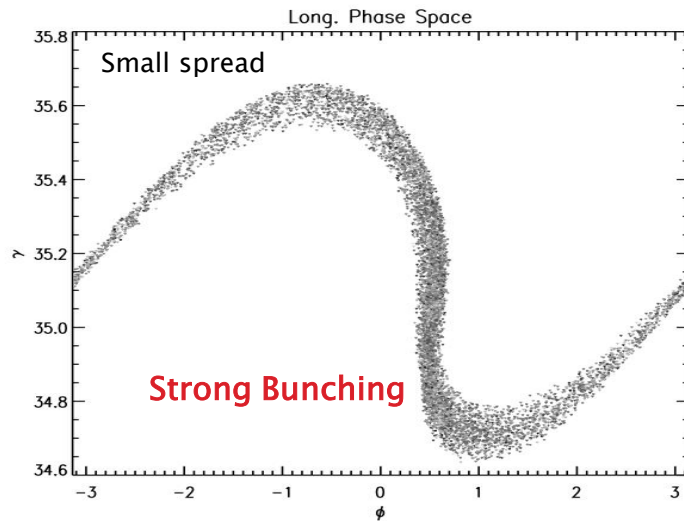
- ▶ FEL utilized the strong coherent emission in the collective instability with the tuning ability of the wavelength.
- ▶ Instability can only occur with a beam with low energy spread and emittance.

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:

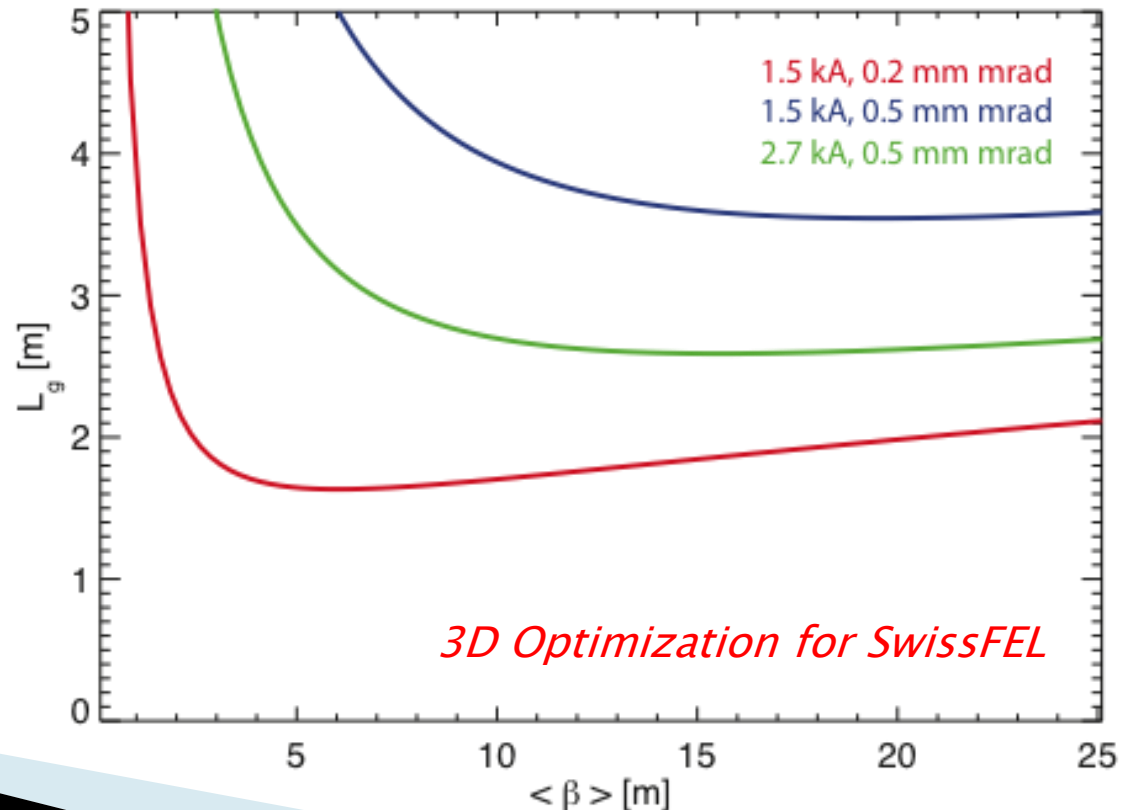
$$\frac{\sigma_{\gamma}}{\gamma} \ll \rho$$

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:

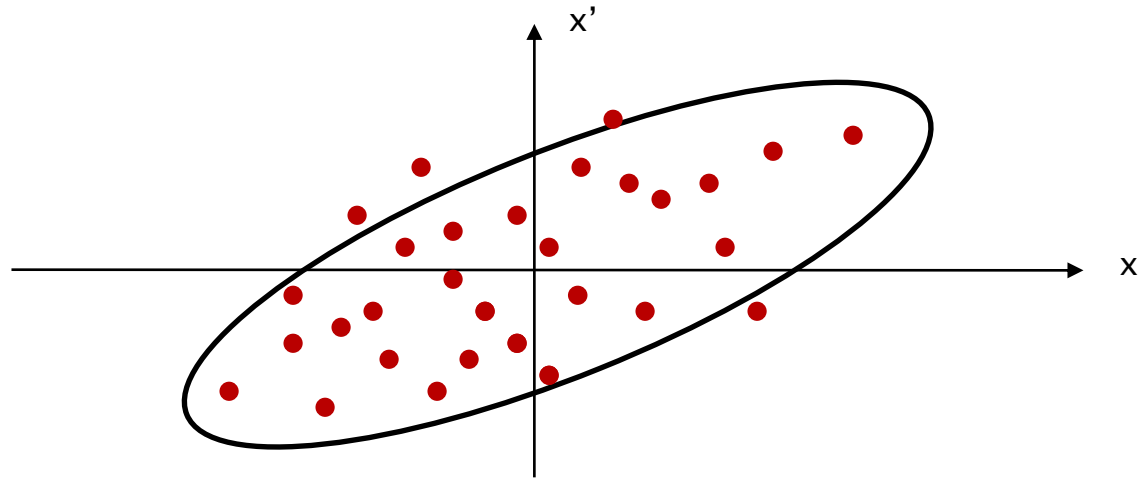
$$\beta_{opt} \approx 3 \sqrt{\frac{\varepsilon_n}{\gamma} \frac{4\pi}{\lambda} L_g}$$



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.

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

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

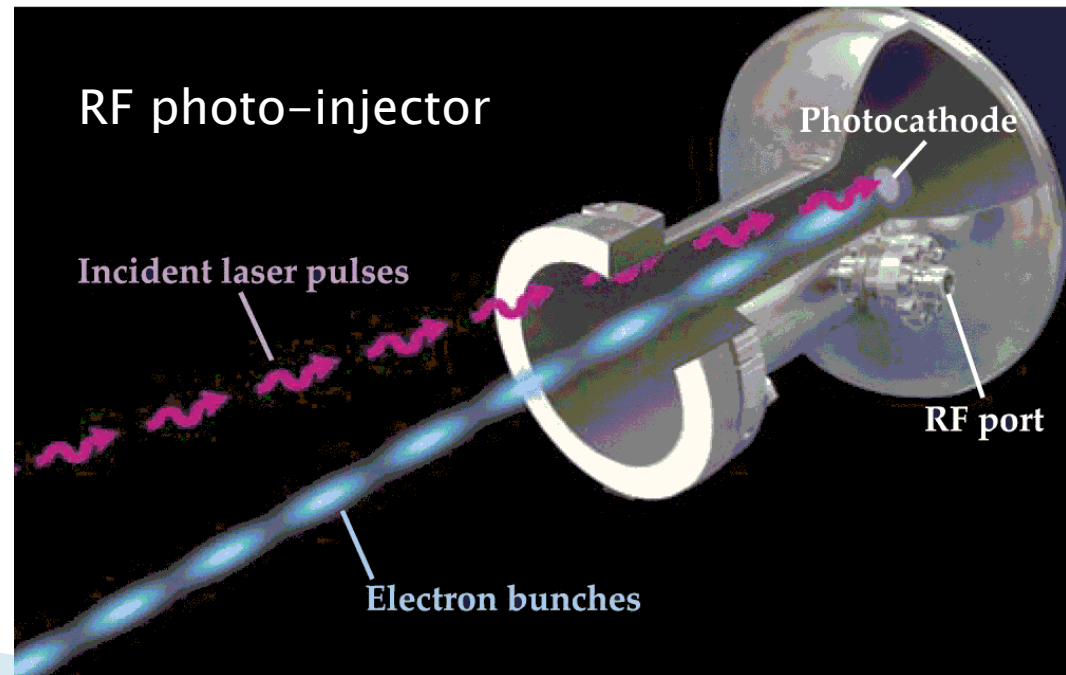
$$\frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{4\pi}$$

- ▶ 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

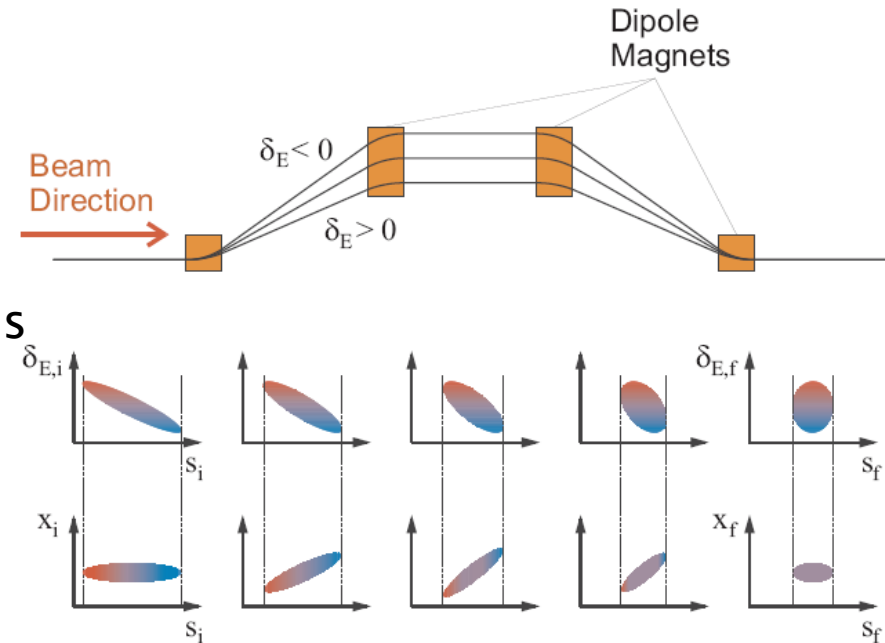
C. Hernandez-Garcia, P. G. O' Shea, and M. L. Stutzman, Phys. Today 61(2), 44 (2008).



Bunch compression

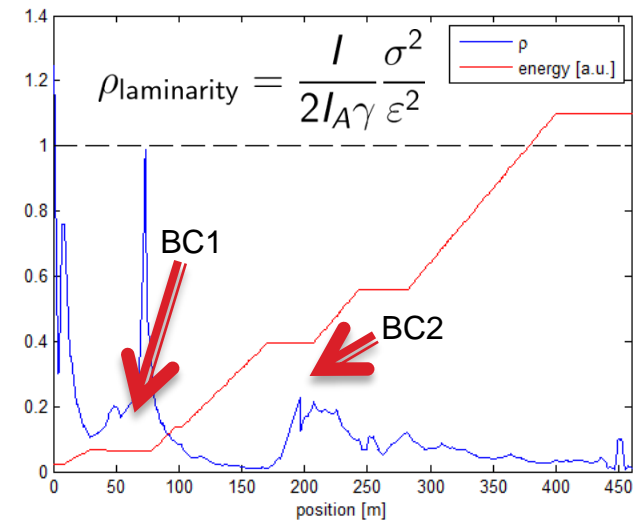
Bunch compression principle

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



Where to compress?

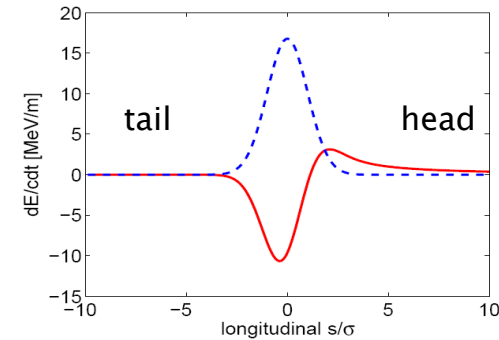
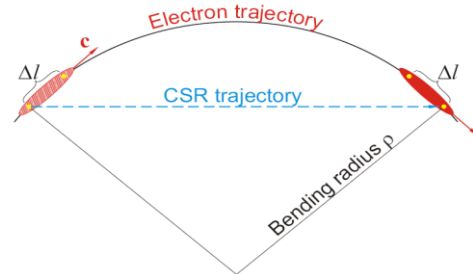
- ▶ Early compression would lead to high charge density beams at low energies which would increase the emittance.
 - ▶ Late compression would require the transport of long bunches through the linac without emittance dilution, which is difficult (RF-curvature, wake fields, ...)
- ⇒ Multi-stage-compression: 2 stages in case of LCLS, FLASH, and SwissFEL



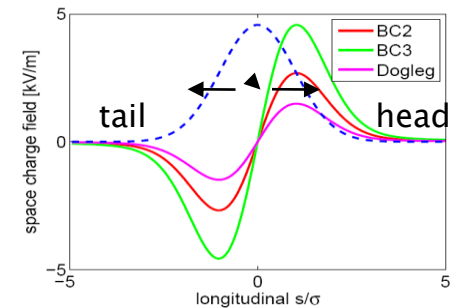
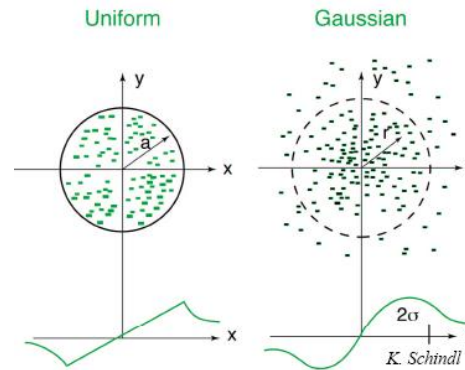
Self Interactions

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

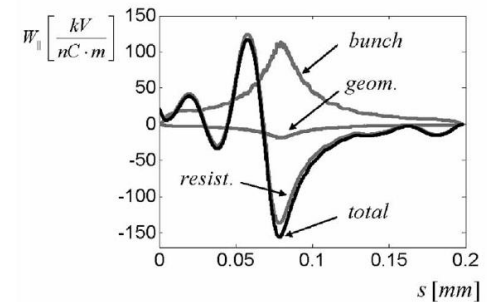
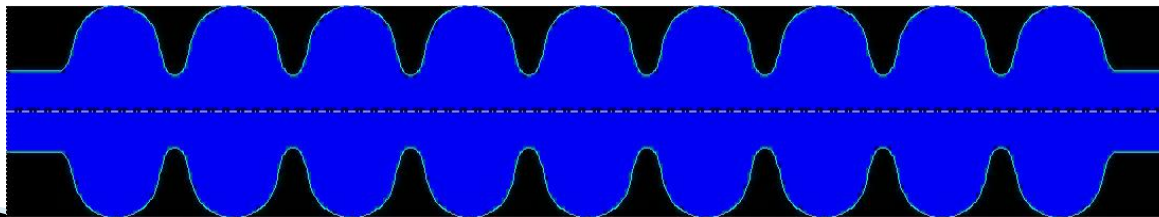
- ▶ Coherent Synchrotron Radiation



- ▶ Space Charge fields



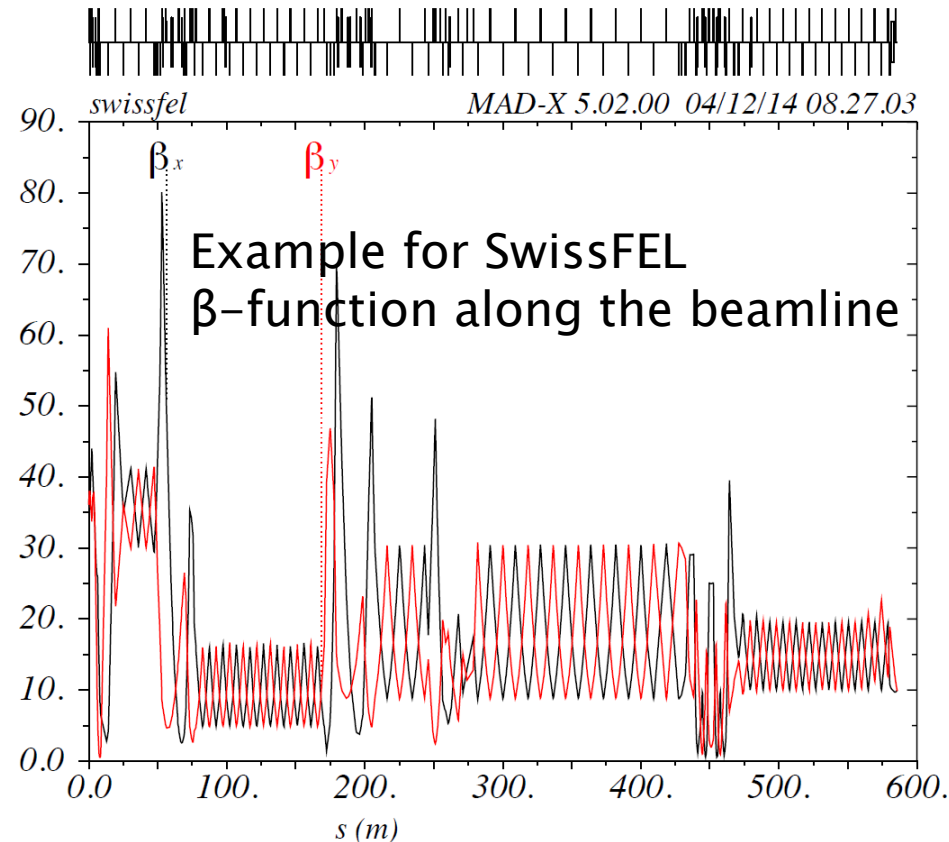
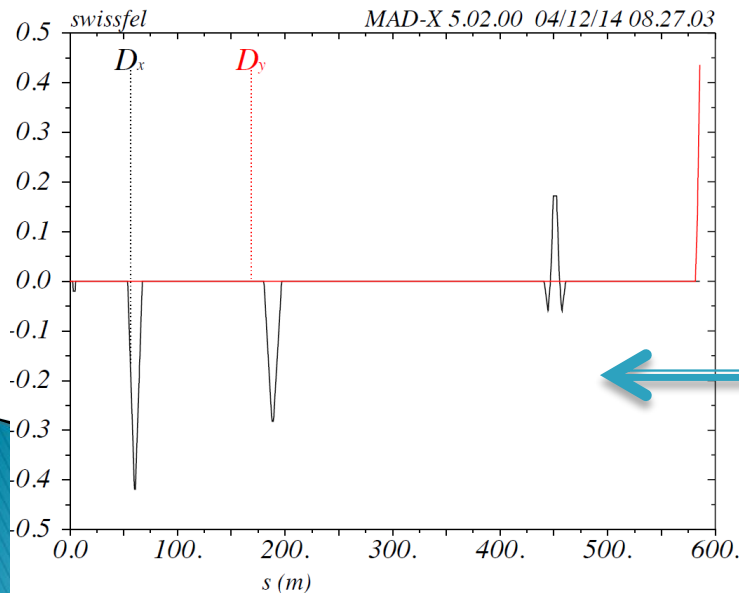
- ▶ Wake fields



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

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	<ul style="list-style-type: none">• Laser pulse shape•Magnetic chicane (bunch compressor)	Beam profile measurement with RF deflector and screen monitor
Beam size / emittance	<ul style="list-style-type: none">• Design electron gun•“emittance compensation”	<ul style="list-style-type: none">•“Pepperpot”/slits (low energies)•Beam optical methods (higher energies)

V. FEL projects around the world

X-ray FEL Projects Around the World



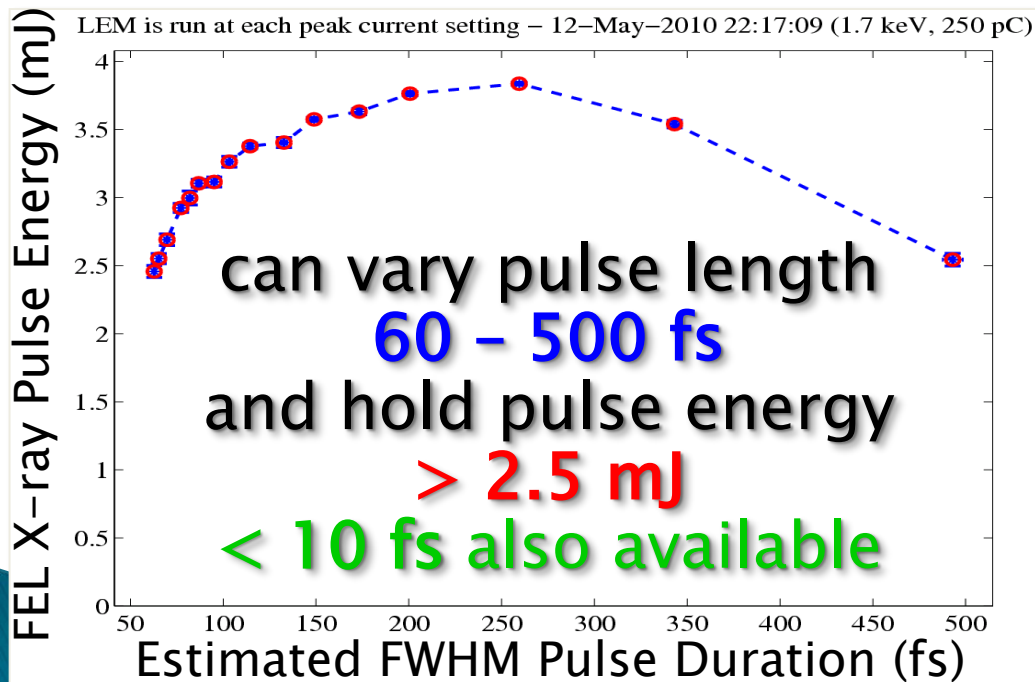
Planned/Existing X-ray FELs

Courtesy of P. Emma

- **FLASH** at **DESY**, De (4-45 nm)^{+FLASH-II 2014}  (2002)
- **LCLS** at **SLAC**, USA (0.11-4.4 nm)  (2009)
- **Fermi** in **Trieste**, Italy (4-80 nm)  (2010)
- **SACLA** at **SPring-8**, Japan (0.1-3.6 nm)  (2011)
- **PAL-XFEL** in **Korea** (0.1-10 nm)  2016
- **European X-FEL** at **DESY**, De (0.1-6 nm)  2017
- **Swiss-FEL** at **PSI**, Ch (0.1-7 nm)  2017
- **LCLS-II** at **SLAC**, USA (0.05-6 nm)  2019

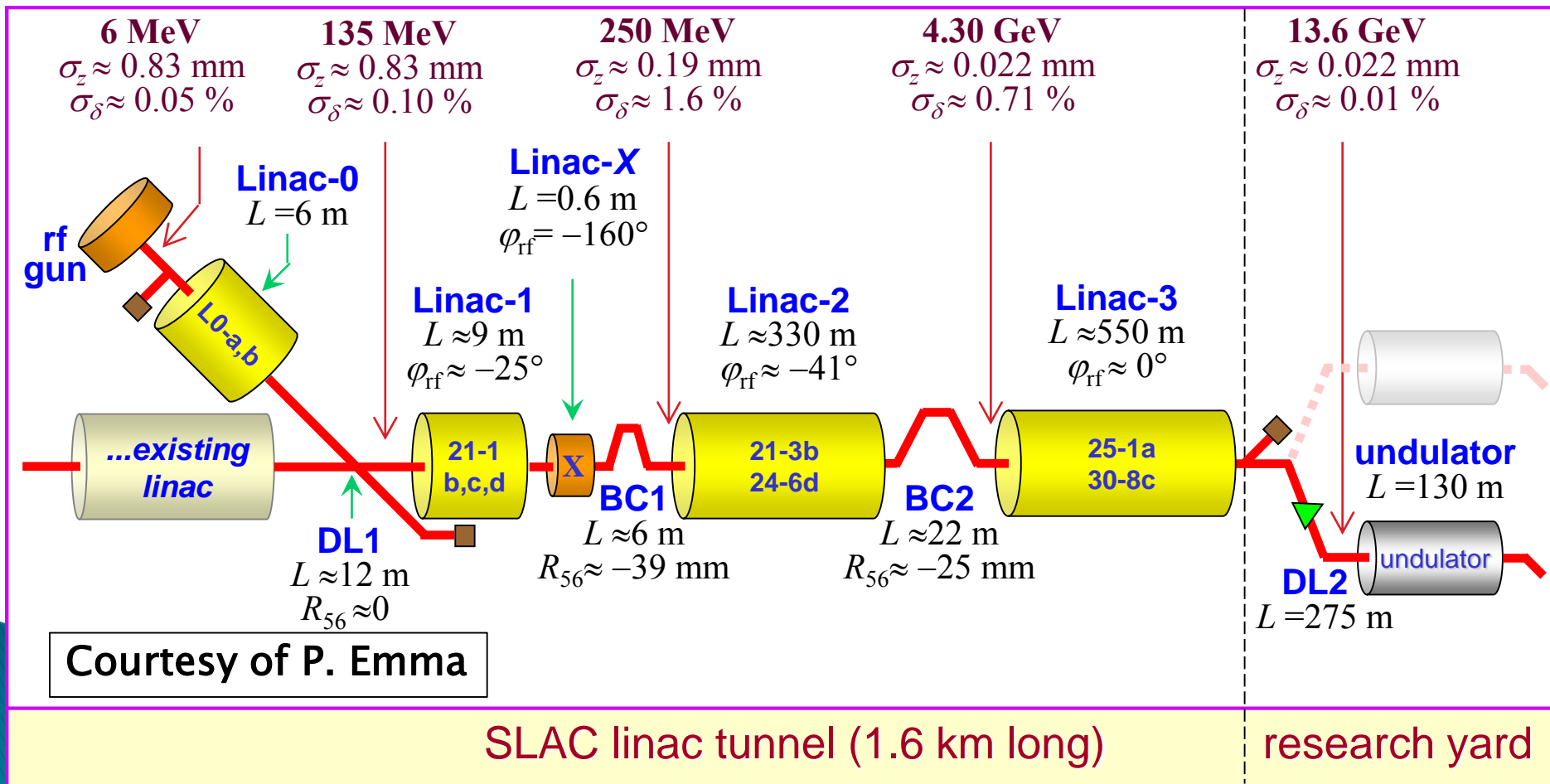
LCLS (Linac Coherent Light Source)

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



Japanese X-ray FEL facility, SACLA

(Spring-8 Angstrom Compact free electron LAsar)

Construction: FY2006~2010

First lasing: June 7, 2011

User Operation: March 2012~

Compact XFEL with 700 m length



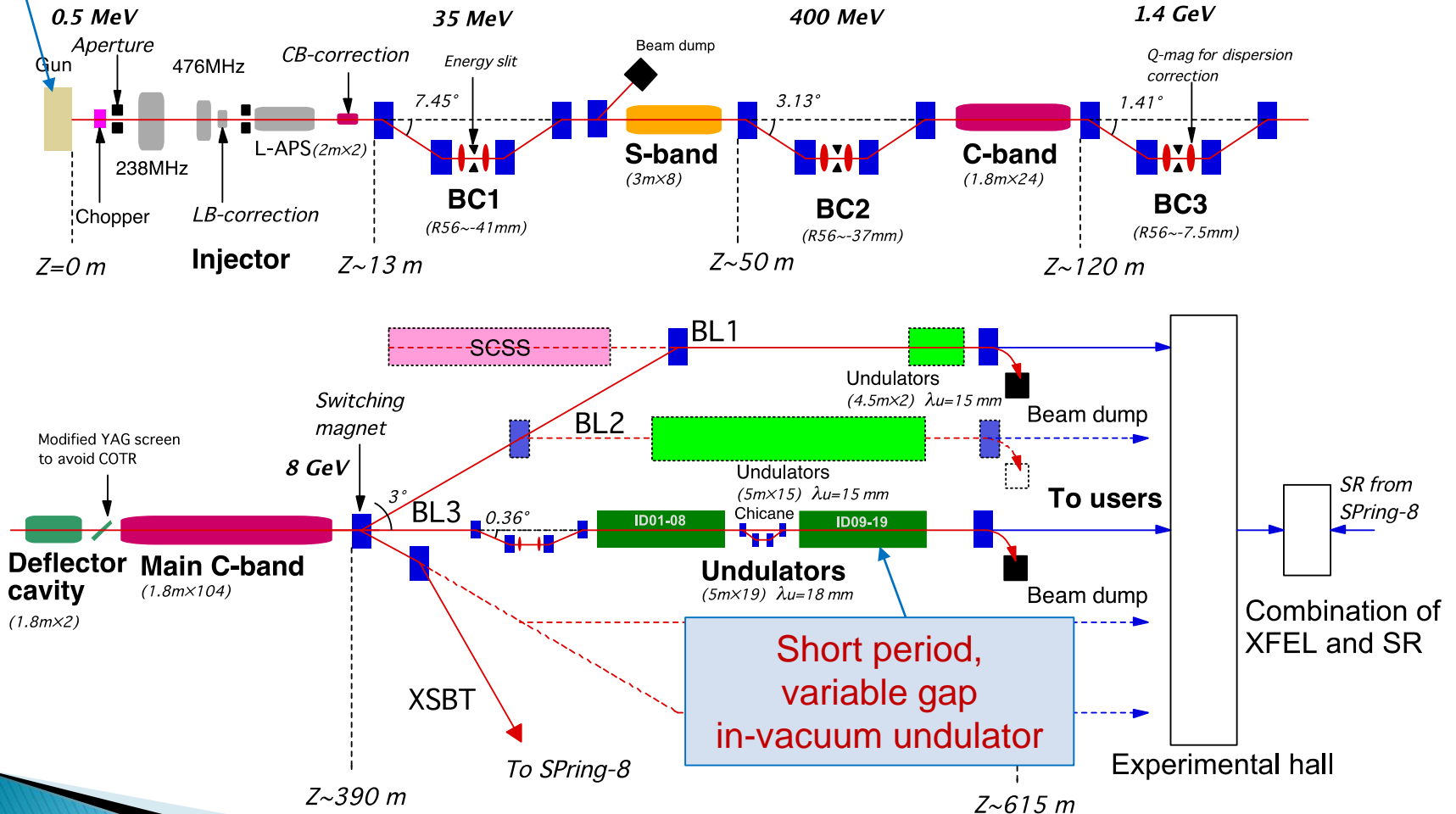
Courtesy of T. Tanaka and T. Inagaki

SACLA Layout

Beam energy: 8.5 GeV max.
 Energy stability: $\sim 1 \times 10^{-4}$ rms.
 Bunch charge: ~ 0.3 nC
 Rep, rate: 60 pps max.
 FEL pulse energies up to \sim mJ

Low emittance thermionic gun

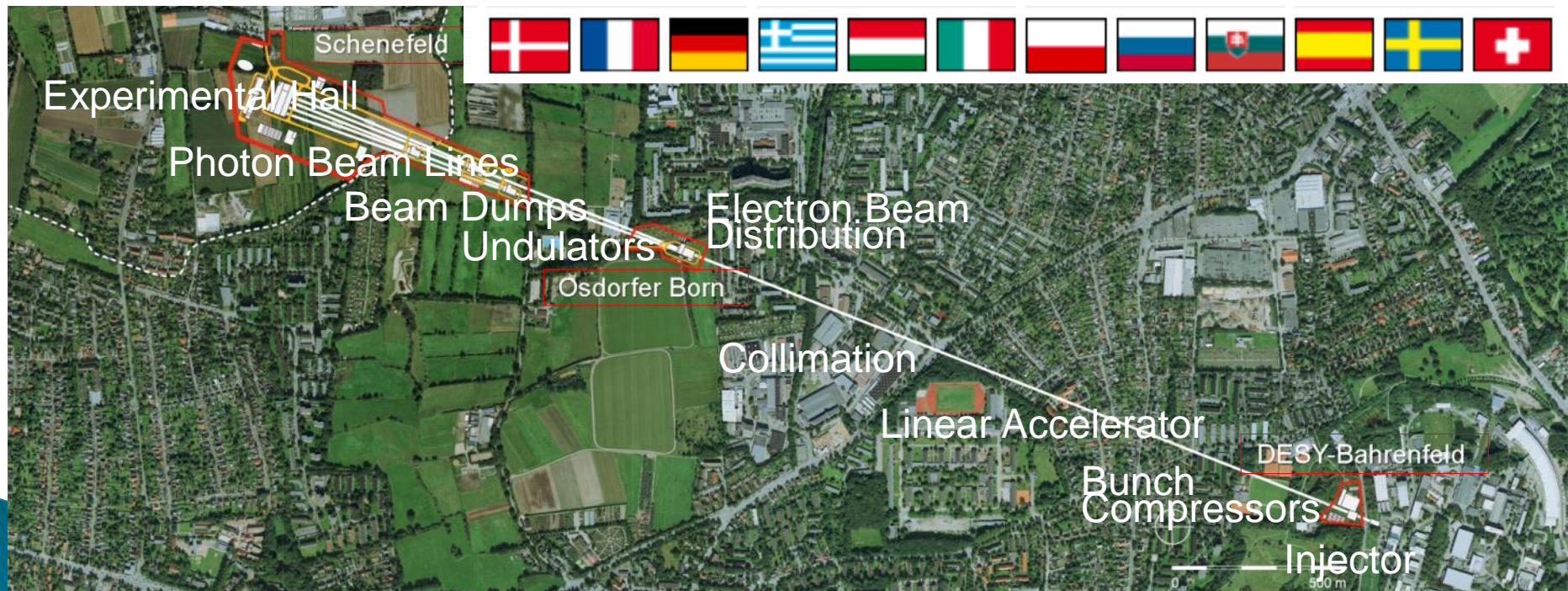
3 stage bunch compression to obtain several kA



Courtesy of T. Tanaka and T. Inagaki

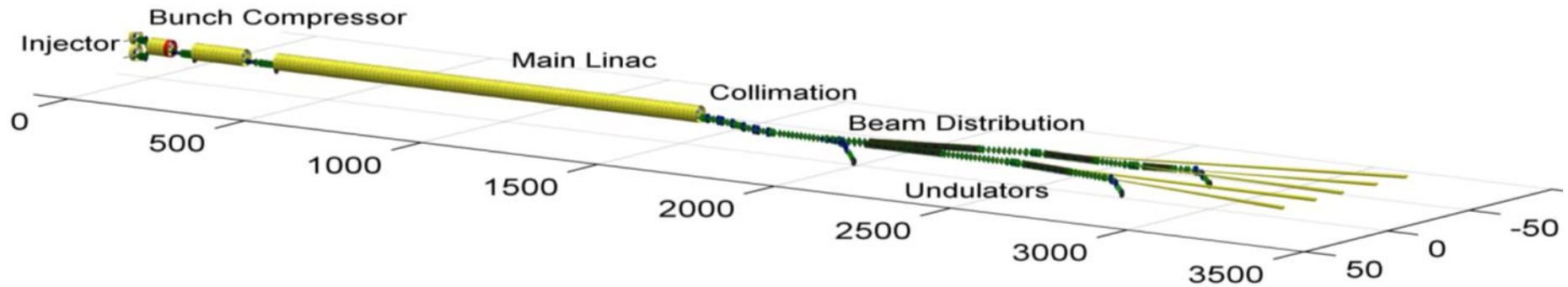
European-XFEL

- 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

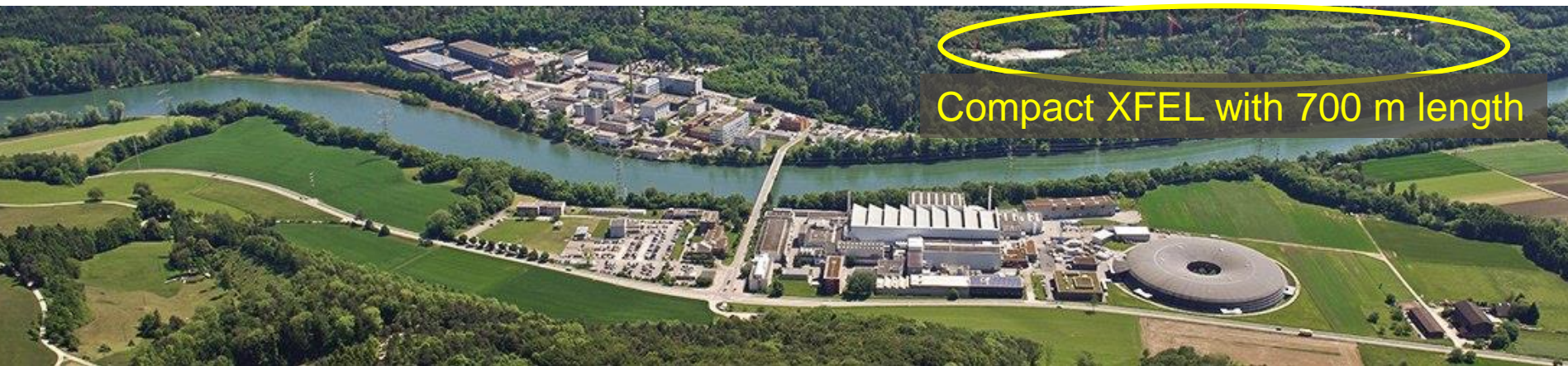
European-XFEL Layout



Courtesy of W. Decking

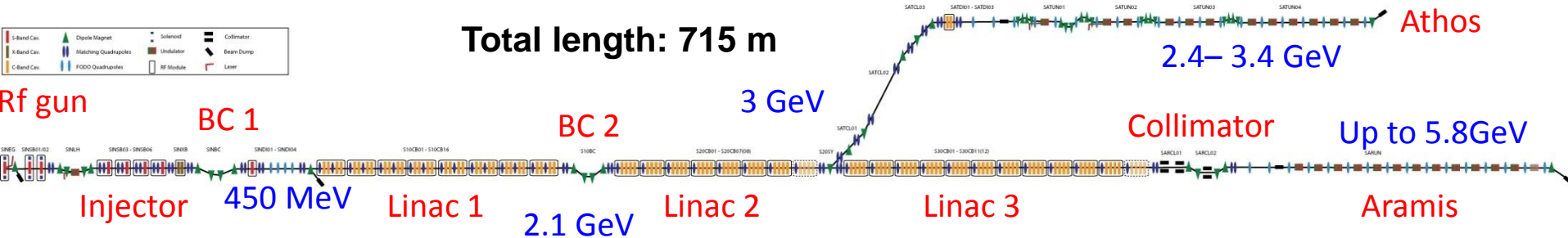
Quantity	Value
pulse repetition rate	10 Hz
beam pulse length	600 μ s
bunch repetition frequency within pulse	4.5 MHz
electron bunch length after compression	2 - 180 fs (FWHM)
bunch charge	0.02 - 1 nC
slice emittance	0.4 - 1.0 mm mrad
slice energy spread	4 - 2 MeV

SwissFEL



- X-ray FEL project in Switzerland (Villigen) with 2 beamlines
 - Aramis (hard X-ray)
 - Athos (soft X-ray)
- First ideas more than 10 years ago
- Construction started in 2013
- Commissioning of Aramis started in 2016
- First lasing at 24 nm on December 2016
- 2017: further commissioning and lasing at shorter wavelengths (down to 0.54 nm)
- Athos: installation will start in 2017, first FEL light by 2020

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:

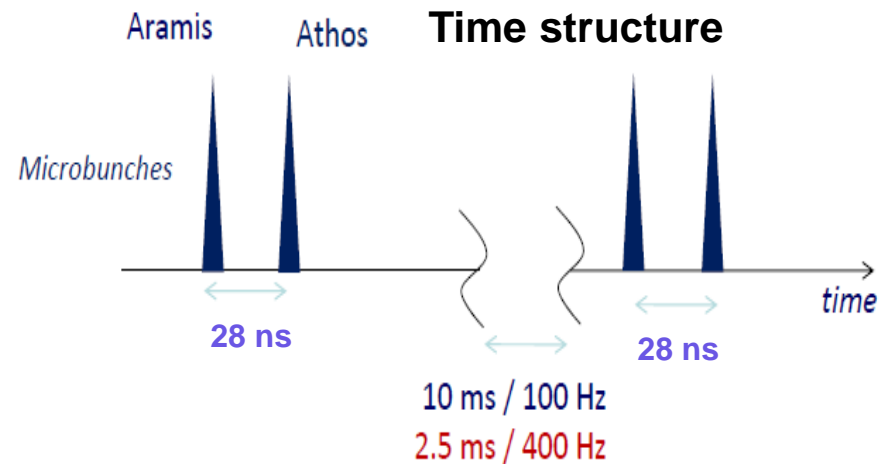
1. Aramis: hard X-ray FEL (1-7 Å)

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



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

SwissFEL

<https://www.youtube.com/watch?v=TcCx0i-ekNI>

References

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