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+ SwissFEL

Introduction to Free Electron Lasers

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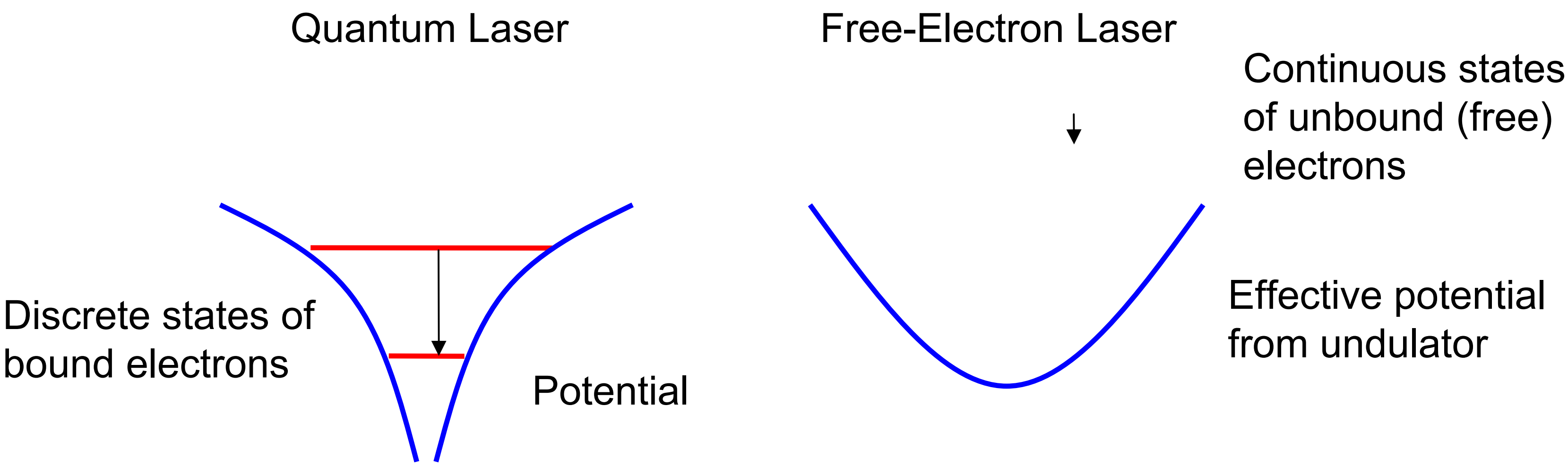
Free electron lasers (FELs) are an active field of research and development in various accelerator labs, including the PSI.

In this talk we introduce and discuss the basics of FEL physics. The requirements and basic layouts of such electron linac facilities are presented to complete the picture.

History of Free-Electron Lasers + SwissFEL

- Madey 1970 - Stimulated emission by ‘unbound’ electrons moving through a periodic magnetic field of an undulator/wiggler



- Tunability of the emitting wavelength

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

λ_u - undulator period, $K = (e/2\pi mc)B_0\lambda_u$ - undulator parameter, γ - electron energy

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History of Free-Electron Lasers

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- Kontradenko/Saldin 1980 and Bonifacio/Pellegrini/Narducco 1984 - Self-interaction of electrons with a radiation field within an undulator can yield a collective instability with an exponential growth in the radiation field.
- The FEL process can be started by the spontaneous radiation and thus eliminating the need of a seeding radiation source (Self-amplified Spontaneous Emission FEL)

Production of laser-like radiation down to the Ångstroem wavelength regime with X-ray Free-Electron Lasers

- Successful operation of SASE FELs down to 6 nm.

FEL as a High-Brightness/Brilliance Light Source

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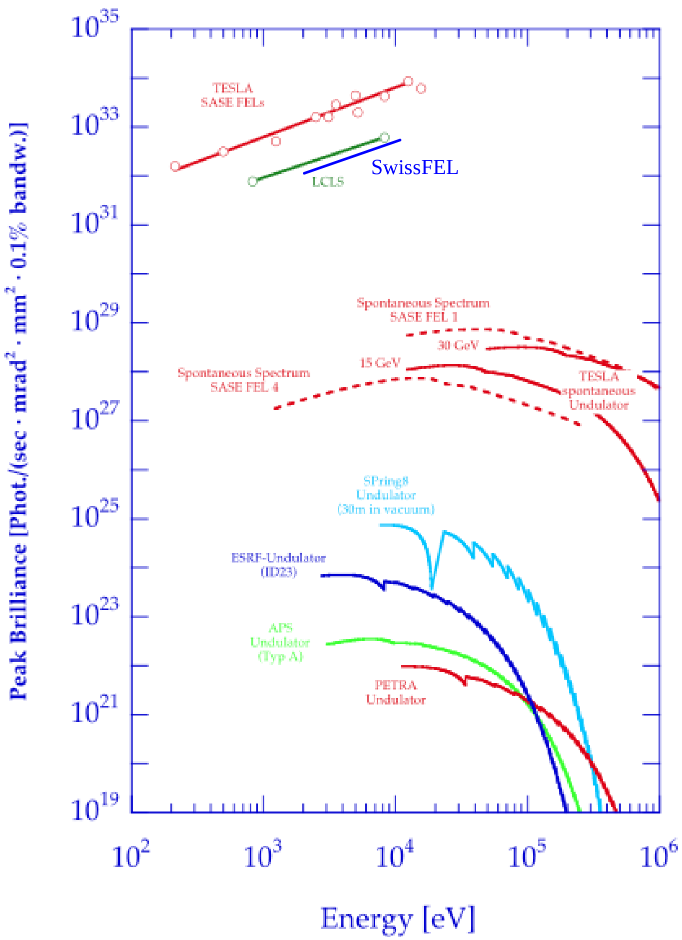
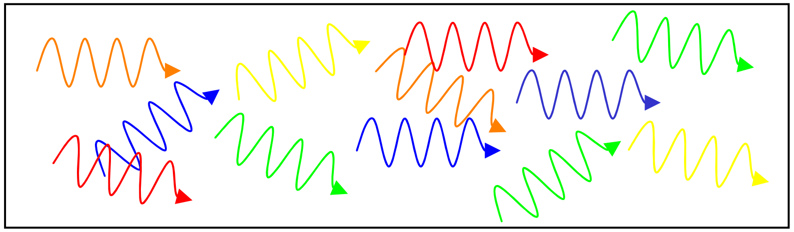
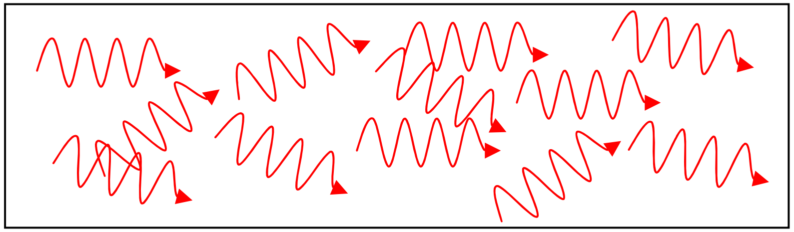


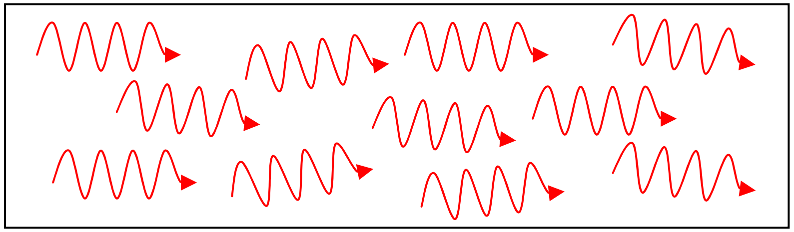
High photon flux



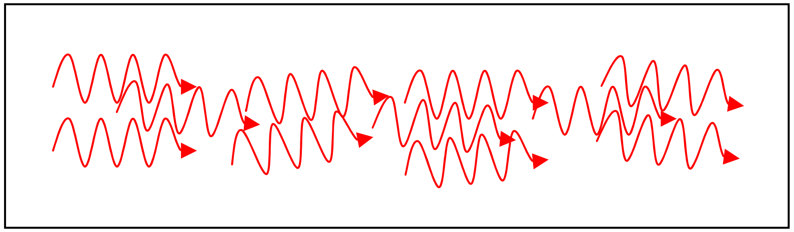
Small freq. bandwidth



Low divergence



Small source size



X-Ray FEL as 4th Generation Light Source

- Ångstrom 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/VUV FEL Projects Around the World

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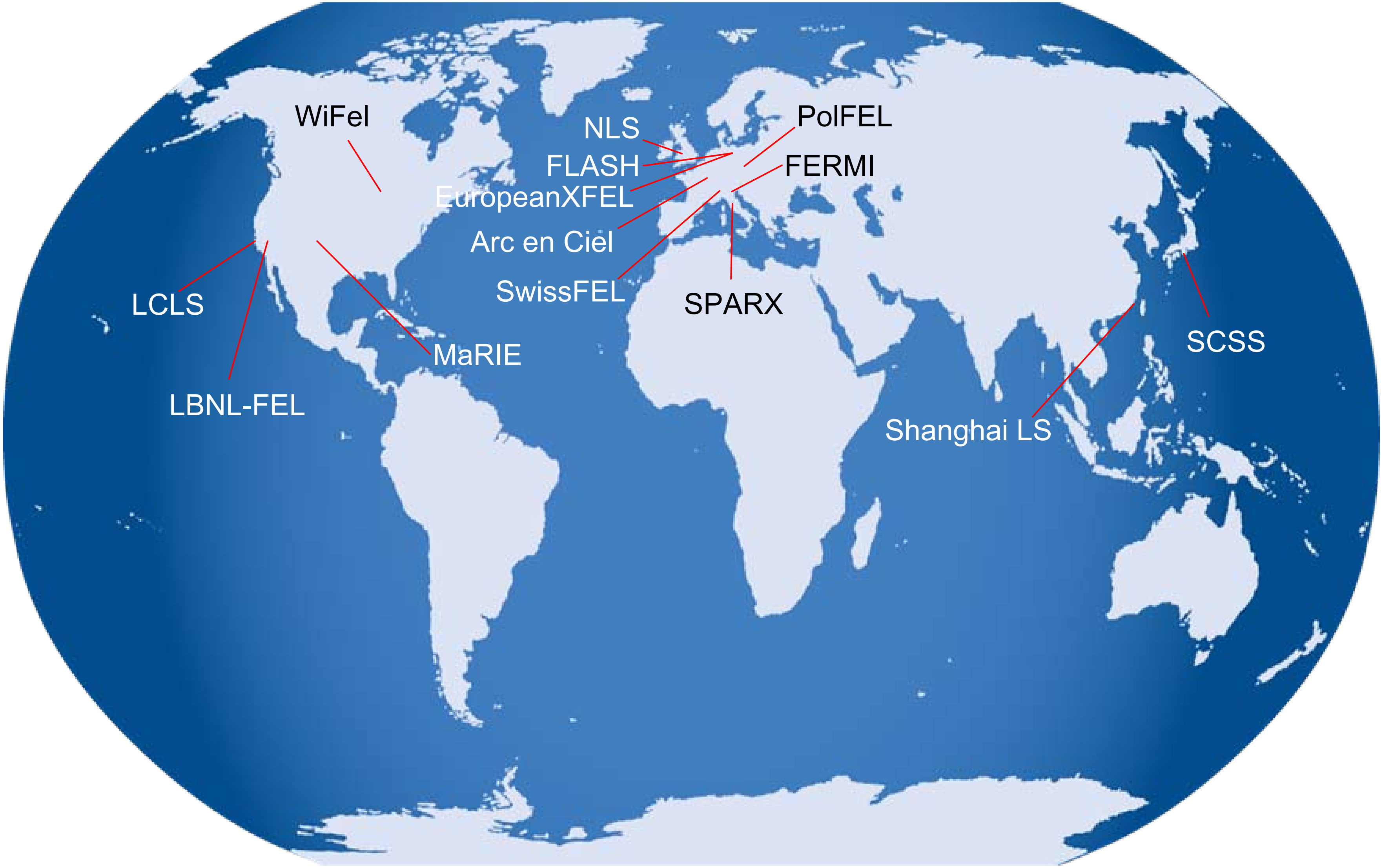
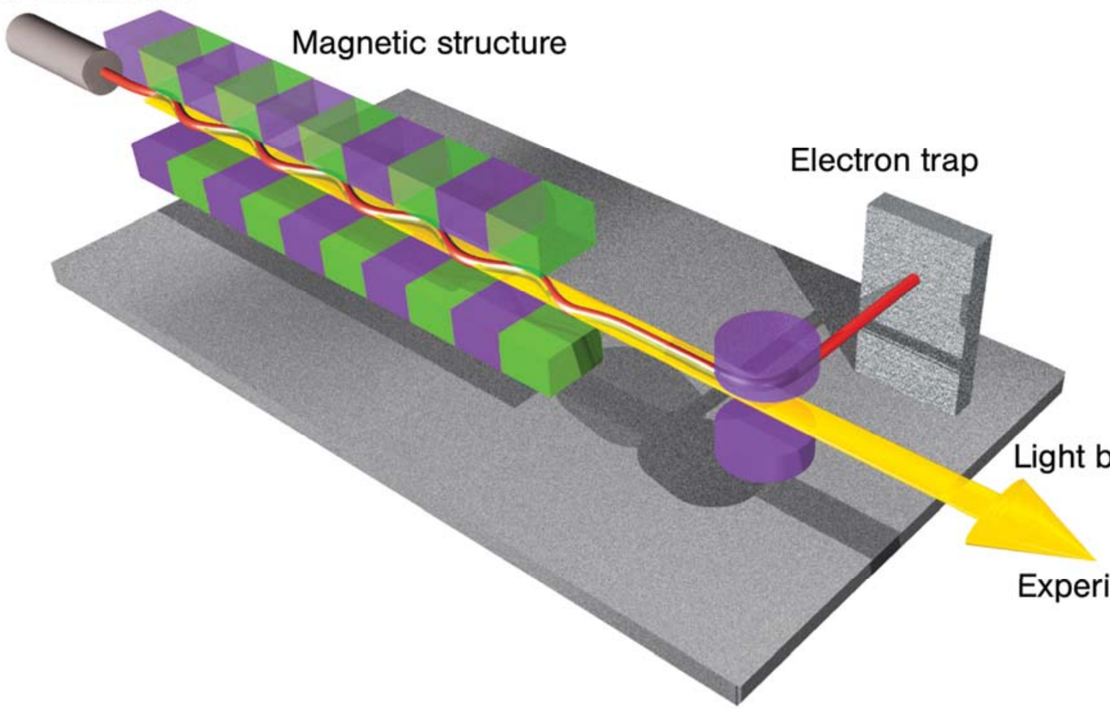


FEL Process


Electron source
and accelerator
Magnetic structure
Electron trap
Light beam
Experiment

Step 0 - Motion in Undulator

- The periodic magnetic field enforces a transverse oscillation of an electron moving along the axis of the undulator.

$$\beta_x = \frac{K}{\gamma} \sin(k_u z) \quad \text{with} \quad K = \frac{e}{2\pi mc} B_0 \lambda_u$$

- *K* is the net deflection strength of the Lorenz force of a single undulator pole and is proportional to the peak field B_0 and pole length (aka undulator period λ_u)

- Because the total energy is preserved the transverse oscillation affects the longitudinal motion. The average longitudinal velocity in an undulator is:

$$\beta_z \approx 1 - \frac{1}{2\gamma^2} - \frac{1}{2}\beta_x^2 = 1 - \frac{1 + K^2/2}{2\gamma^2}$$

Step I - Energy Change of Electrons

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- The **sole purpose** of an undulator is to induce transverse velocity components in the electron motion, so that the electrons can **couple** with a co-propagating radiation field.

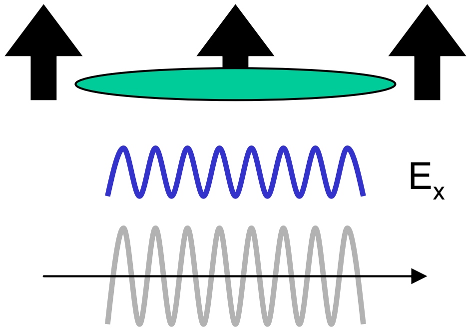
$$\frac{d}{dz}\gamma = \frac{e}{mc^2}\vec{E}\cdot\vec{\beta} = k\frac{K_r K}{\gamma}\sin(k_u z)\cos(kz - \omega t + \phi)$$

- For bunch length shorter than the undulator period the electron bunch oscillates collectively => sinusoidal change in energy with the periodicity of the radiation field.

Electron motion

x Radiation Field

= Energy Modulation



Step I (cont') - Resonance Condition

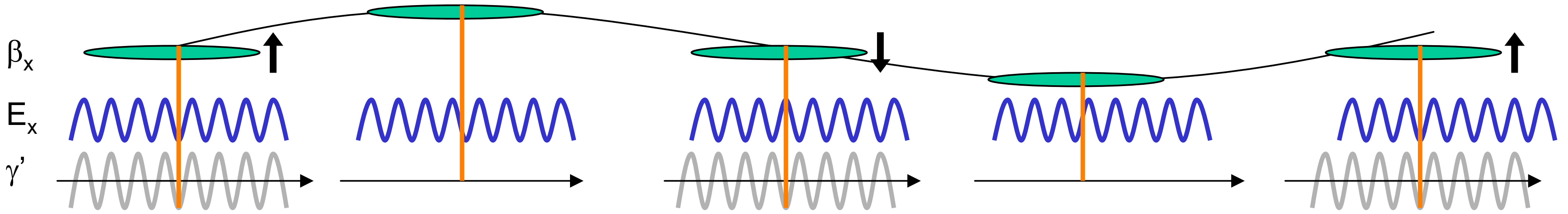
Because the radiation field propagates faster than electron beam the energy change is not constant along the undulator. However for a certain longitudinal velocity a net gain energy change can be accumulated.

$$\gamma' \propto 2\sin(k_u z)\cos(kz-\omega t) = \sin((k+k_u)z-\omega t) + \sin((k-k_u)z-\omega t)$$

Phase is constant for $\beta_z = k/(k+k_u)$

At resonance, the sine function oscillates as $\sin(2k_u z)$.

For a given wavelength there is a beam energy where the energy change is resonant.



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Step I (cont') - Resonance Condition

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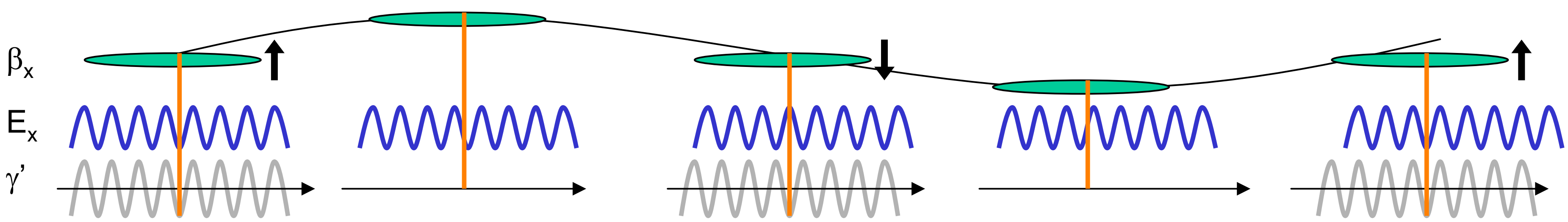


Step II - Longitudinal Motion + SwissFEL

It is convenient to express the longitudinal position in terms of the interaction phase with the radiation field ("ponderomotive phase")

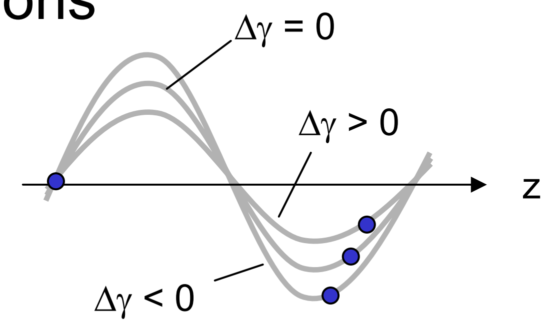
$$\theta = (k + k_u)c(\beta_z - \beta_{z,r})t + \theta_0 + \phi \rightarrow \text{Radiation Phase}$$

$(\beta_z - \beta_{z,r})$ ↓ Velocity Deviation θ_0 ↓ Injection Phase

At resonance the ponderomotive phase is constant. Deviation in the resonant energy $\Delta\gamma=\gamma-\gamma_r$ causes the electron to slip in phase. The effect is identical to the dispersion in a bunch compressor.

=> density modulations

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



The FEL Instability

Induced energy modulation → Increasing density modulation

Run-away process (collective instability)

Enhanced emission

The FEL process saturates when maximum density modulation (bunching) is achieved. All electrons would have the same interaction phase θ.

The FEL Instability (cont')

- The FEL process can be start when at least one of the following initial conditions is present:
  - Radiation field (FEL amplifier)
  - Density modulation (Self-amplified spontaneous emission FEL - SASE FEL)
  - Energy modulation

- Due to the finite number of electrons and their discreet nature an intrinsic fluctuation in the density is always present and can drive a SASE FEL

- To operate as an FEL amplifier the seeding power level must be higher than the equivalent power level from the SASE start-up (shot noise power).

The Generic Amplification Process

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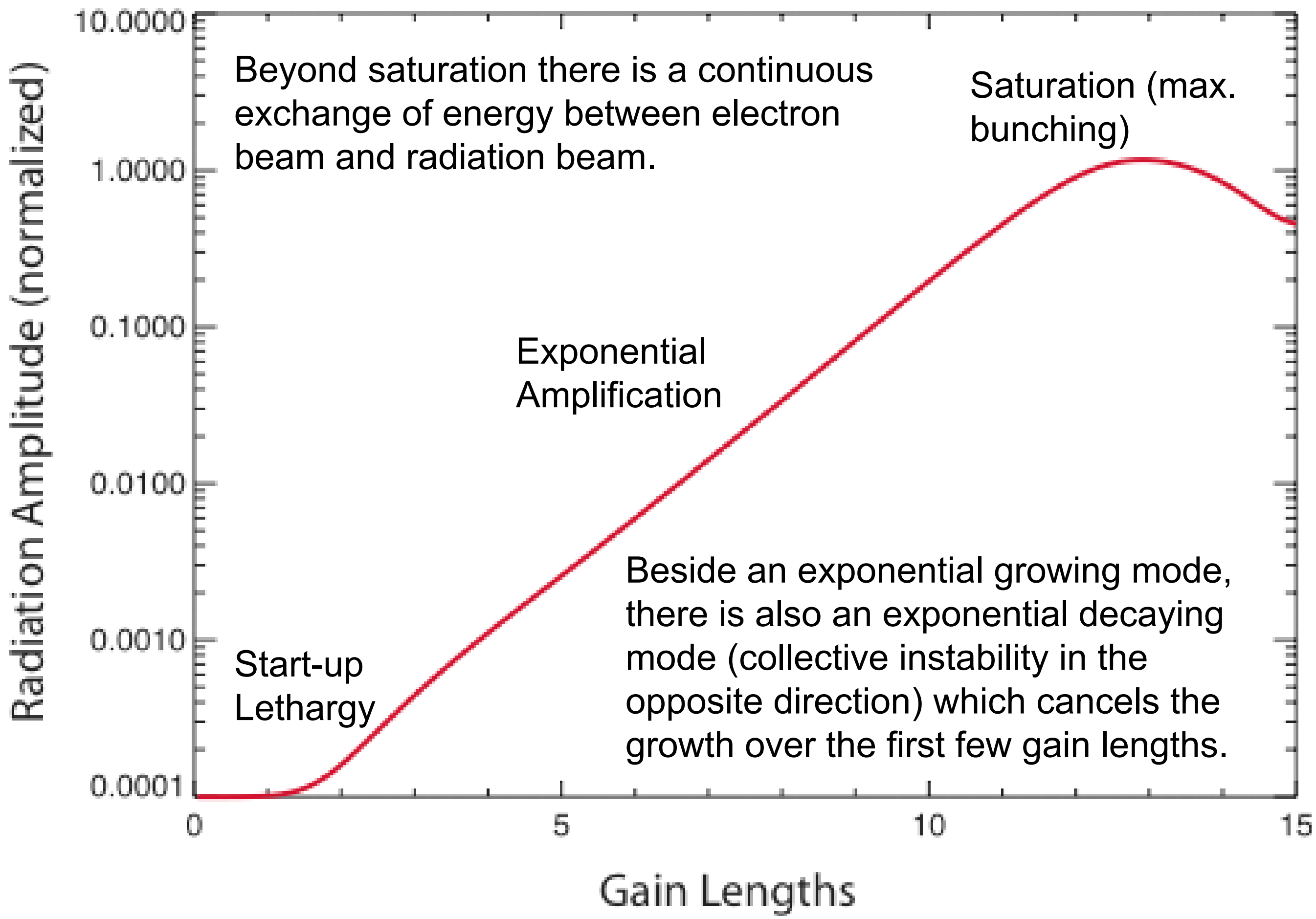

3D Effects – Transverse Coherence

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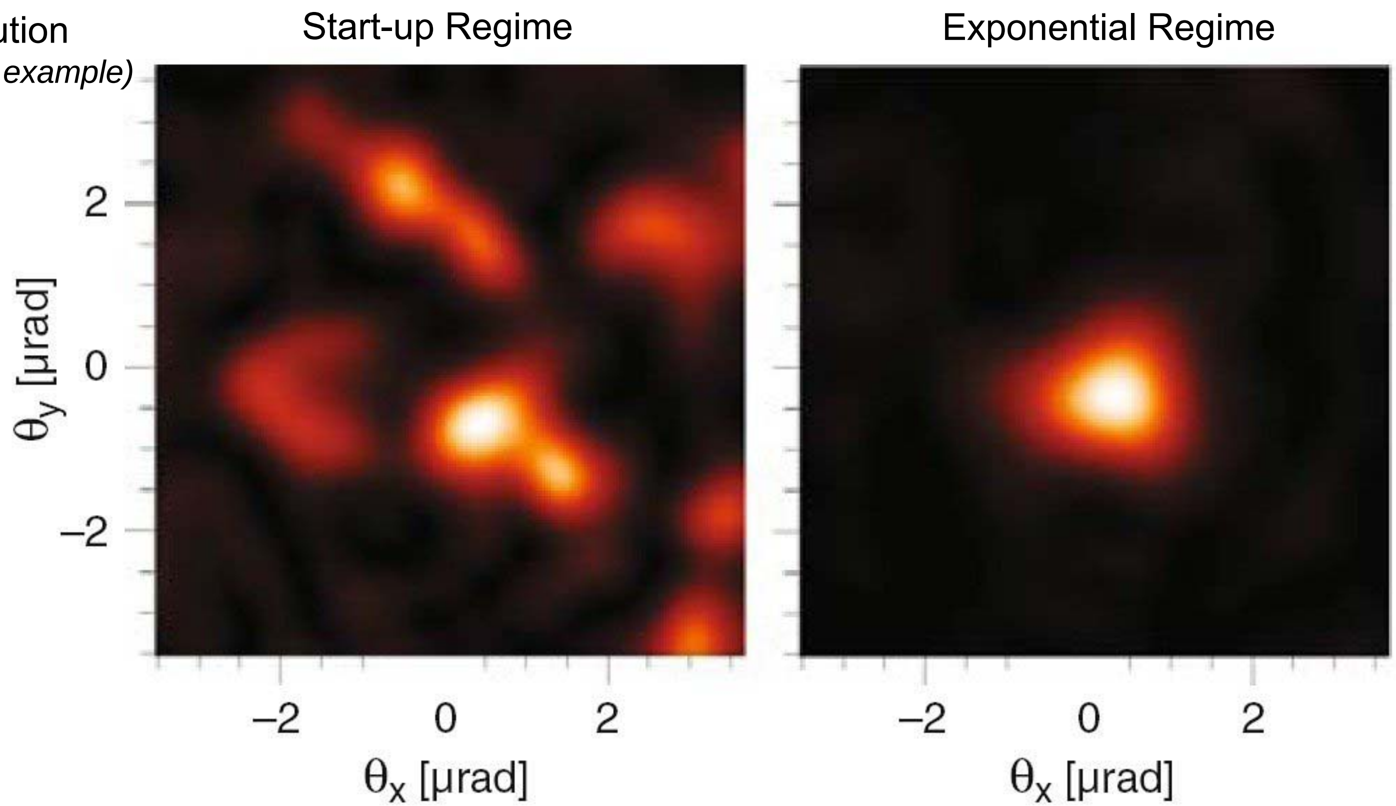
- In SASE FELs, the emission depends on the fluctuation in the electron distribution. In the start-up it couples to many modes.
- During amplification one mode starts to dominate, introducing transverse coherence (through gain guiding).

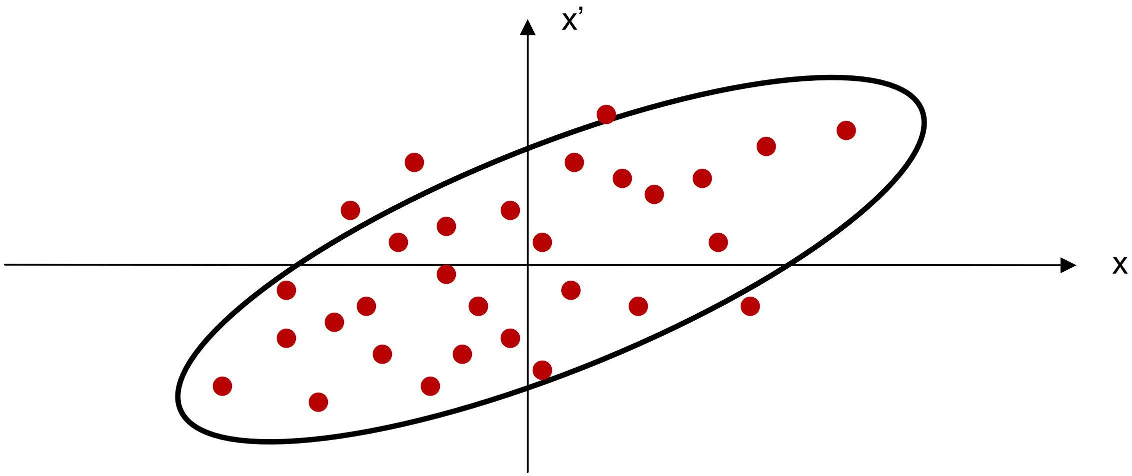
Far Field Distribution
(generic X-ray FEL example)



3D Effects – Emittance I

- 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.

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



Transverse + Spectral Coherence in SASE FELs

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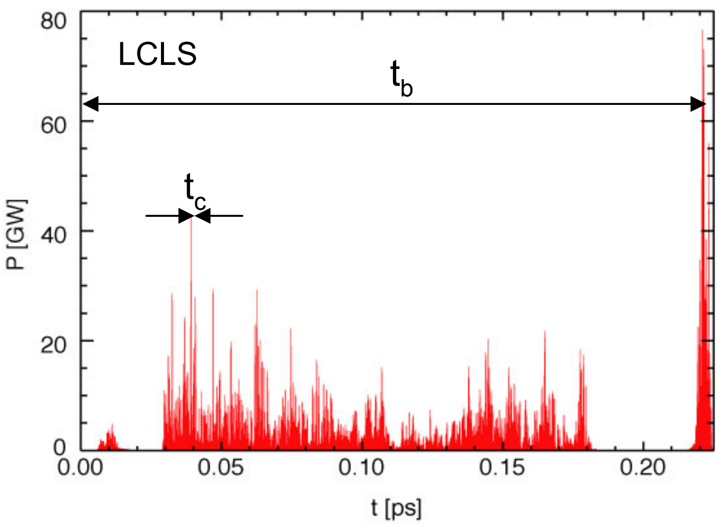
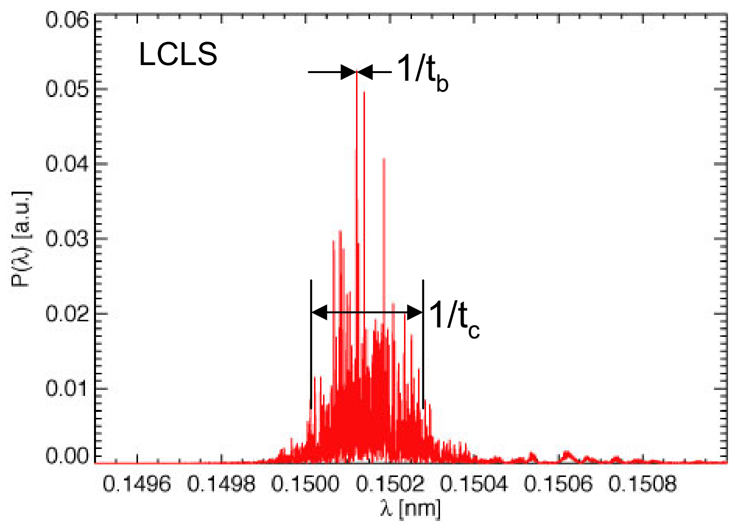
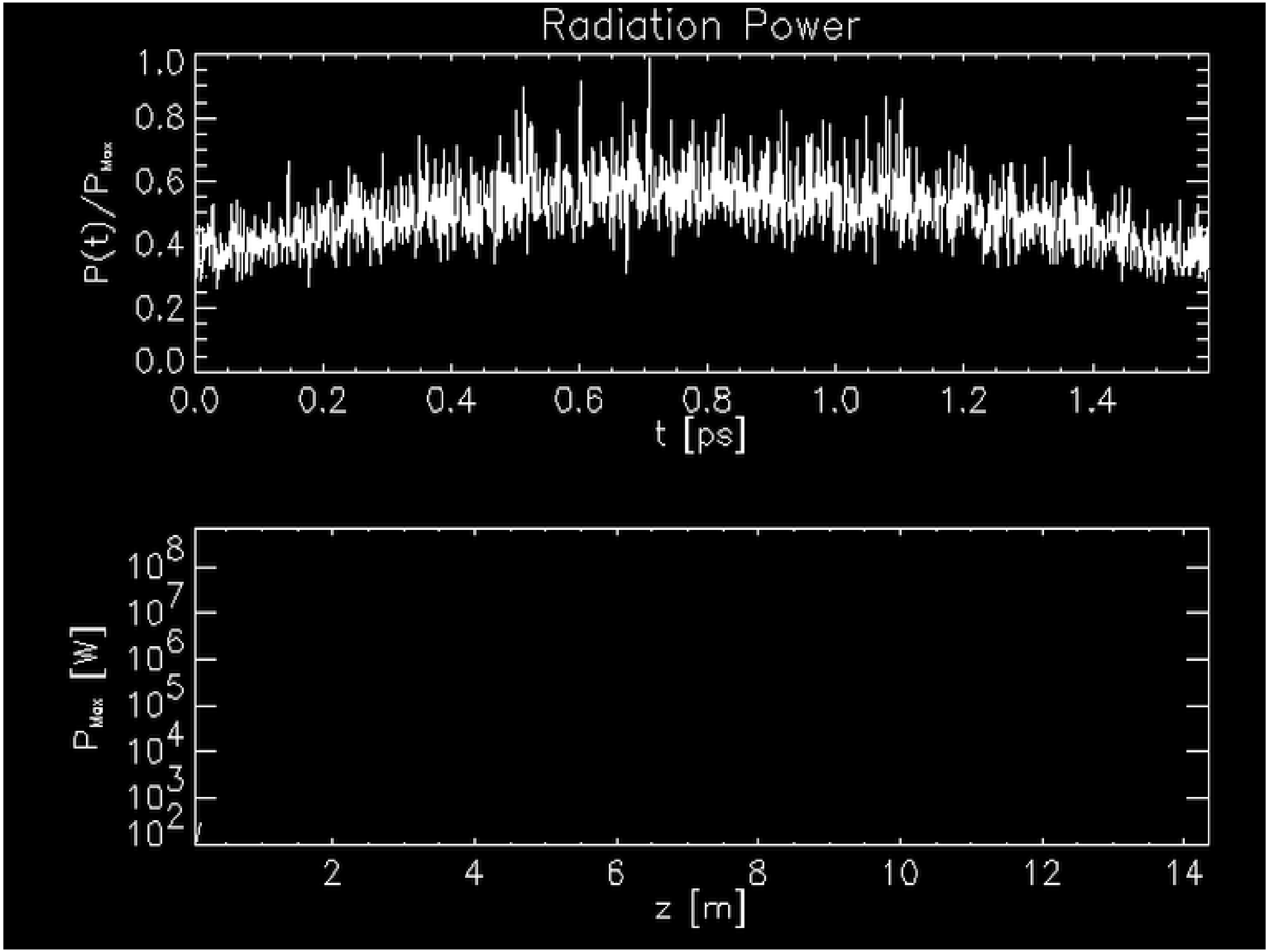
- The radiation advances one radiation wavelength per undulator period. The total slippage length is $N_u \cdot \lambda$
- SASE FELs have limited longitudinal coherence t_c when the pulse length is longer than the slippage length.
- The spectral width narrows during the amplification because the longitudinal coherence grows. The minimum value is $\Delta\omega/\omega=2\rho$.
- FEL process averages the electron beam parameters over t_c. Areas further apart are amplified independently.

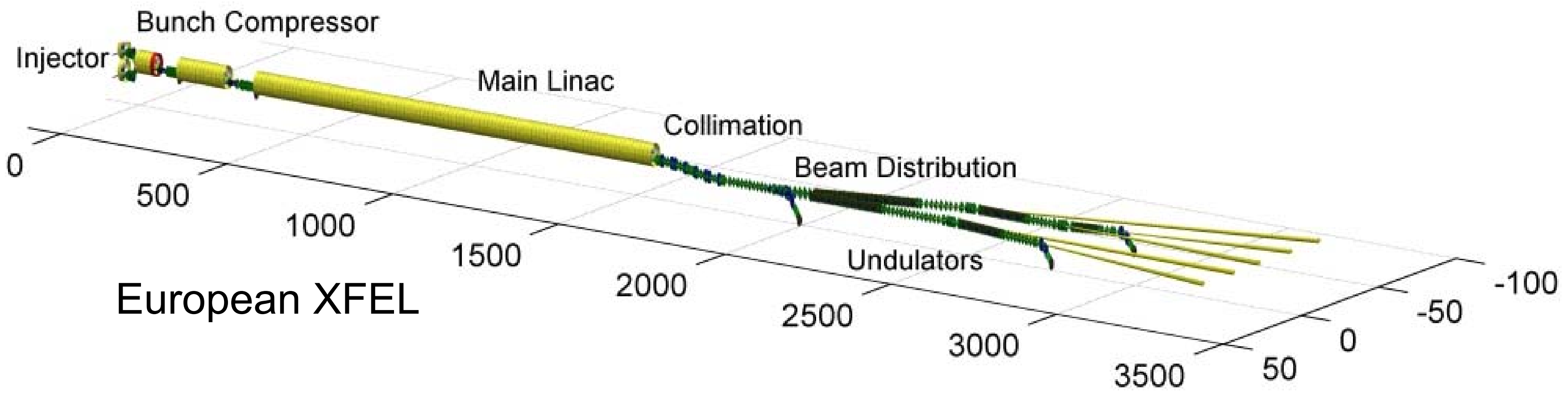




Time-Dependent Effects - SASE

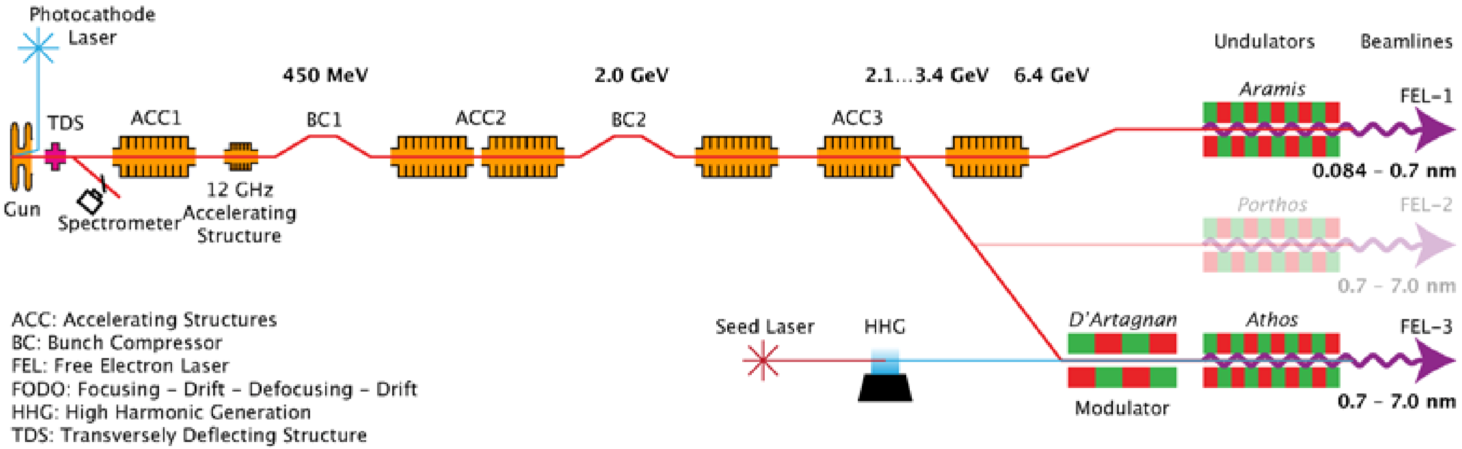


FEL Accelerators

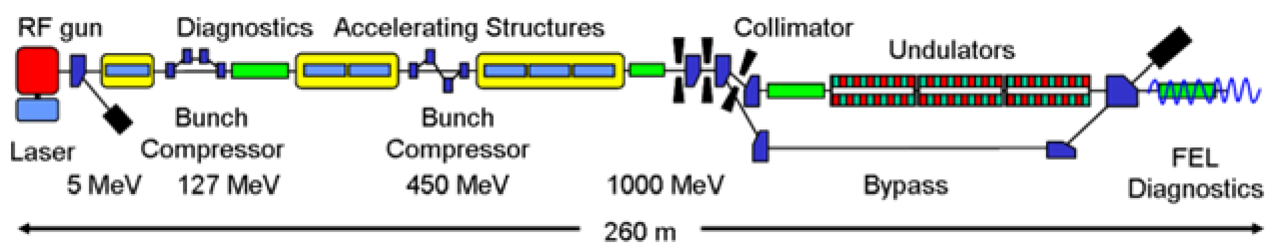


European XFEL

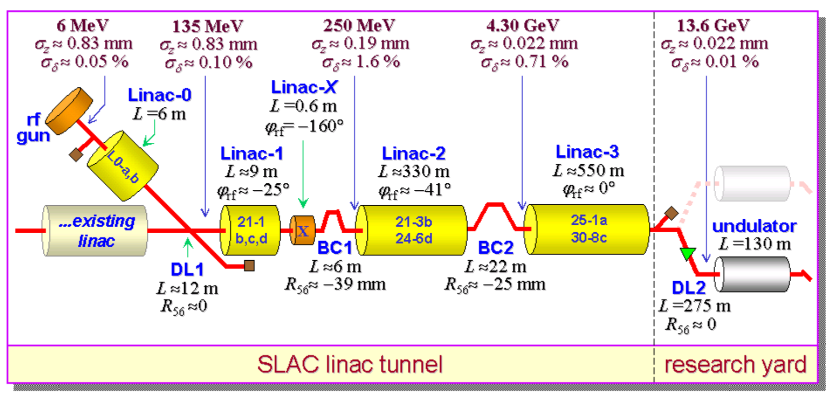
- SwissFEL



- FLASH

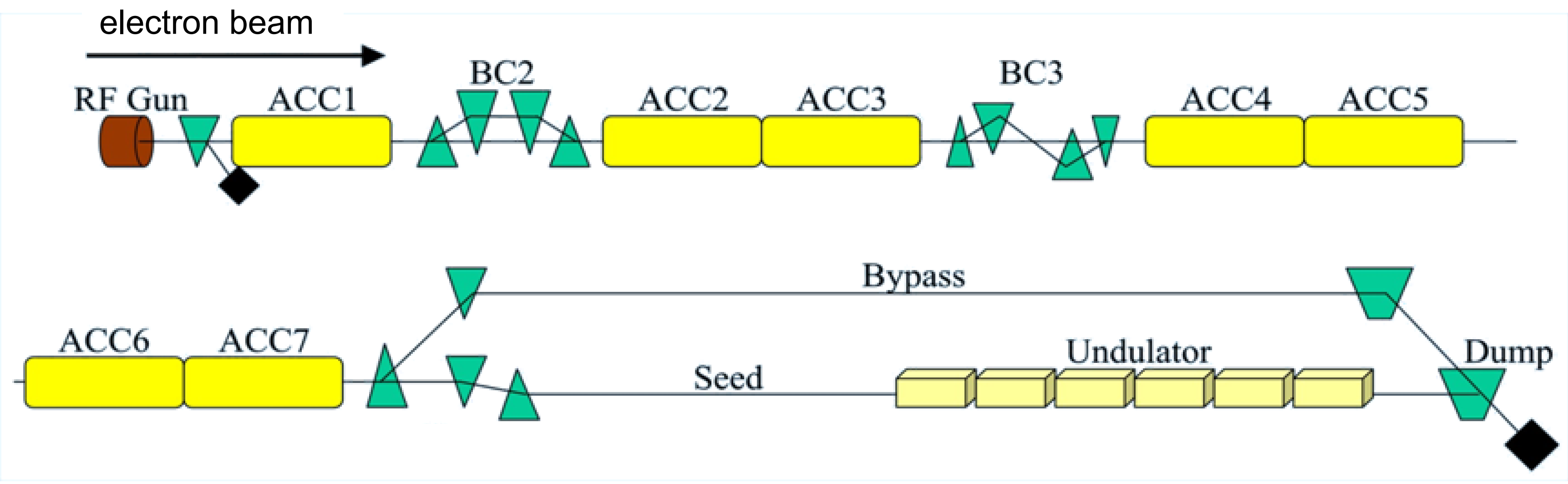


- LCLS

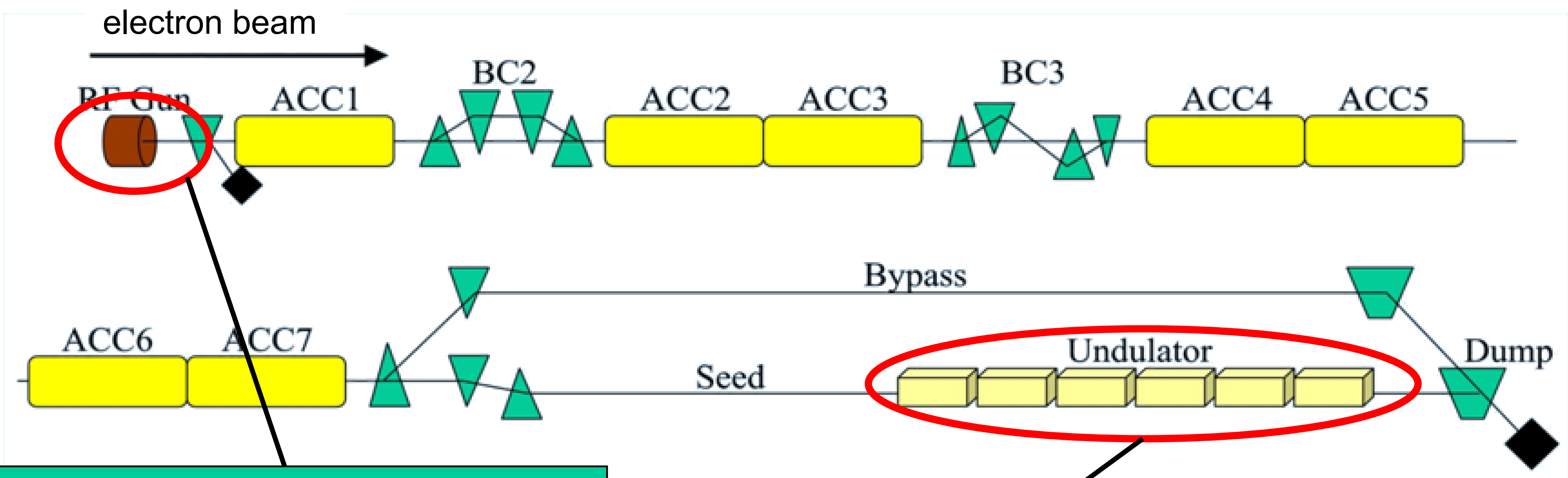


FLASH

+ SwissFEL



FLASH



Electron beam parameters at the RF Gun:

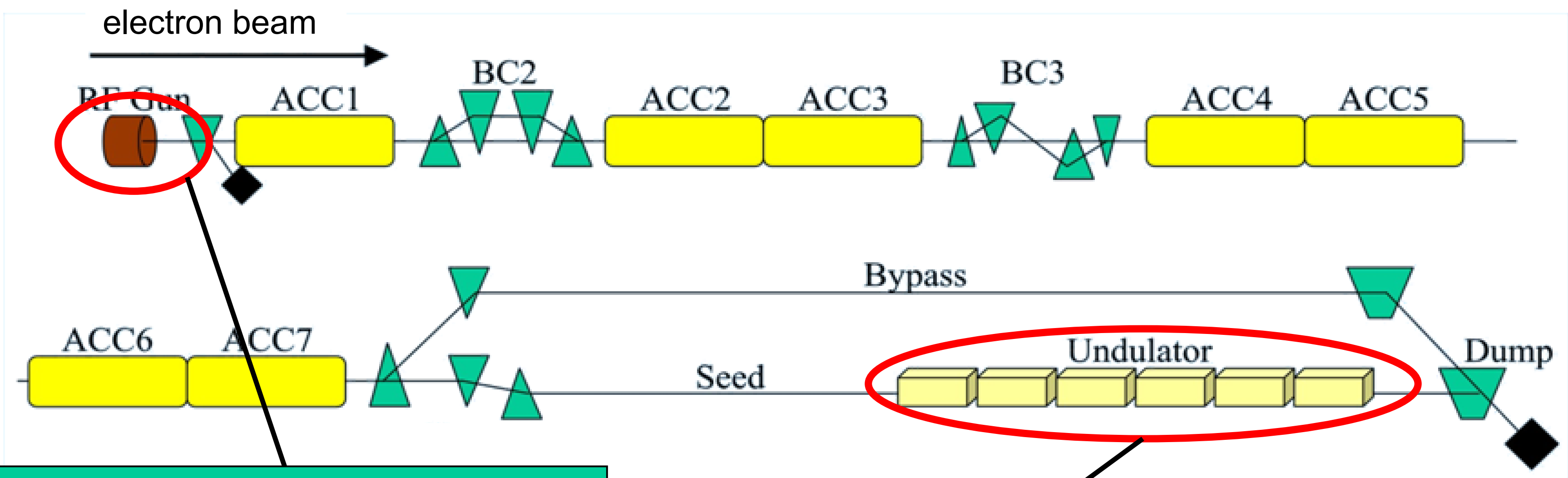
- Charge Q=1nC
- Bunchlength σ_s=2mm
- Current I=62.5A
- Emittance e=1mm mrad
- Energy spread σ_E=30keV

Electron beam parameters at the Undulator for λ_L=6nm:

- Energy E_0=1GeV
- Energy spread σ_E<3MeV
- Emittance ε<2mm mrad
- Current I=2500A

FLASH

+ SwissFEL



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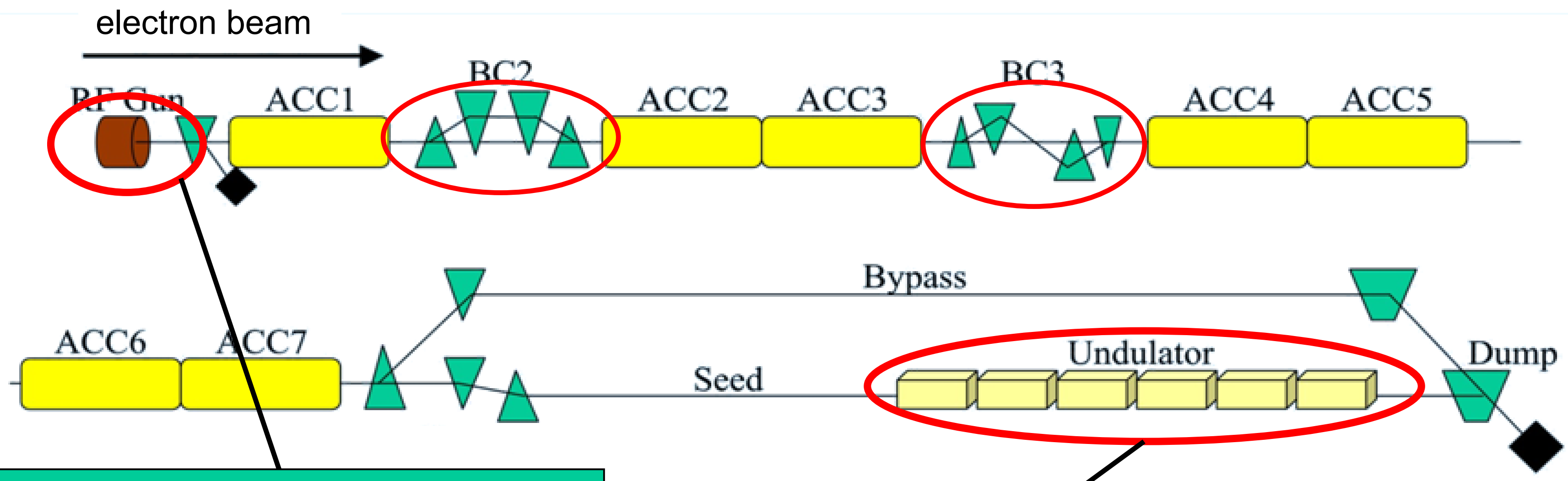
longitudinal compression of the electron beam is required!

FLASH

+ SwissFEL



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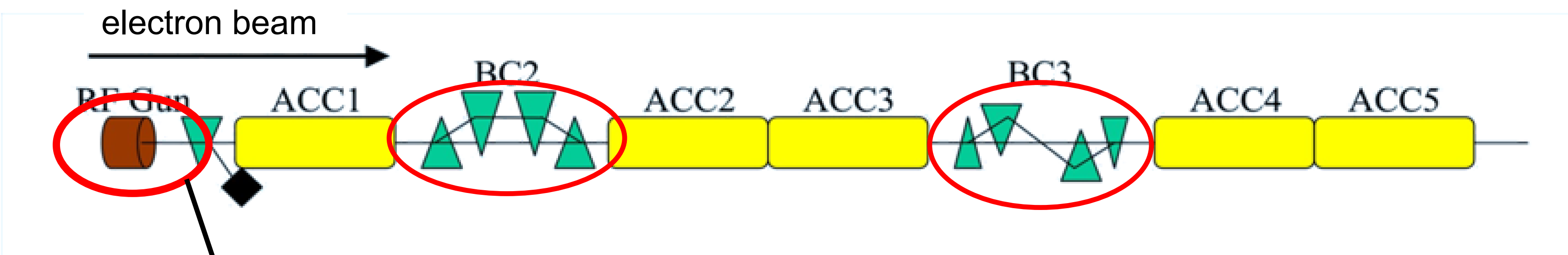

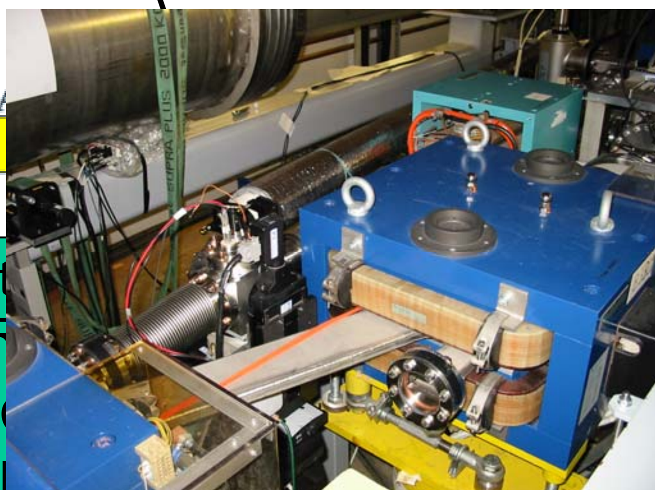

Elect
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Current I=62.5A

Emittance e=1mm mrad

Energy spread σ_E=30keV

the

Energy spread σ_E<3MeV

Emittance ε<2mm mrad

Current I=2500A

longitudinal compression of the electron beam is required!

RF Gun

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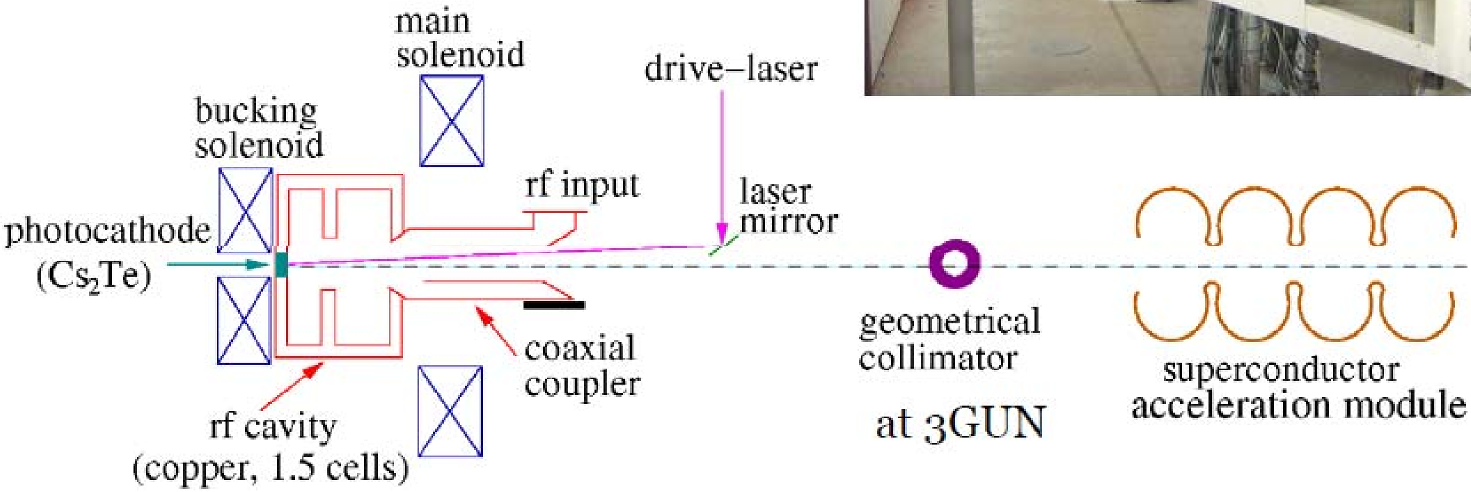
1.3 GHz RF Cu cavity gun
Pulsed, 5 or 10 Hz
RF pulse length up to 900 µs

RF power 3.2 MW
(42 MV/m max field at cathode)

Dark current ~0.1 mA

Dark current collimator at 3GUN



J.H. Han

Bunch Compression

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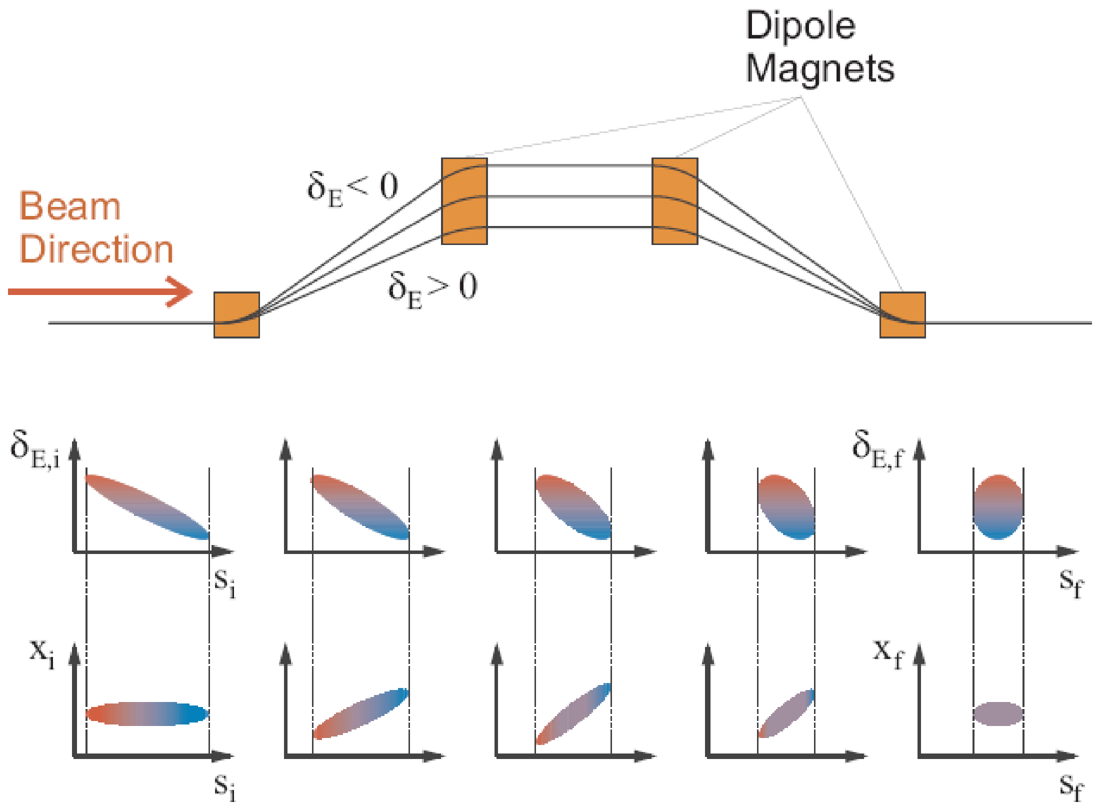
Head particles have a lower energy…

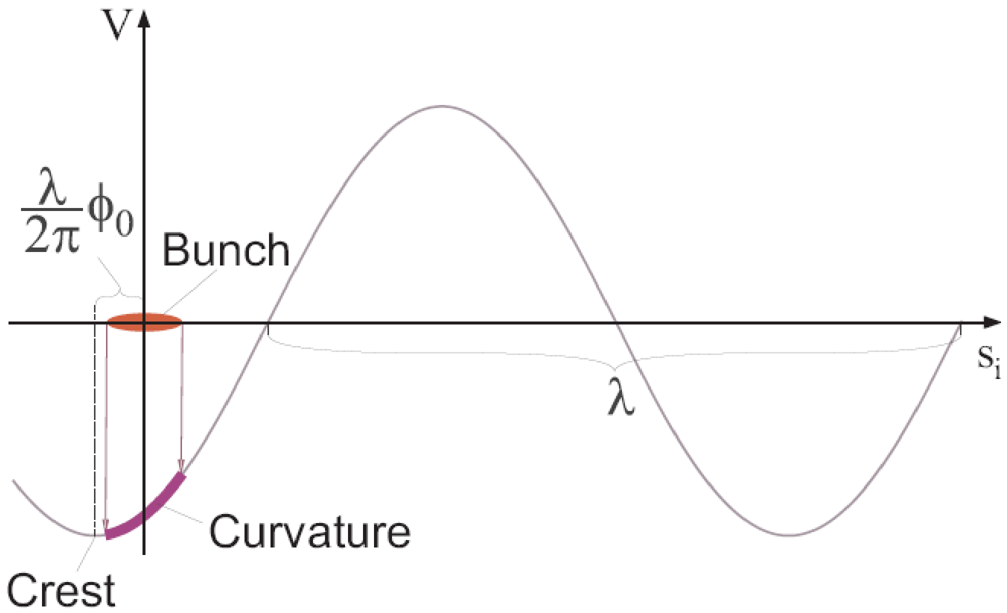
…than the tail particles.



The tail electrons move on a shorter path which allows them to overtake the leading electrons.

RF-Acceleration

Accelerating field in a RF-cavity: $E(s) = eV \cos\left(\phi + \frac{2\pi}{\lambda}s\right)$



Correlated energy offset along the bunch:

$$
\begin{aligned}
\delta_{\mathrm{RF}}(s) &= \frac{\Delta E}{E} = \frac{E(s) - E(0)}{E} \\
&= -\frac{2\pi eV}{E\lambda}\sin\phi s - \frac{2\pi^2 eV}{E\lambda^2}\cos\phi s^2 \\
&\approx As + Bs^2
\end{aligned}
$$

Bunch Compression

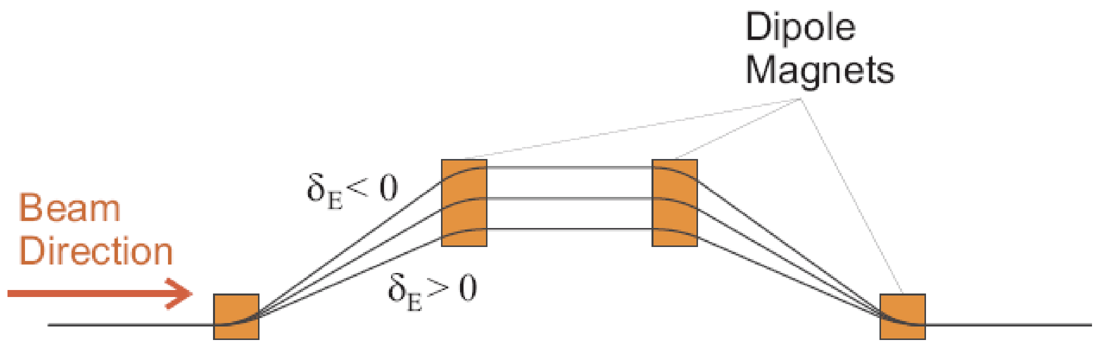
For a particle with an relative energy offset

$$\delta = \frac{\Delta E}{E_0} = \frac{E - E_0}{E_0}$$

the path length difference to a particle with design energy E_0 is given as a power series:

$$\Delta s = R_{56} \cdot \delta + T_{566} \cdot \delta^2 + U_{5666} \cdot \delta^3 + \cdots$$

R_{56}, T_{566},… are called the *longitudinal dispersion*.



Bunch Compression

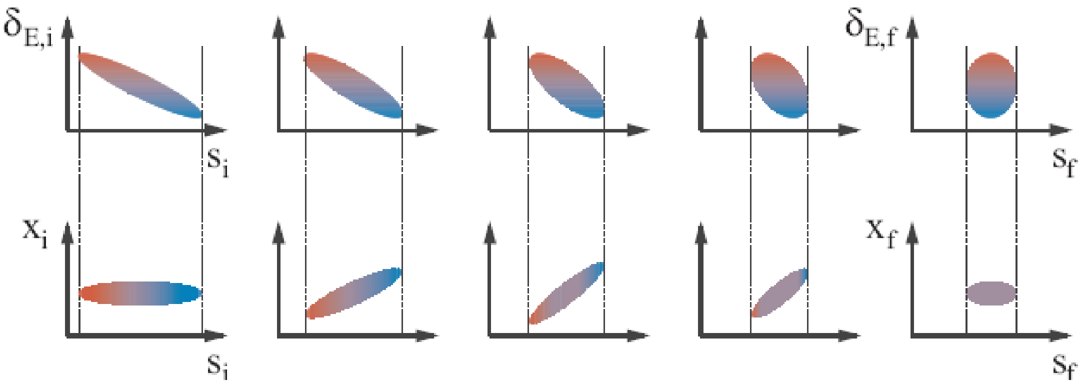
To first order the final RMS bunch length is given by:

$$\sigma_{s_f} = \sqrt{\left(1 - \frac{2\pi eV}{E\lambda}\sin\varphi R_{56}\right)^2 \sigma_{s_i}^2 + R_{56}^2 \sigma_{\delta_i}^2}$$

By minimizing the first term one gets the minimal bunch length, which is given by:

$$\breve{\sigma}_{s_f} \approx |R_{56}|\sigma_{\delta_i}$$

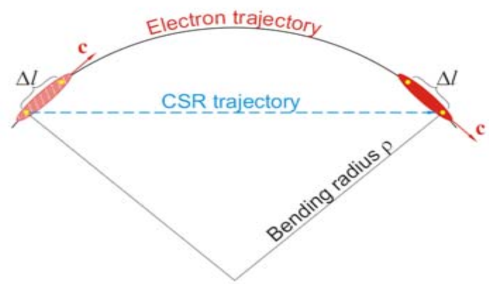
The minimal bunch length is therefore determined by the uncorrelated RMS energy spread of the bunch.

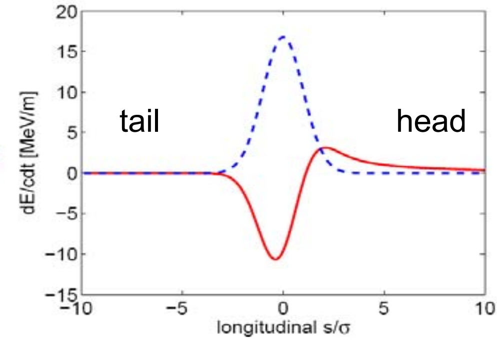


Self Interactions

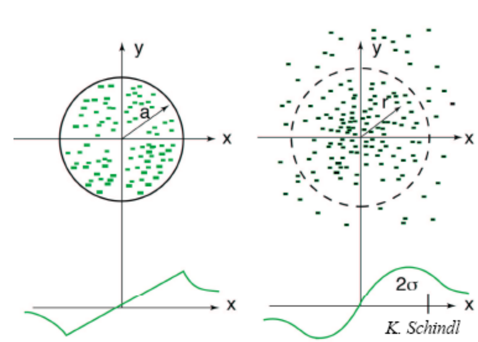
High charge densities give rise to strong electro-magnetic fields generated by the electron bunches. Electrons within the bunch experience these fields.

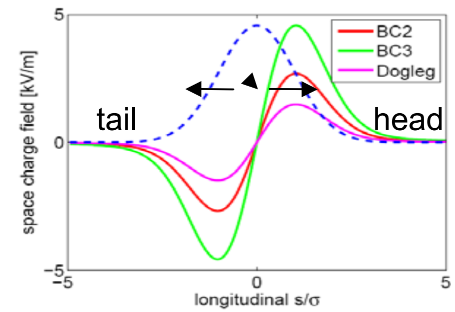
- Coherent Synchrotron Radiation



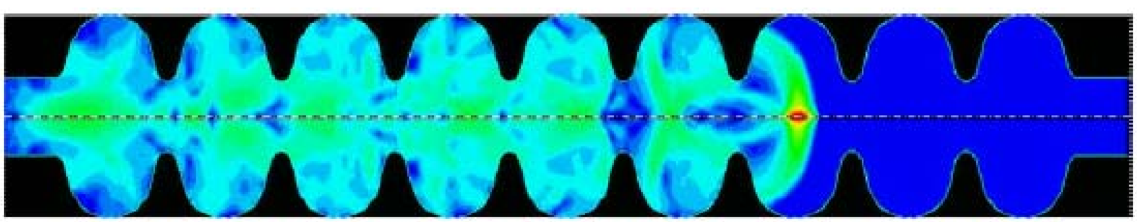


- Space Charge fields

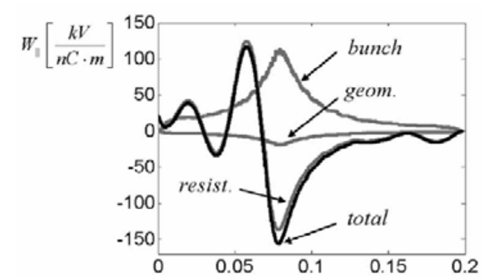




- Wake fields

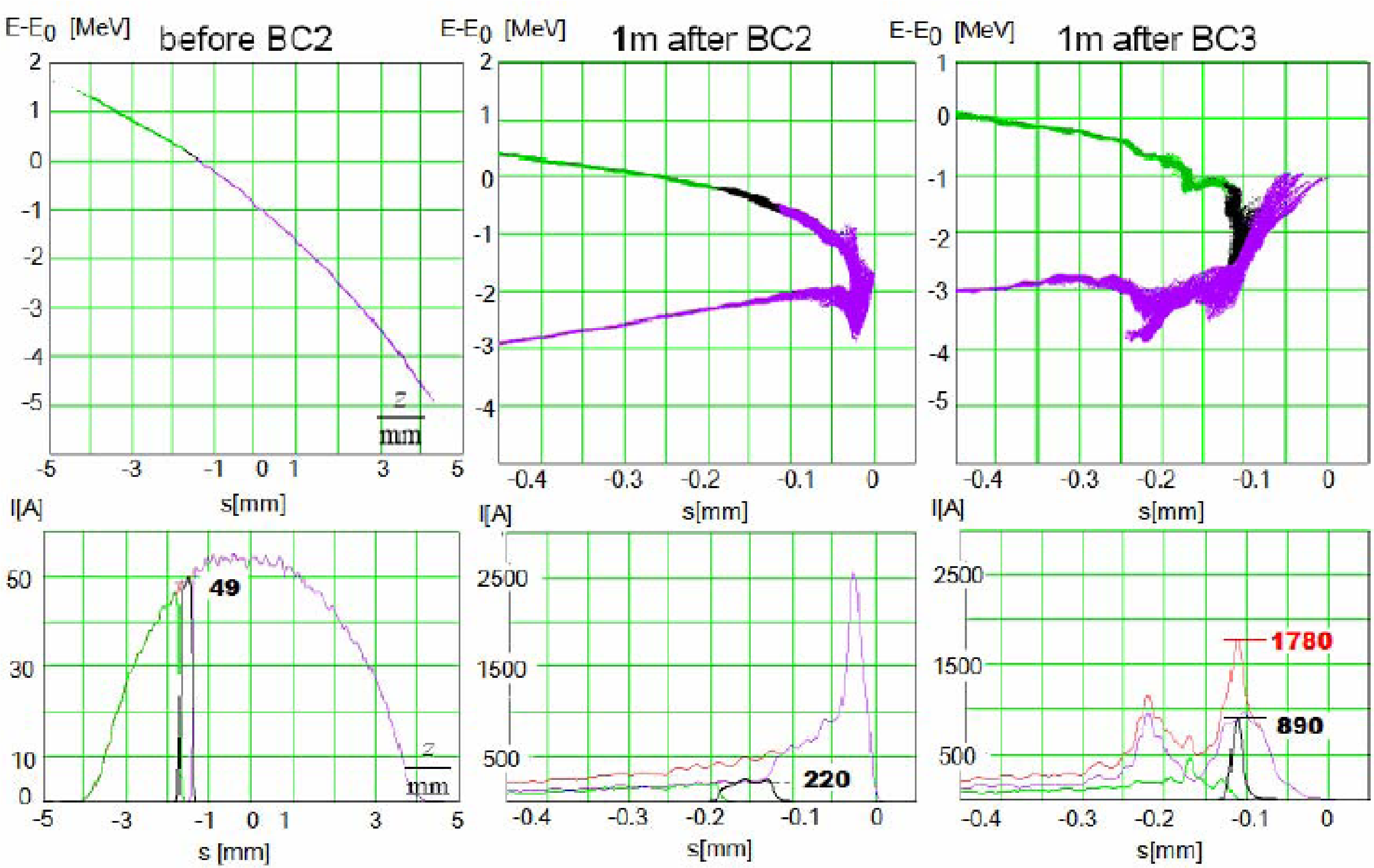


M. Dohlus



I.A. Zagorodnov

Beam Dynamics



M. Dohlus

SASE at FLASH

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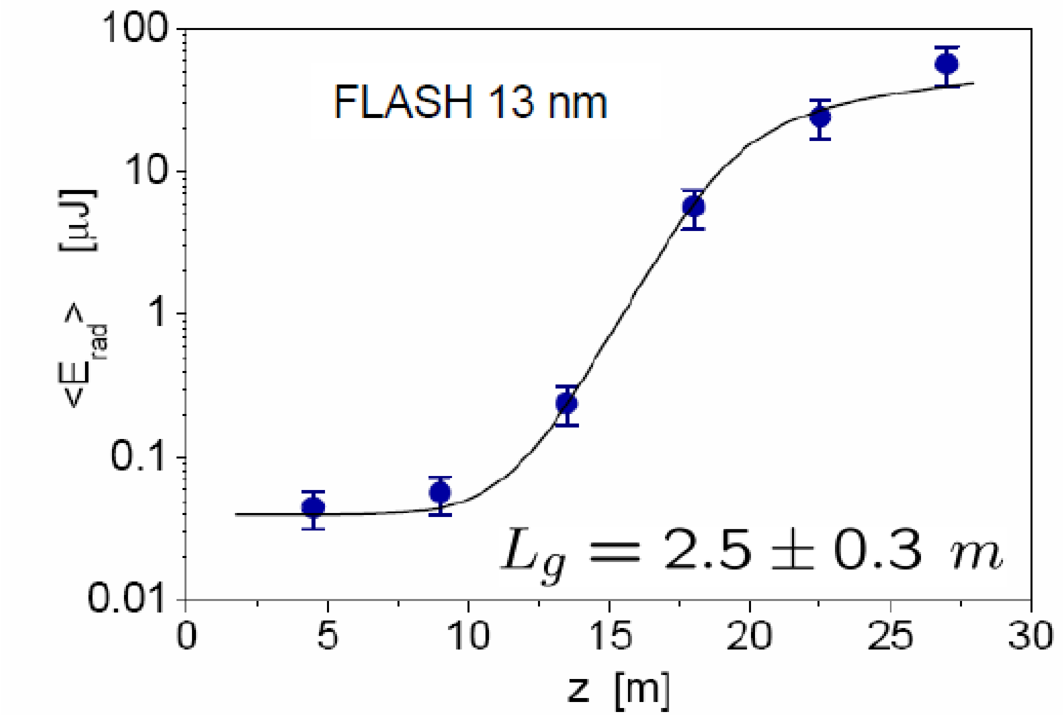

SASE at FLASH:	Wavelength	47 – 6 nm
	Energy per pulse (peak/average)	70µJ / 40µJ (at 13.7 nm)
	Photon pulse duration	10 fs
	Power (peak/average)	10 GW / 20 mW