Photon production

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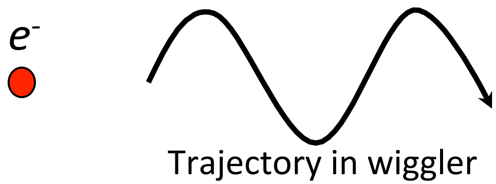
Outline

1. X-ray production.
2. Light parameters from beam and undulator parameters.
3. Performance and tolerance studies.
4. Advanced FEL options.
5. Comments.

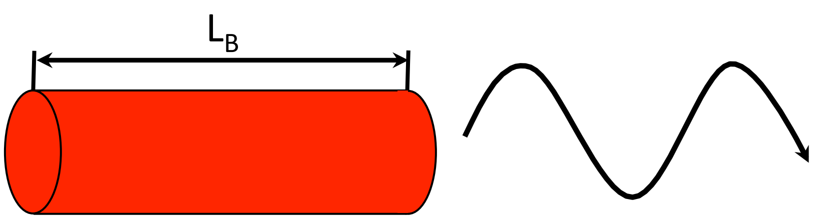
1. X-ray production

X-ray radiation of a beam in a wiggler

1. Single electron:



2. Homogenous charge cylinder:



- Lamor's formula in electron's rest frame

$$P_T = \frac{e^2}{6\pi\epsilon_0 c^3}\left(\frac{d\vec{v}}{dt}\right)^2$$

- Lorentz transform to get *v* in wiggler

$$P_T = \frac{e^2 c\gamma^2 K^2 k_u^2}{12\pi\epsilon_0}$$

- Radiation in the x-ray regime ($L_B >> \lambda_X$)

$$P_X \approx 0$$

- EM waves of the individual electrons average out.

3. Realistic beam with Shot noise:

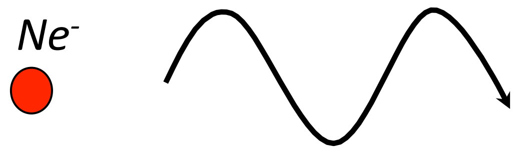
- Radiation with ($L_B >> \lambda_X$) exist.
- It is due to natural charge density variations (Shot noise).

$$P_X \propto N$$

- Incoherent synchrotron radiation, but only due to coherent fluctuations.

X-ray radiation in an FEL

1. Dipole radiation of moving charge



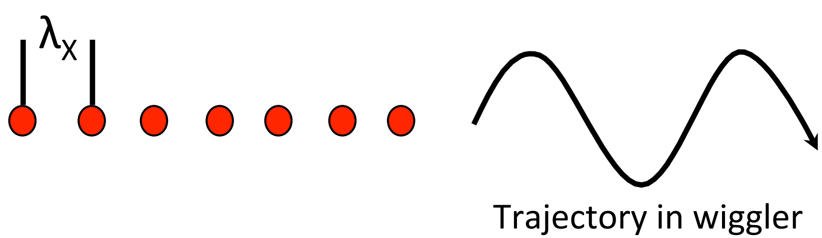
- Power radiated over all frequencies

$$P_T = N^2 \frac{e^2 c \gamma^2 K^2 k_u^2}{12\pi\epsilon_0}.$$

- Coherent synchrotron radiation
- Power radiated at main mode λ_X

$$P_X = N^2 \frac{e^2 c \gamma^2 K^2 k_u^2}{12\pi\epsilon_0 (1+K^2/2)^2}.$$

2. Charge distribution in an FEL



- Slightly different setup in a FEL, since single very short bunch cannot be created.

Comparison model and SwissFEL:

$P_{beam,peak}$ = 16000 GW

$P_{T,dipole}$ = 544 GW

P_X = 184 GW

P_{CDR} = 3 GW

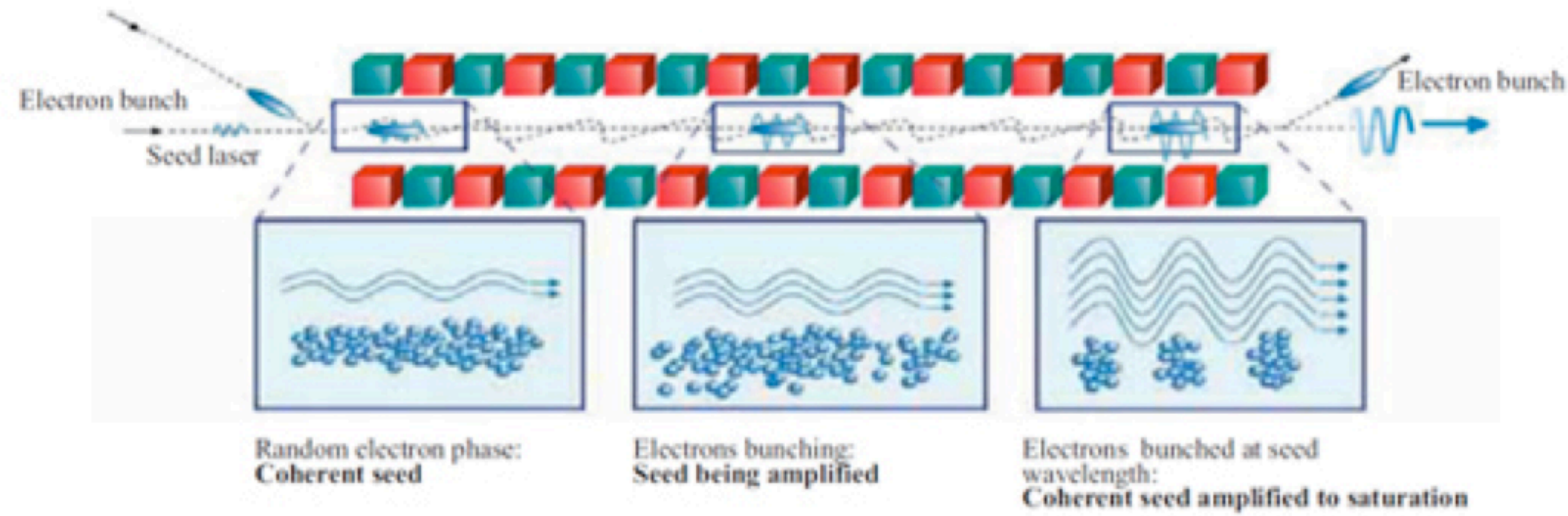
x 30

x 3

x 60

x 5500

Micro-bunching instability



Source: ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)

- Coherent light (from seeding or ISR) travels with the e^- beam in undulator.
- Energy is transferred between light and e^- beam and creates an periodic energy modulation of e^- beam.
- Due to dispersion in undulator, energy modulation is converted to charge modulation with period of light wavelength.
- Coherent radiation from e- beam.

2. Light parameters from beam and undulator parameters

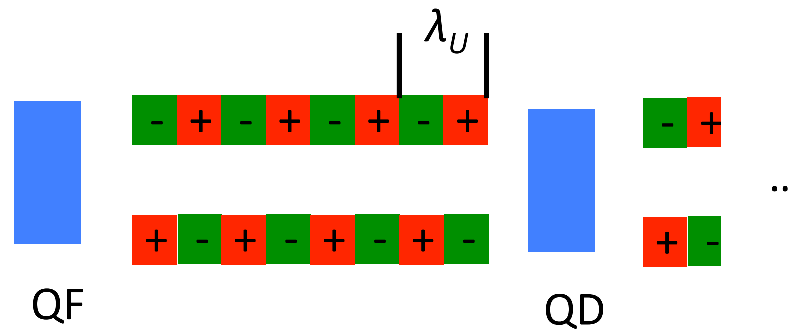
Bunch and undulator parameter

Electron beam:

Usually modeled as cylindrical and round.

ε … emittance ($\varepsilon_x = \varepsilon_y$)
E … beam energy
σ_z … bunch length (one or two sigma)
N … bunch charge
σ_η … energy spread

Undulator:



If very small beta functions are needed, focusing magnets are integrated in undulator modules.

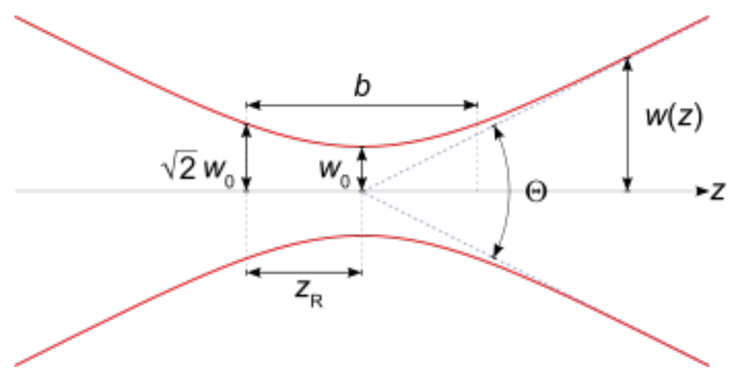
λ_u … Undulator period
K … Undulator strength
$K = 0.934\, B_0\,[\mathrm{T}]\, \lambda_u\,[\mathrm{cm}]$
β … Beta function through undulator
L_{sat} … Saturation length

X-ray laser parameter

- λ_l ... light wave length
- $\Sigma_x, \Sigma_{\vartheta x}$ ... beam size and angular divergence

  For transversally fully coherent X-ray beams they can be described as Gaussian beams (diffraction limited). In this case X-ray beams behave very similar as e^- beams ("X-ray emittance").

$$\Sigma_x \Sigma_{\theta_x} = \Sigma_y \Sigma_{\theta_y} = \frac{\lambda_l}{4\pi}$$



- P_l ... X-ray beam power
- Φ ... Flux (Number of Photons per time in given energy range)

$$\Phi = \frac{P_l}{h f_l}$$

- B_{peak} ... Brightness (Flux per emittance)

$$B = \frac{\Phi}{4\pi \Sigma_x \Sigma_{\theta_x} \Sigma_y \Sigma_{\theta_y}} = \frac{4\Phi}{\lambda_l^2} \qquad \left[\frac{\text{photons}}{\text{s mrad}^2 \text{ mm}^2 \text{ } 0.1\% \text{ BW}}\right]$$

Limits on e⁻-beam parameters

Bunch lengths:

- e⁻-beam velocity is nearly the same as the X-ray light group velocity.
- Bunch lengths are newly equal.

$$\sigma_{z,l} \approx \sigma_{z,e^-}$$

- Only for sub-fs beams, velocity difference starts to play a role.

Beams overlap:

- To get a good overlap of e⁻ and light beam, their emittances should be similar

$$\epsilon < \epsilon_l = \frac{\lambda_l}{4\pi}$$

- This is a very hard limit on ε of e⁻ beam.
- But also higher values work (factor 2 - 3), but increase saturation length L_{SAT}.

Parasitic motion in undulator:

- For micro-bunching instability perfect sinus motion in the undulators is assumed.
- Motion due to σ_η (dispersion) and ε (betatron oscillations) reduce FEL efficiency.
- Limits on max values of σ_η and ε have been derived.

e⁻-beam charge:

- As high as possible to max. P_l and minimize L_{SAT}.
- But for lower e⁻ energies, space charge effects can be a problem.
- Also β can be increased.

Wave length and power

X-ray wave length:

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

Radiation power:

$$P_l \approx \rho_{FEL} P_{e^-} \propto (\lambda_u K)^{2/3}$$

Undulator length

$$L_{SAT} \approx \frac{20}{4\pi\sqrt{3}} \frac{\lambda_U}{\rho_{FEL}} \propto \frac{\lambda_u^{1/3}}{K^{2/3}}$$

- For fixed λ_l there are two options:
  1. γ λ_u K high -> P_l and cost high
  2. γ λ_u K low -> P_l and cost low

- To achieve low cost, it is likely to go to low energies.
- Then combination of λ_u and K is fixed, but one degree of freedom
- Undulator is shorter if λ_u is small and K large.

3. Performance and Tolerance studies

Tool for parameter scans

- Ideally, also the cost for the necessary undulator with focusing magnets could be added. This could be added to the cost of the linac to perform a cost minimisation cost(λ_l, P_l). As an input cost(λ_u, K) would be necessary.
- Design formulas often do fit only up to a factor 5. Especially L_{sat} and P_l are varying.

X-ray parameter for hard XFEL

e^- beam parameter
(from A. Latina)

E = 6 GeV
σ_z = 50 fs (15 μm)
N = 200pC
ε = 0.5 μm
σ_η = 0.6×10^{-4}

Undulator parameter
(very close to
SwissFEL Aramis)

λ_u = 15 mm
K = 1.3
β = 15 m

Laser beam parameter

λ_l = 0.1 nm
P_l = 3.5 GW
Φ = 1.7×10^{24} ph/s/0.1%
B_{peak} = 7×10^{32} ph/s/mm/mrad/0.1%
L_{sat} = 65m

Limits

ε < 0.1 um (laser)
ε < 0.23 um (undulator)
σ_η < 2.6×10^{-4}
K_p = 0.03 << 0.4
β_{opt} = 14.7 m

Assumptions for soft X-ray FEL

- Aim for wavelength of λ_l = 1nm.
- For minimal cost: save on e$^-$-beam energy as much as possible.
- Therefore, take e$^-$-beam directly after second bunch compressor with 2 GeV.

- The following limits scale favorable:

$$\epsilon_{N,max} \propto \frac{1}{\gamma}$$ Light

$$\epsilon_{N,max} \propto \frac{1}{\gamma^{1/3}}$$ Undulator motion

$$\sigma_{\eta,N,max} \propto \frac{1}{\gamma^{1/3}}$$

- Only the space charge limit scale unfavorable:

$$k_{p,N,max} \propto \gamma^{2/3}$$

X-ray parameter for soft XFEL

e^- beam parameter
(from A. Latina)

E = 2 GeV
σ_z = 50 fs (15 µm)
N = 200pC
ε = 0.5 µm
σ_η = 1.8×10^{-4}

Undulator parameter

λ_u = 15 mm
K = 1.45
β = 5 m

Laser beam parameter

λ_l = 1.0 nm
P_l = 8.9 GW
Φ = 4.5×10^{25} ph/s/0.1%
B_{peak} = 1.8×10^{32} ph/s/mm/mrad/0.1%
L_{sat} = 13 m

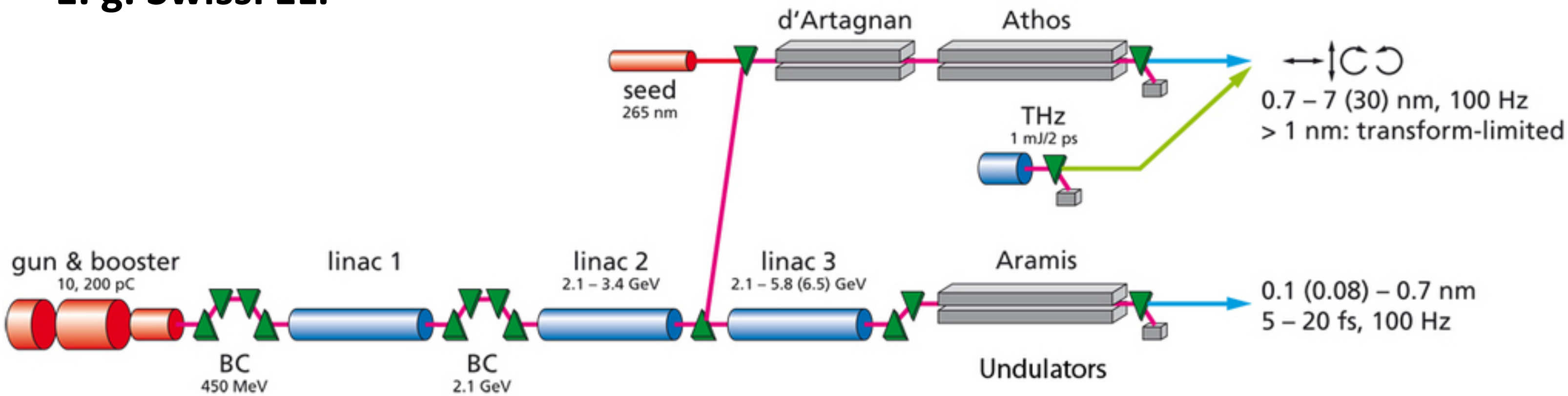
Limits

ε < 0.3 um (laser)
ε < 0.7 um (undulator)
σ_η < 8×10^{-4}
K_p = 0.18 << 1.3
β_{opt} = 1.4 m (to be confirmed)

4. Advanced FEL options

X-ray energy scans (not so advanced)

- Many experiments need to vary energy very precisely, e.g. tune to absorption edge.
- **E. g. SwissFEL:**



Hard X-rays (Aramis):
- Tuning from 0.1 nm to 0.7 nm.
- Energy change in Linac 2 and 3 from 2.1 to 5.8 GeV.

Soft X-rays (Arthos):
- Tuning from 0.7 nm to 7 nm.
- Energy change in Linac 4 from 2.6 to 3.4 GeV.
- Gap change from 6.5 to 24 mm

- The XbFEL will most likely also have tuning capabilities.
- Challenge for the linac design, since gradient change, changes also WF compensation.

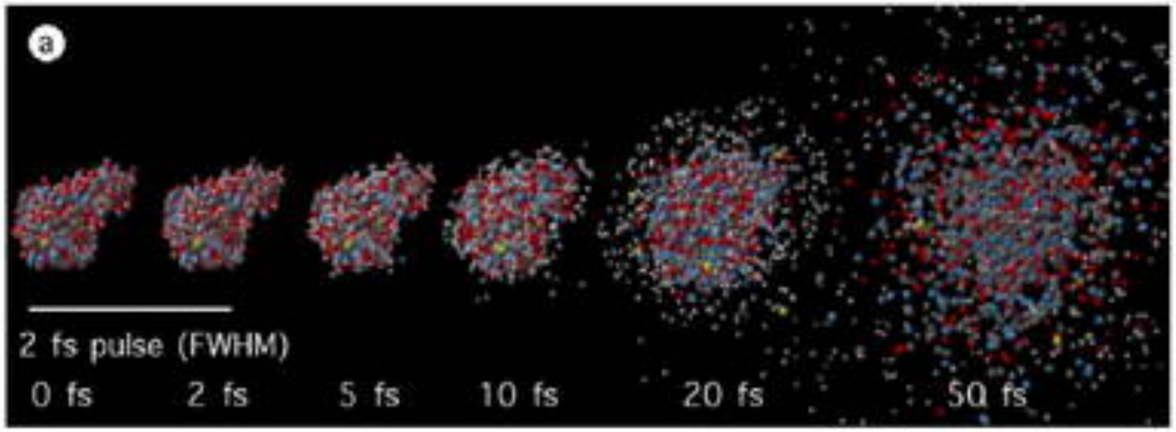
Short X-ray pulse mode

Coulomb explosion:

- Photon beam ionizes probe and hence destroys it completely.
- Time scale is about 20-50fs.
- Usual FEL pulses are 100-500fs.
- Picture is smeared out.

Short bunch mode:

- By reducing bunch charge *N* (20pC), bunches can be made shorter 1-2fs.
- Injector has to produce shorter bunches and small *N* helps with BC.
- But lower average brilliance.
- Dynamics of probes can be studied.
- In use at LCLS and planned for SwissFEL.



R. Neutze, et al, Nature 406, 752 (2000)

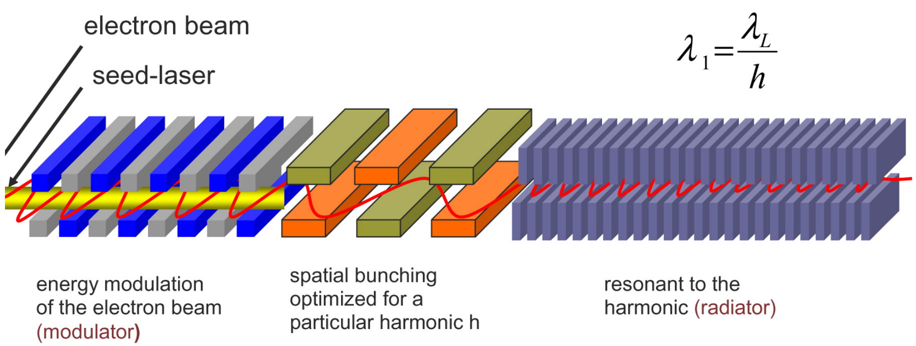
Seeding schemes

SASE FEL:

- FEL amplifies input light.
- Usually the input light is created by the beam itself due to random charge variations along the beam (SASE).
- Spectral purity is only 10^{-3}-10^{-4}.
- Some experiment need narrower band.

Seeded FEL:

- If FEL process is started from coherent light, the output light has a spectral purity of about 10^{-6} and high longitudinal coherence and stability.
- No laser available in X-ray regime
- Different schemes exist, but depend on the light wave length.
- Which wave length should be aim for?



Source: R. Follath, SPIE Newsroom 2007

HGHG seeding scheme

- Hard X-ray: self-seeding
- Soft X-ray: many options depending on wave length.

5. Comments

- Analytic design formulas are just a rough estimate and detailed simulations have to set up.
- Basic SASE design of undulator section seems to be manageable, due to the mature FEL theory and simulation codes.
- A cost model could be helpful to minimise the overall cost of linac and undulator.
- There are also many advanced options (short beam length and seeding schemes) that could be of interest. It has to be narrowed done, which options are of interest for the XbFEL collaboration and should be studied.
- For example, to study seeding schemes for the soft X-ray, the photon energy would have to fixed since it determines which seeding scheme could be used.

Many thanks for your attention!