Free-Electron Laser

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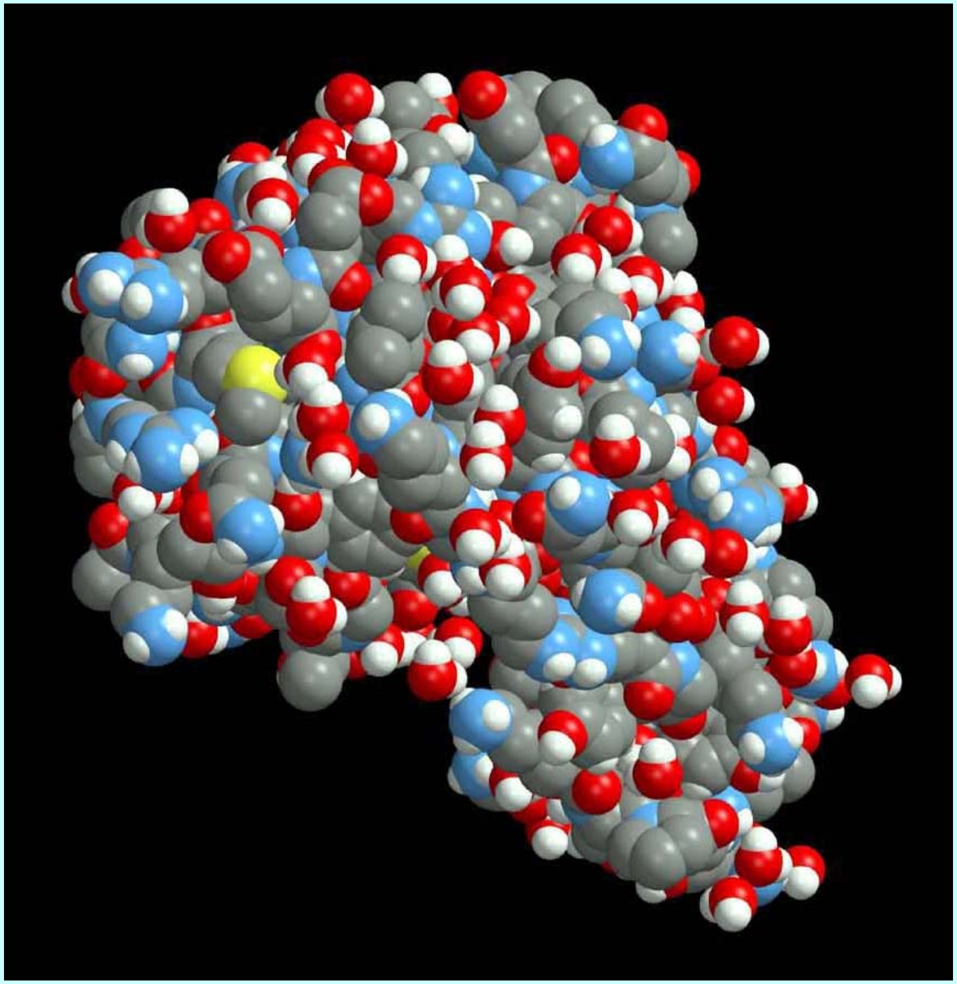
Outline:

- Motivation & Free Electron Laser by finger physics
- Free Electron Laser: Low Gain
- Free Electron Laser: High Gain, Start-up from noise (SASE)
- Experimental realization, technical challenges, future plans

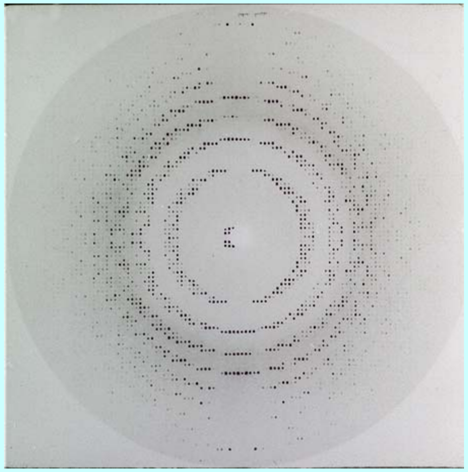
Why SASE FELs?



LYSOZYME , MW=19,806

State of the art:
Structure of biological macromolecule

reconstructed from diffraction pattern of protein crystal:



Needs ≈10^{15} samples

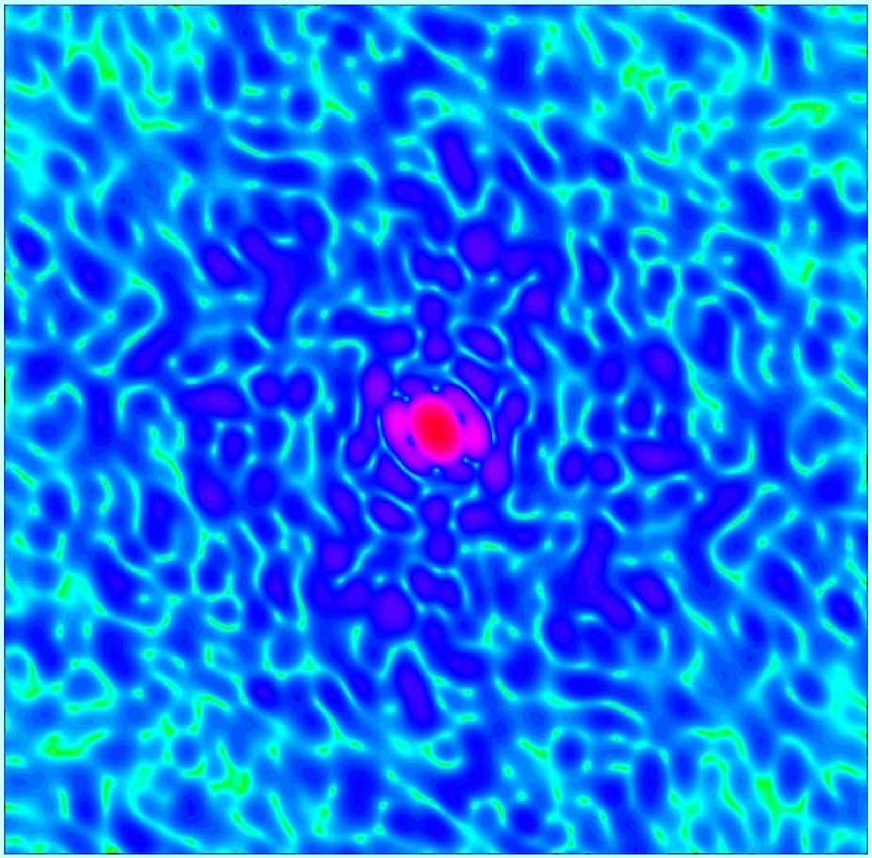
Crystallized → not in life environment

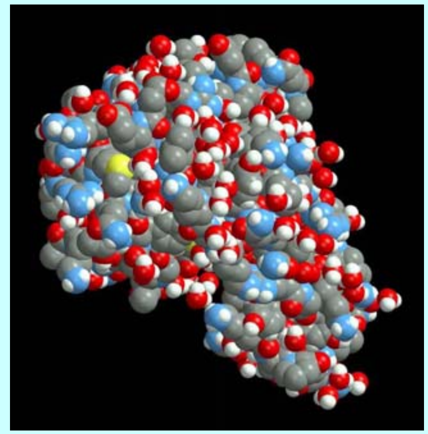
The crystal lattice imposes restrictions on molecular motion

Images courtesy Janos Hajdu

Why SASE FELs?

courtesy Janos Hajdu





SINGLE MACROMOLECULE,
Planar section, simulated image

Resol. does not depend on sample quality

Needs very high radiation power @ $\lambda \approx 1Å$

Can see dynamics if pulse length < 100 fs

Why SASE FELs?

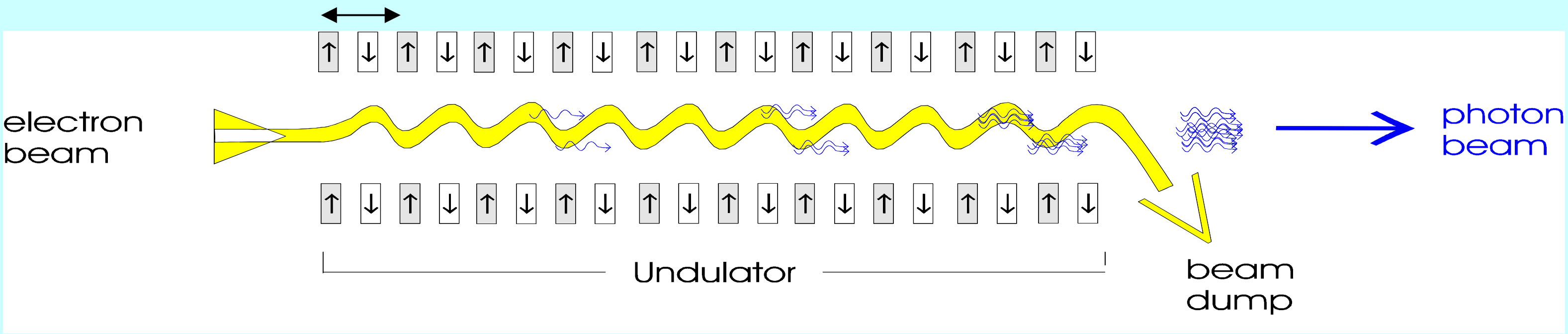
We need a radiation source with

- · very high peak and average power
- · wavelengths down to atomic scale $\lambda \sim 1$Å
- · spatially coherent
- · monochromatic
- · fast tunability in wavelength & timing
- · sub-picosecond pulse length

For wavelengths below ~150 nm: SASE FELs.

Undulator Radiation

$\lambda_u = 25\text{mm}$



Radiation of an <u>ultrarelativistic</u> electron:

1) Moving coordinate system (*):

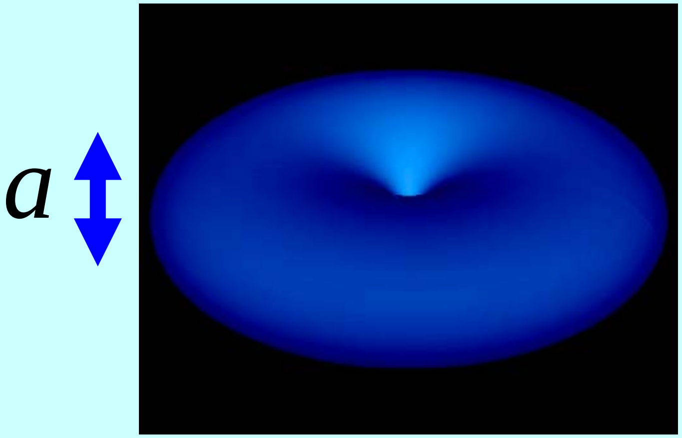
$\lambda_u^* = \frac{\lambda_u}{\gamma}$ Lorentz length contraction $\rightarrow$ electron oscillates with $\omega^* = 2\pi \frac{c}{\lambda_u^*} = \gamma \cdot \frac{2\pi c}{\lambda_u} = \gamma \cdot \omega$

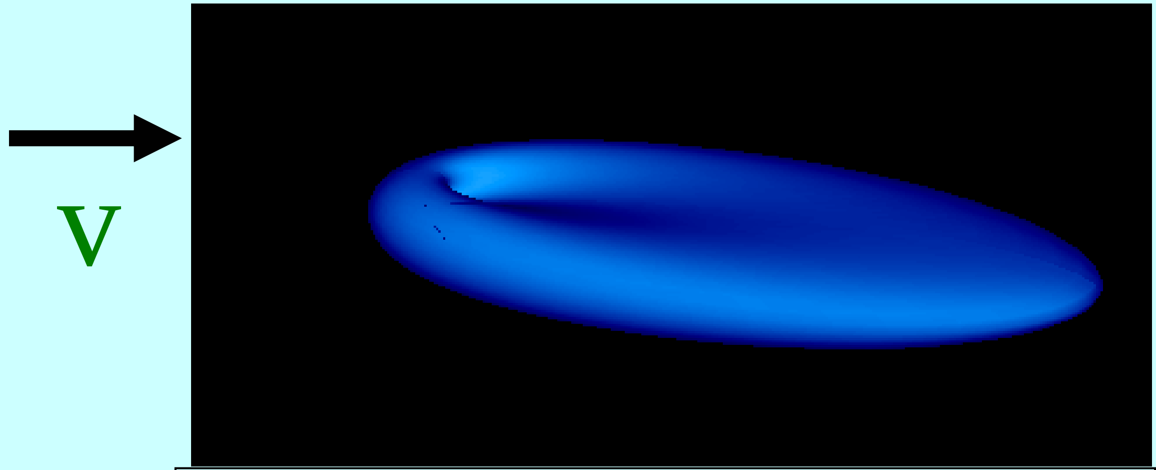
2) Lorentz transformation of radiation to lab-system (relativistic Doppler-effect):

$$\lambda_{lab} = \frac{\lambda_u^*}{\gamma(1+\beta)} \approx \frac{\lambda_u}{2\gamma^2}$$

3) correction for $v_{long} \neq v$: $\boxed{\lambda_{lab} = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)}$ $K = \frac{e\lambda_u B}{2\pi m_0 c} \approx 1$: undulator parameter

Radiation of a moving oscillating dipole





v = 0

local oscillator

$$\dot{v}_{\perp} = a\omega^2 \sin(\omega t)$$

$$P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\omega^4$$

$$(a < \lambda)$$

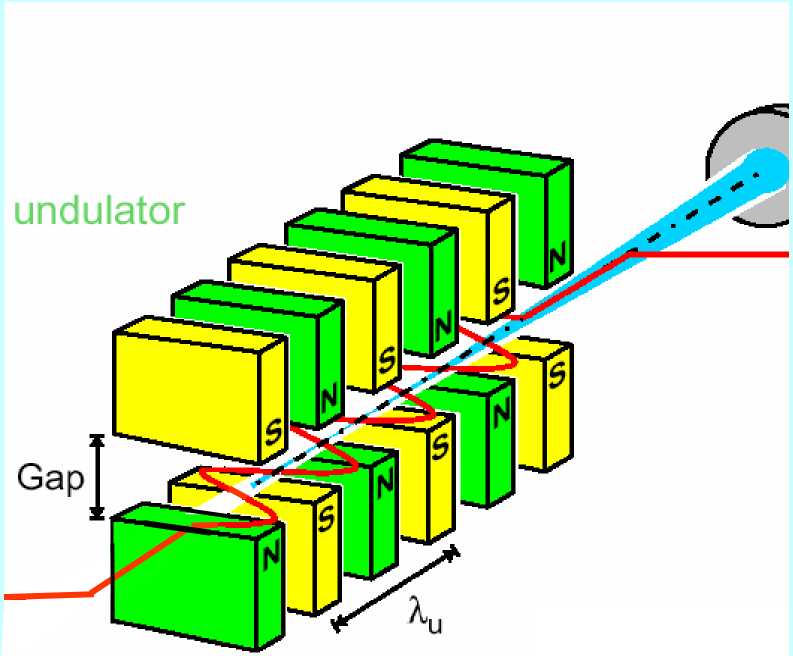
v = 0.9 c

moving oscillator

$$P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$$

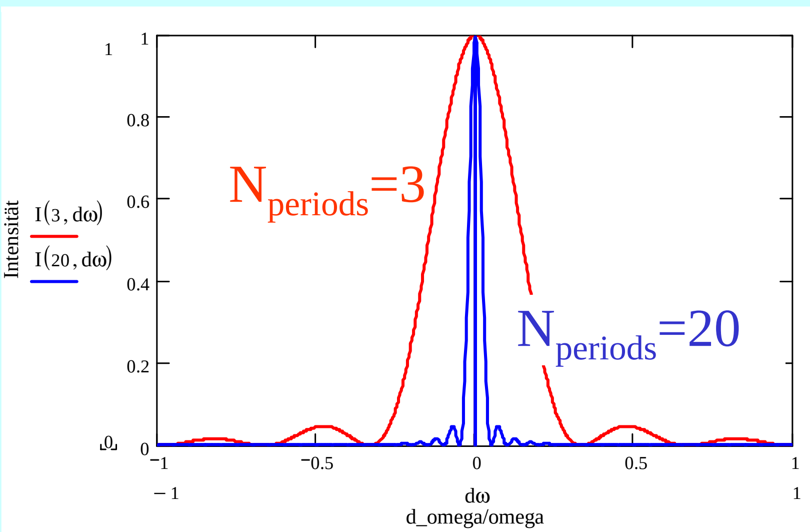
$$\lambda_{rad} = \frac{\lambda_{undulation}}{2\gamma^2}$$

We gain a factor of γ^4 in power!



Undulator radiation is emitted into narrow cone:

$$\sphericalangle \approx \frac{K}{\gamma}$$



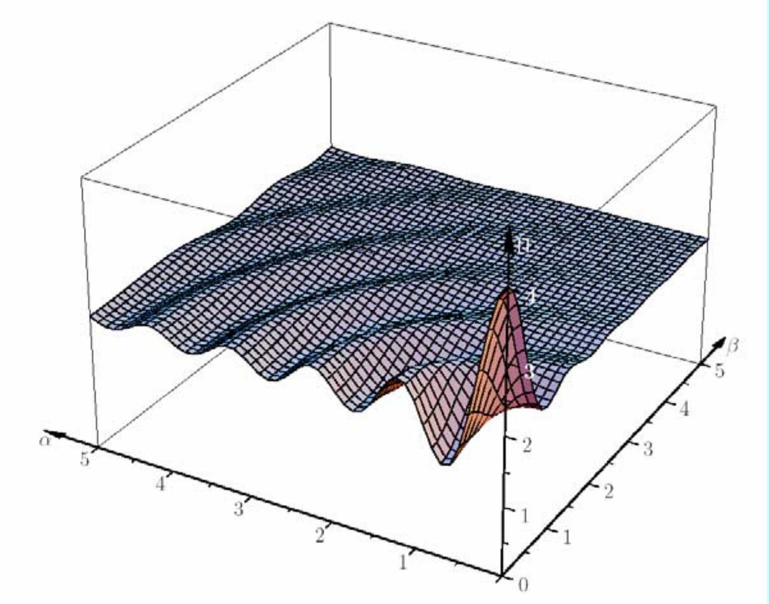
Line width of $N_{periods}$:

$$\frac{d\omega}{\omega} \approx \frac{1}{N_{periods}}$$

www-xfel.spring8.or.jp

NOTE: $P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$ assumes point-like charge Q !

How much is radiation of two charges Q ?



Power is <u>four</u> times larger for <u>two</u> charges Q separated by distance < λ !!

Now consider $Q = N \cdot e_0 \rightarrow P_\gamma = N^2 \frac{e_0{}^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$

$\rightarrow$ power per electron $\frac{P_\gamma}{N} = N \frac{e_0{}^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$ "stimulated emission"

→ FREE-ELECTRON LASER

Summary so far:

Use ultra-relativistic electrons:

•Boost radiation power by factor γ^4

•Generate microscopic wavelengths from macroscopic undulators by relativistic Doppler effect

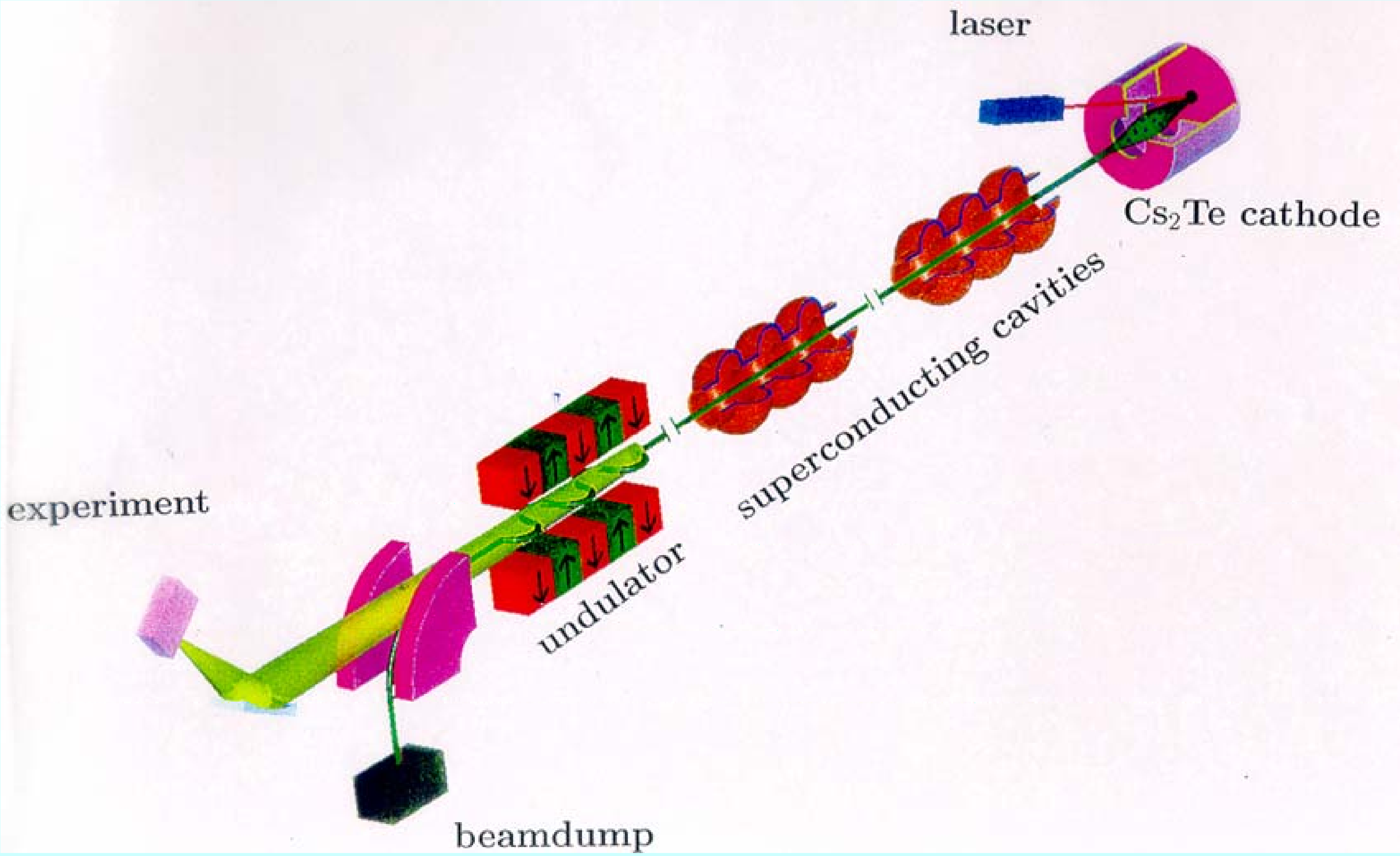
→ Undulator Radiation $I_N = NI_1$

Find mechanism to concentrate electrons within bunches of size of radiation wavelength

Boost radiation power by factor N due to coherent emission

→ Free-Electron Laser $I_N = N^2 I_1$

Schematic of a (single-pass) free electron laser (FEL)



Basic principle of a Free-Electron Laser (FEL)

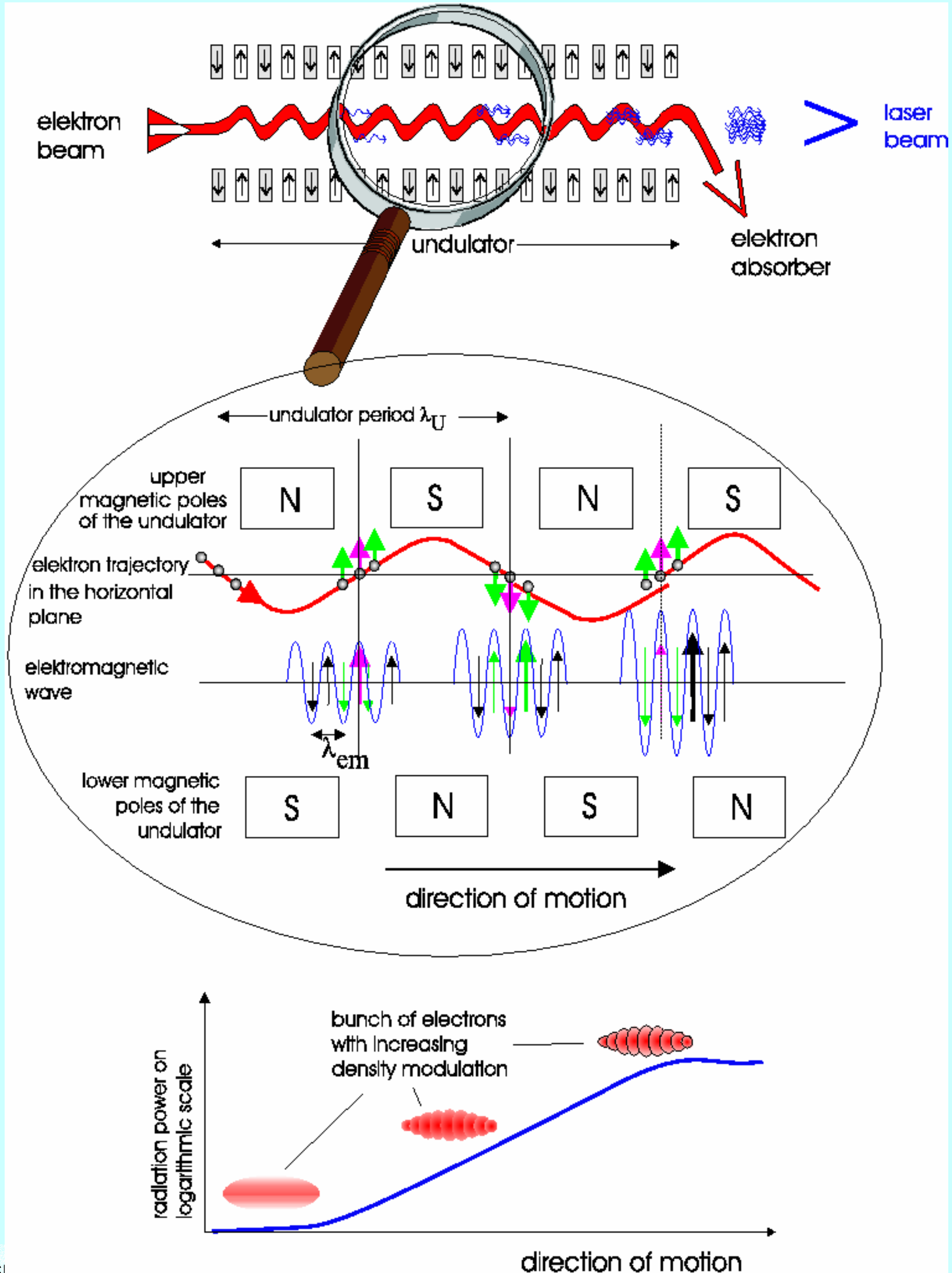
A) Due to oscillation in undulator field, electron velocity receives (transverse) component parallel to electric field vector of e.m. wave

→ electrons may loose or gain energy, depending on relative phase between electron oscillation and e.m. wave.

→ For a certain combination of parameters, this effect is stationary within the electron bunch →

Resonance wavelength:

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



B) Modulation of electron energy leads to longitudinal density modulation of electron bunch at the optical wavelength. Thus, radiation starts to scale ~ N^2 , eventually leading to exponential growth of rad. power.

Coherent motion is all we need !!

Basic theory of free electron laser

1) Low gain approximation =

we assume an initial, external e.m. field that changes only slightly (few % in power) during FEL process

Step 1: electron motion in undulator

field of helical undulator with period λ_u: $\vec{B} = B\begin{pmatrix} -\sin(k_u z) \\ \cos(k_u z) \\ 0 \end{pmatrix} + O(r^2) \quad \left(\text{using } k_u = \frac{2\pi}{\lambda_u}\right)$

electron motion: $m\gamma\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = q\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix} \times \vec{B} = qB\begin{pmatrix} -\dot{z}\cdot\cos(k_u z) \\ -\dot{z}\cdot\sin(k_u z) \\ \dot{x}\cdot\cos(k_u z) + \dot{y}\cdot\sin(k_u z) \end{pmatrix}$

$\mathbf{exp}(i\cdot x) = \mathbf{cos}\,x + i\cdot\mathbf{sin}\,x$

One solution (prove it!) is a periodic, helical motion:

longitudinal motion: v_z =const., $z = v_z t = \beta_z ct$

(1)

transverse motion on a circle: $\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \end{pmatrix} = c\frac{K}{\gamma}\begin{pmatrix} -\sin(k_u z) \\ \cos(k_u z) \end{pmatrix}$, or, using $w = x + iy$, $\dot{w} = ic\frac{K}{\gamma}\mathbf{exp}(ik_u z) \quad \rightarrow w = \frac{cK}{\gamma k_u v_z}\mathbf{exp}(ik_u z)$

$K = \frac{e\lambda_u B}{2\pi m_0 c}$ is called undulator parameter. It is typically $K \approx 1$ $\rightarrow$ opening angle of helical motion $\frac{v_\perp}{c} = \frac{K}{\gamma} \approx \frac{1}{\gamma}$

We can now determine $\beta_z = \frac{v_z}{c}$: $\beta_z = \frac{1}{c}\sqrt{v^2 - \dot{x}^2 - \dot{y}^2} = \sqrt{\beta^2 - \left(\frac{K}{\gamma}\right)^2} = \sqrt{1 - \frac{1}{\gamma^2} - \left(\frac{K}{\gamma}\right)^2} \approx 1 - \frac{1}{2\gamma^2}\left(1 + K^2\right)$

External electromagnetic wave moving parallel to electron beam (i.e. in z-direction):

$$\vec{\mathbf{E}}_L = \mathbf{E}_0 \begin{pmatrix} \cos(\omega_L t - k_L z - \varphi_0) \\ \sin(\omega_L t - k_L z - \varphi_0) \\ 0 \end{pmatrix} \quad ; \quad \vec{B}_L = \frac{1}{c\omega_L}\dot{\vec{\mathbf{E}}}_L \quad ;$$

again: complex notation: $\mathbf{E}_L = \mathbf{E}_{L,x} + i\mathbf{E}_{L,y} \quad \rightarrow \quad \mathbf{E}_L = \mathbf{E}_0 \exp i(\omega_L t - k_L z - \varphi_0)$

Change of electron energy in presence of undulator and wave:

$$\frac{dE}{dz} = \frac{dE}{dt}\frac{dt}{dz} = \vec{v}\vec{F}\frac{1}{v_z} = \frac{q}{v_z}\Re\left(\dot{w}\mathsf{E}_L^*\right) = -\frac{q\mathsf{E}_0 K}{\gamma\beta_z}\sin\Psi \qquad (2)$$

with $\Psi = (k_u + k_L) z - \omega_L t + \varphi_0 = (k_u + k_L) z - \frac{\omega_L z}{\beta_z c} + \varphi_0$ (using $z = v_z t = \beta_z c t$)

The energy dE is taken from or transferred to the radiation field. For most frequencies, dE/dt oscillates very rapidly. A significant energy transfer will only be accumulated if the phase difference Ψ between particle motion and e.m. wave stays constant with time.

$\Psi = \text{const.} \rightarrow \frac{d\Psi}{dz} = (k_u + k_L) - \frac{\omega_L}{\beta_z c} = 0$. Using $\omega_L = ck_L$ yields $k_u + k_L - \frac{k_L}{\beta_z} = 0$

→ Resonance condition: $\lambda_L = \lambda_u \frac{1-\beta_z}{\beta_z} \approx \lambda_u (1-\beta_z) \approx \frac{\lambda_u}{2\gamma^2}(1+K^2)$

The same equation as for undulator radiation!

We have seen what happens <u>on</u> resonance.

For particles slightly <u>off</u> resonance energy, the phase Ψ will slip. By how much?

In $\Psi = (k_u + k_L) z - \frac{\omega_L z}{\beta_z c} + \varphi_0$ only $\beta_z \approx 1 - \frac{1}{2\gamma^2}(1+K^2)$ depends on energy. Writing $\gamma = \gamma_{res} + \Delta\gamma$ we get

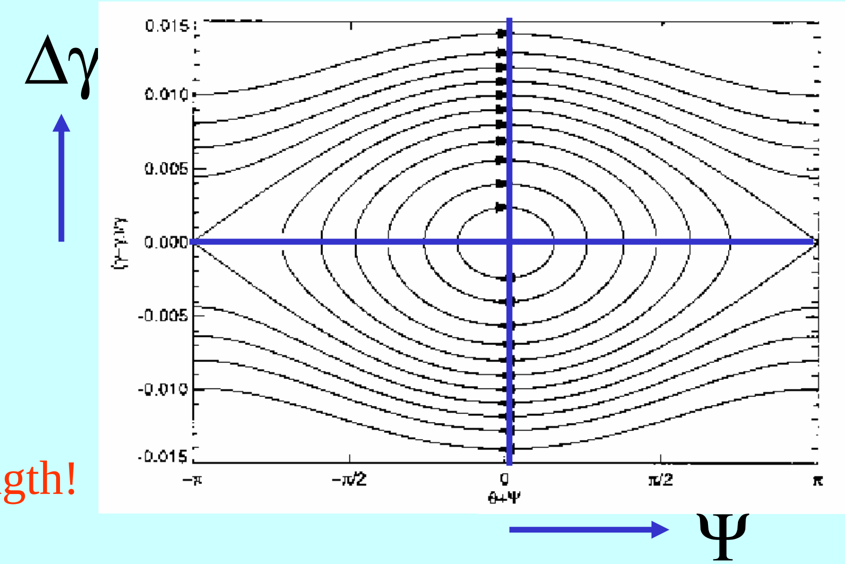
$$\frac{d\Psi}{dz} = (k_u + k_L) - \frac{\omega_L}{c\left(1 - \frac{1+K^2}{2(\gamma_{res}+\Delta\gamma)^2}\right)} \approx k_u + k_L - \frac{\omega_L}{\beta_z(\gamma_{res}) \cdot c} + \frac{\omega_L}{c}\frac{1+K^2}{\gamma_{res}{}^3}\Delta\gamma = \frac{\omega_L}{c}\frac{1+K^2}{\gamma_{res}{}^3}\Delta\gamma = k_u \frac{2}{\gamma_{res}}\Delta\gamma \qquad (3)$$

Deriving once more with respect to z yields: $\frac{d^2\Psi}{dz^2} = k_u \frac{2}{\gamma_{res}}\frac{d\gamma}{dz}$. Now using $\frac{d\gamma}{dz} = -\frac{q\mathbf{E}_0 K}{m_0 c^2 \gamma \beta_z}\sin\Psi$ (see Eq. 2)

we get

$$\frac{d^2\Psi}{dz^2} = -\frac{2q}{m_0 c^2}\frac{\mathbf{E}_0 K k_u}{\gamma_{res}^2 \beta_z}\sin\Psi = -\Omega^2 \sin\Psi \quad \text{with} \quad \Omega^2 = \frac{2q}{m_0 c^2}\frac{\mathbf{E}_0 K k_u}{\gamma_{res}^2 \beta_z}$$

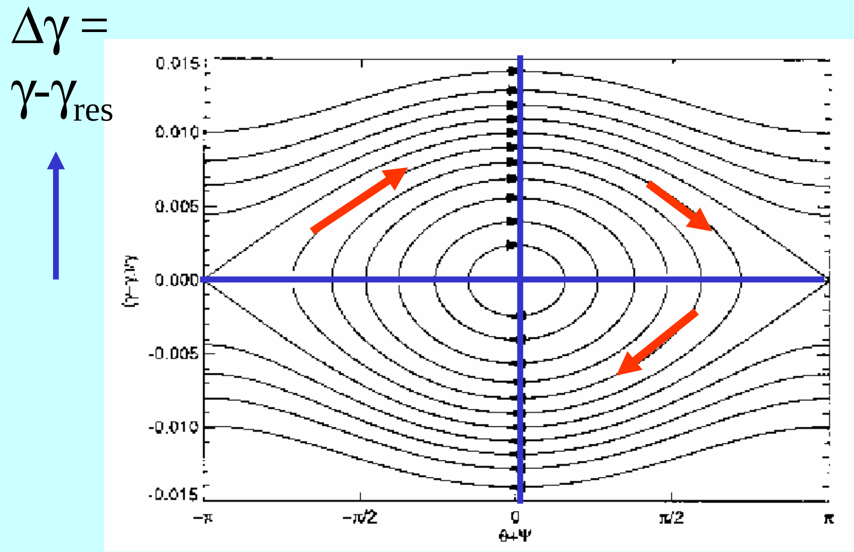
This is a pendulum equation in the $\Delta\gamma$ - Ψ phase space:



electrons with little deviation from synchronous phase or from resonance energy perform periodic oscillation.

Identical to synchrotron oscillation,
but „bucket“ length is now the optical wavength!
Particles within <u>separatrix</u> get bunched

Gain (or loss) in field energy per undulator passage,depending on where to start in phase space :



Ψ

$$G_i = \frac{\text{gain of field energy produced by electron i}}{\text{total field energy}} = \frac{-mc^2\left(\gamma_i(z=L_u)-\gamma_i(0)\right)}{\frac{\varepsilon_0}{2}\mathbf{E}_0^2\cdot V}$$

$\rightarrow$ requires solution of pendulum equation for $\gamma(z)$.

→ Integral equation; solution by iteration.

Real electron beam has well defined energy, but all phases are equally probable.

→ Need to average gain for fixed $\Delta\gamma$ over all phases.

→ Motion within separatrix leads to longitudinal density modulation (microbunching)!

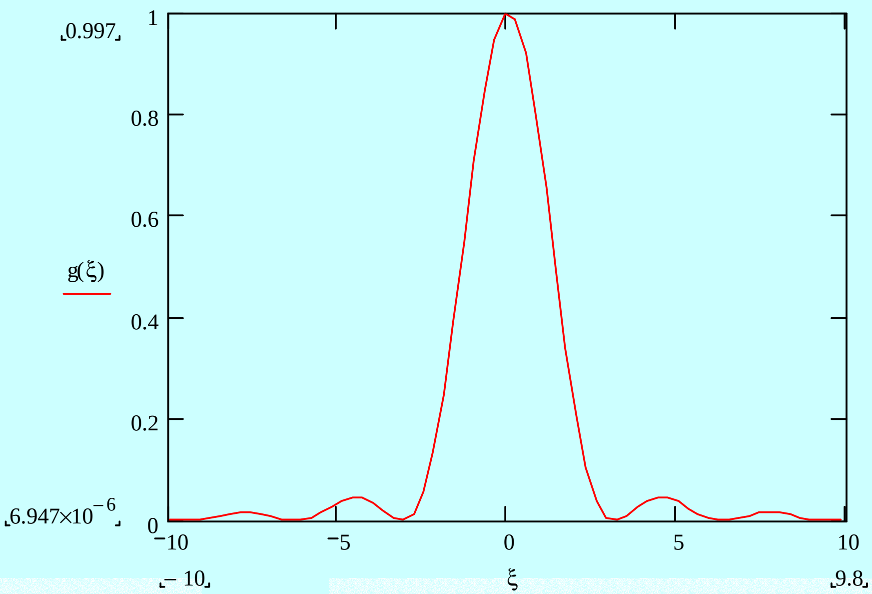
To first order in the iteration, there is no net gain (G=0), because motion in phase space is (almost) symmetric: As many particles move up as down.
In second order it is seen however that, for positive $\Delta\gamma$, the motion of particles with positive phase goes more rapidly downwards than the motion of the others goes upwards.

Using $\frac{\Delta\omega}{2\omega_{res}} = \frac{\Delta\gamma}{\gamma_{res}}$, we can write: $\text{Gain} \propto -\frac{d}{d\gamma}\frac{\sin^2\left(2\pi N_u \frac{\Delta\gamma}{\gamma_{res}}\right)}{(\Delta\gamma)^2} \propto -\frac{d}{d\omega}\frac{\sin^2\left(\pi N_u \frac{\Delta\omega}{\omega_{res}}\right)}{(\Delta\omega)^2}$

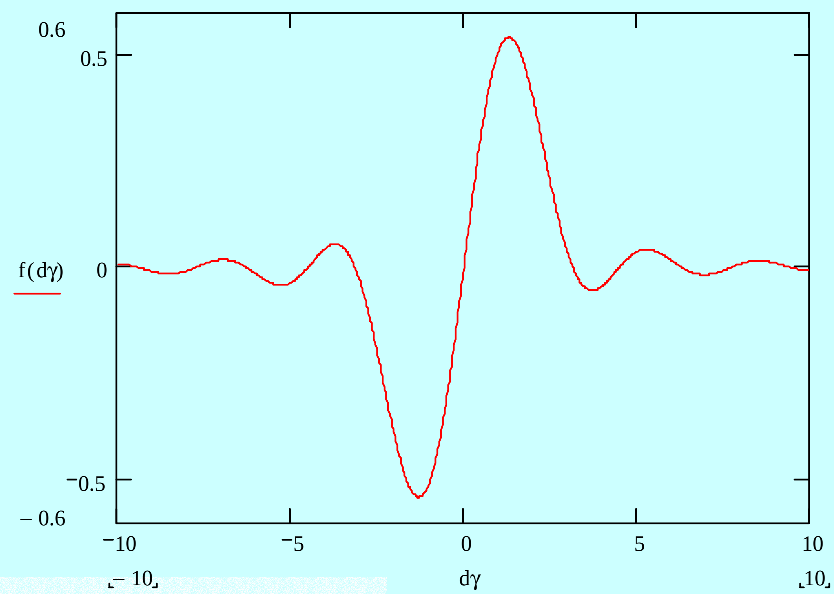
The line shape function of low gain FEL emission is
the derivative of the line shape of spontaneous undulator radiation

Madey-Theorem

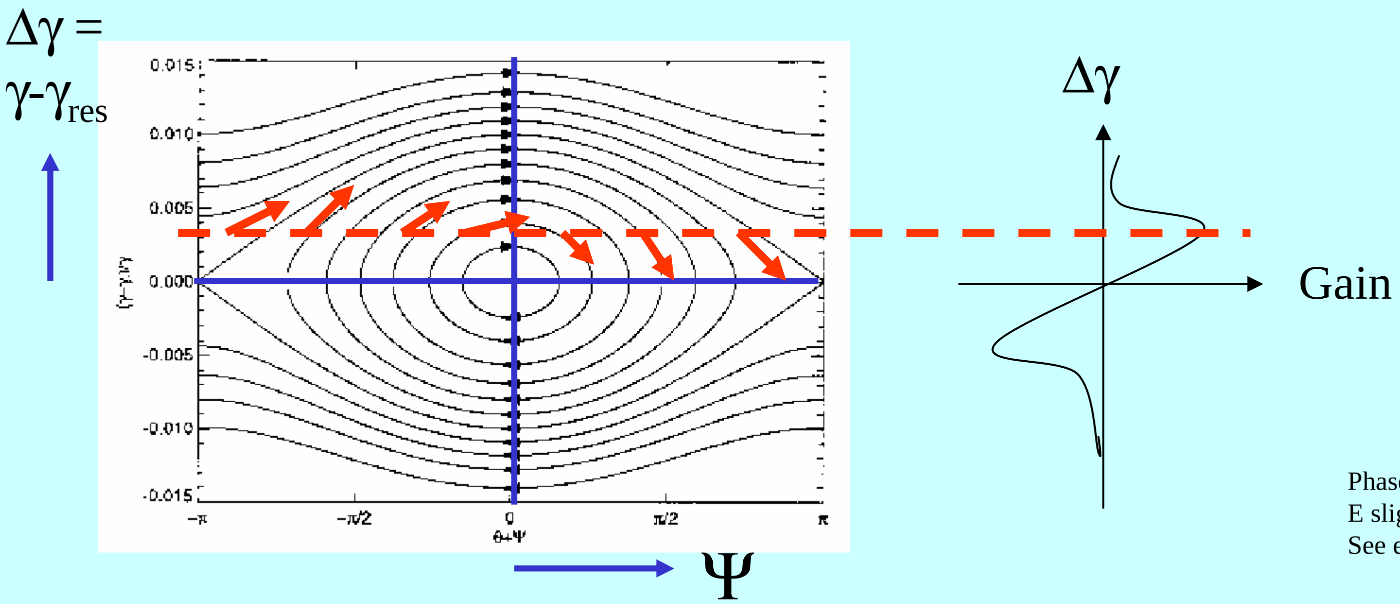
$$\frac{\sin^2\xi}{\xi^2}$$

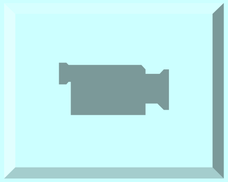


$$-\frac{d}{d\xi}\frac{\sin^2\xi}{\xi^2} = \frac{1}{\xi^3}\left(1 - \cos(2\xi) - \xi\sin(2\xi)\right)$$



e.m. field is amplified if electron energy is slightly above resonance





Phase space simulation of low gain FEL
E slightly above resonance →
See electron bunch losing energy in averave

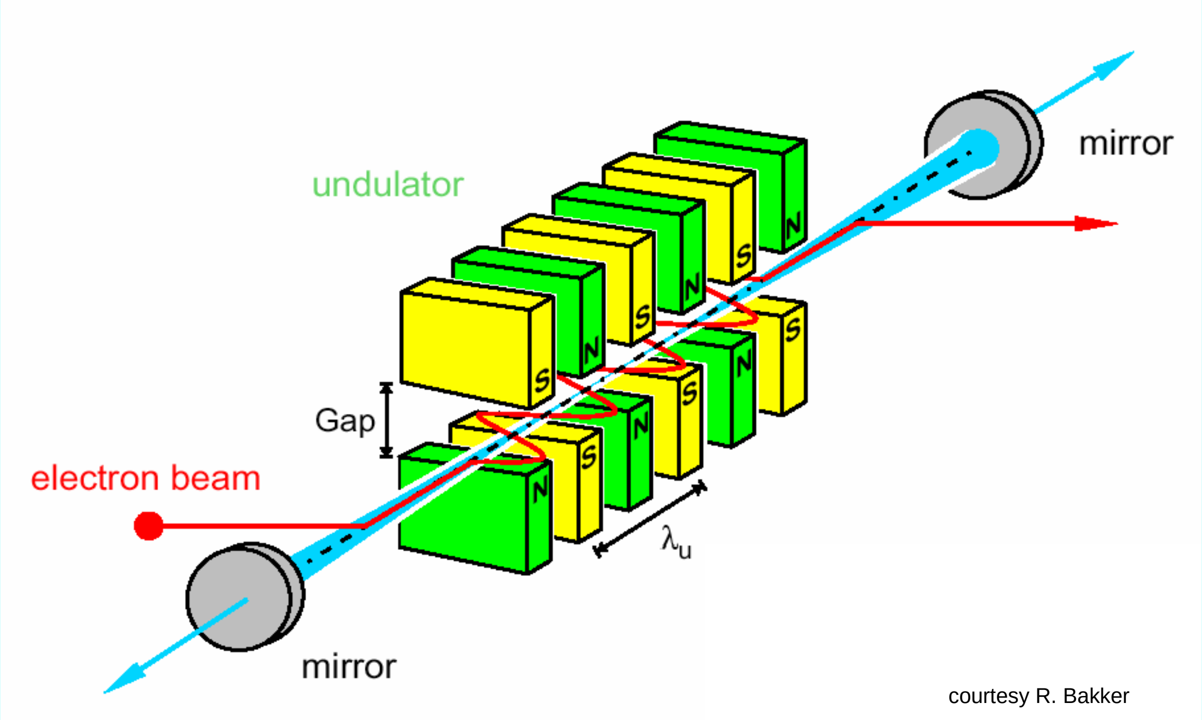
Radiation energy produced per undulator passage is $\Delta E = G \cdot E_i$ (field energy before passage of undulator).

Note that:

1. ΔE adds to spontaneous radiation
2. $\Delta E \propto E_i$ i.e. electrons are stimulated to emit due to presence of E_i
3. ΔE may become arbitrarily large if only E_i is large enough

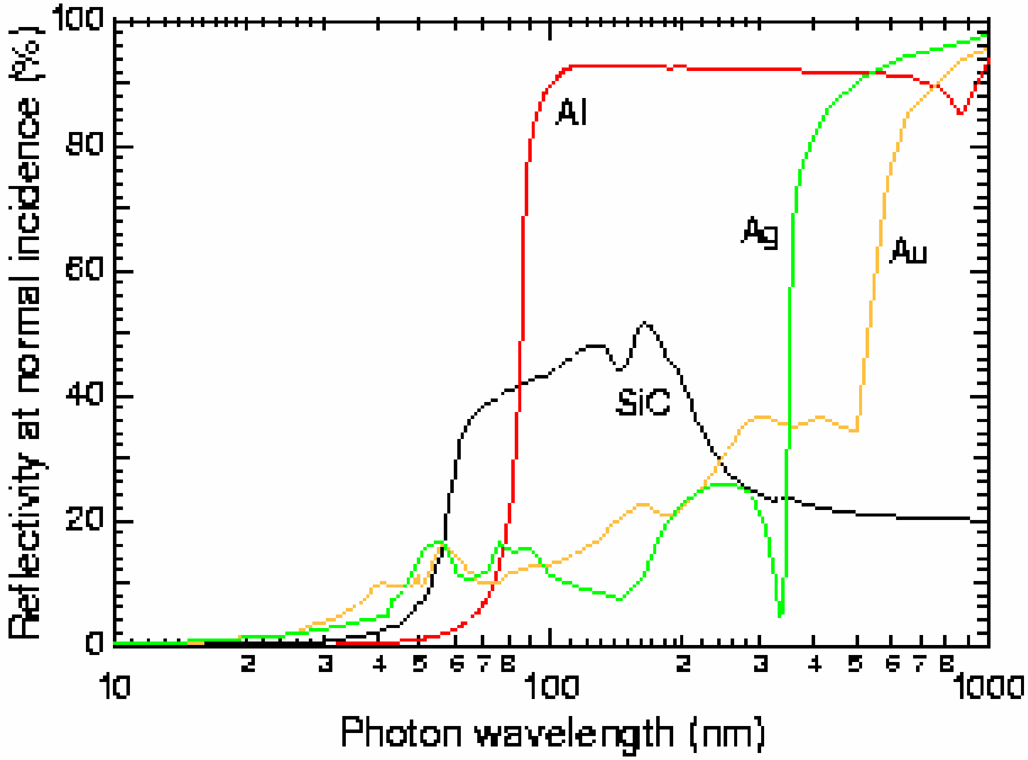
For applications, a few % power gain (i.e. a low gain FEL) don't seem to be of interest. However, with a pair of mirrors, one can multiply the gain, if on each round trip of radiation there is a fresh electron bunch available.

After N round trips, $G_{total} = G^N$, and the e.m. field is so strong that microbunching is almost perfect. → **saturation**



Only few % of radiation intensity is extracted per electron passage (mirror reflectivity) to keep stored field high

Very nice scheme.
But what if we want wavelength < approx. 200nm where no good mirrors exist?



Reflectivity of most surfaces at normal incidence drops drastically at wavelengths below 100 – 200 nm.

2) High gain FEL =

we take into account that the initial, external e.m. field changes during FEL process

See e.g. Ref. 3 Saldin et al.

Wave equation for purely transverse electric field:

$$\frac{\partial^2 \mathbf{E}_\perp}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}_\perp}{\partial t^2} = \mu_0 \frac{\partial j_\perp}{\partial t}$$

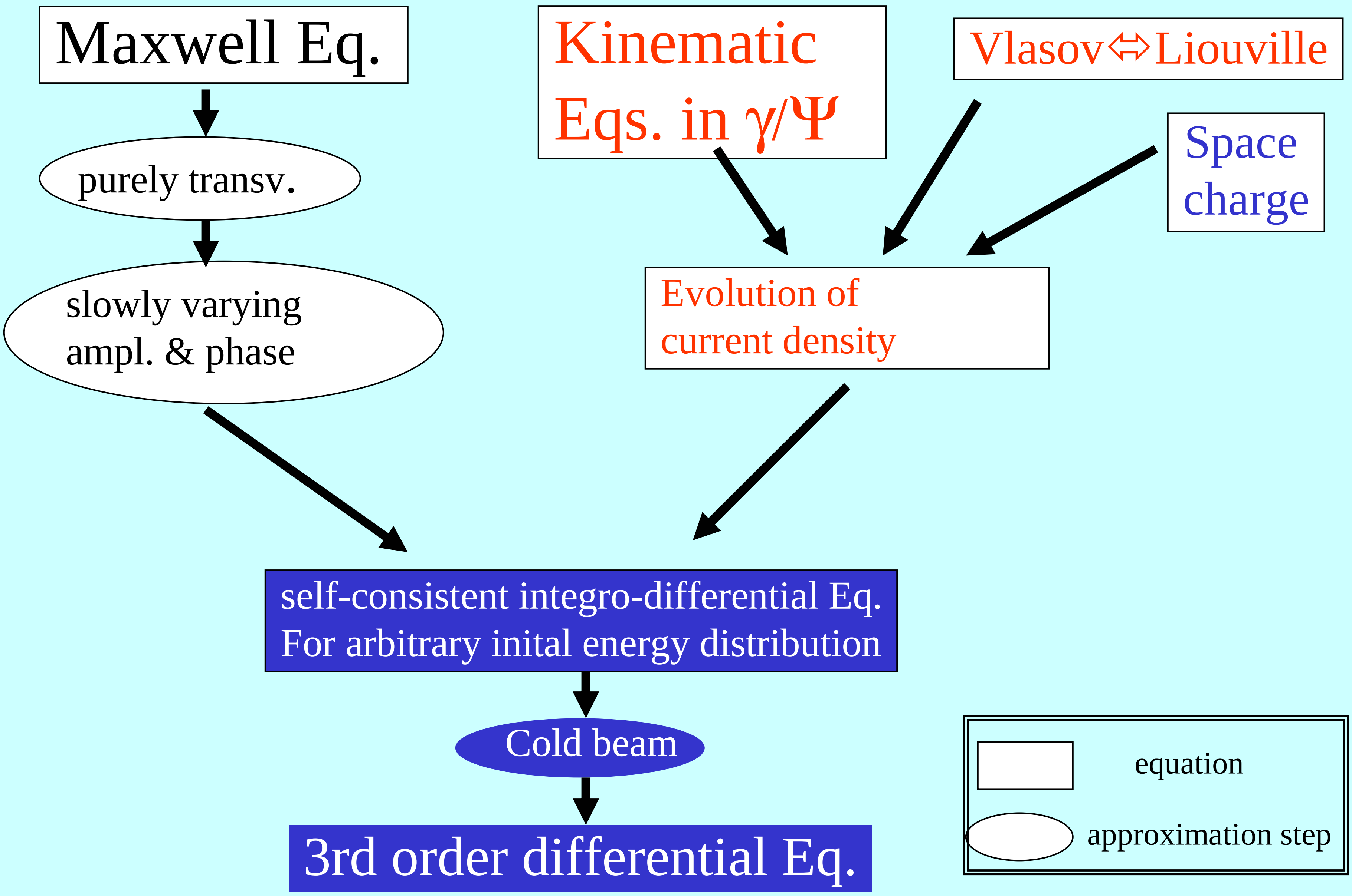
e.m. fields are generated by currents.

The development of beam current j is determined by motion of particle density in coordinates z, γ, Ψ

Vlasov equation for phase space density of Hamiltonian system: $\frac{\partial f}{\partial z} + \frac{\partial f}{\partial \Psi}\frac{\partial \Psi}{\partial z} + \frac{\partial f}{\partial \gamma}\frac{\partial \gamma}{\partial z} = 0$

$\frac{\partial \gamma}{\partial z}$ is known from eq. (2), $\frac{\partial \Psi}{\partial z}$ from eq. (3).

Major steps to derive the 3rd order Diff. Eq. for High Gain FEL



Ansatz : $j(z) = j_0 + j_1(z)\cos(\Psi + \psi_0)$ i.e. we assume a density modulation at the optical wavelength, growing with z (in a way to be calculated).

For this current, Maxwell equations result in: $$\frac{\partial(\mathbf{E}_{L,x} + i\mathbf{E}_{L,y})}{\partial z} = \frac{\partial \mathbf{E}_L}{\partial z} = -\frac{\pi K}{c\gamma} j_1(z) e^{i\psi_0} \qquad (4)$$

For the most simple case of a monoenergetic electron beam, the Vlasov equation results in

$$j_1(z)e^{i\psi_0} = j_0 \frac{qK}{2\gamma^4} \frac{\omega(1+K^2)}{m_0 c^3} i \int_0^z dz' \mathbf{E}(z')(z'-z) \exp iC(z'-z) \text{ with } C = k_u + k_L - \frac{\omega_L}{v_z} = \text{"detuning parameter"}$$

Insertion into eq. (4) yields a linear integro-differential equation for **E**.

Using the Gain Factor $\Gamma = \left(\frac{\pi j_0 K^2 (1+K^2)\omega_L}{I_A c \gamma^5} \right)^{1/3}$ it can be written ($I_A = 17$ kA Alfven current):

$$\frac{d^3\mathbf{E}}{dz^3} + 2iC\frac{d^2\mathbf{E}}{dz^2} - C^2\frac{d\mathbf{E}}{dz} = i\Gamma^3\mathbf{E}$$

. Ansatz: $\mathbf{E} = A\exp(\Lambda z) \quad \rightarrow \quad \Lambda(\Lambda + iC)^2 = i\Gamma^3$

most simple case: No detuning $C = 0$: $\Lambda^3 = i\Gamma^3 \Rightarrow \Lambda_1 = -i\Gamma; \Lambda_2 = \frac{i+\sqrt{3}}{2}\Gamma; \Lambda_3 = \frac{i-\sqrt{3}}{2}\Gamma$

The general solution is: $\mathbf{E}(z) = A_1 \,\mathbf{exp}(-i\Gamma z) + A_2 \,\mathbf{exp}(\frac{i+\sqrt{3}}{2}\Gamma z) + A_3 (\mathbf{exp}\frac{i-\sqrt{3}}{2}\Gamma z)$

All contributions to solution oscillate or vanish, except for: $\frac{i+\sqrt{3}}{2}\Gamma z$

For an undulator much longer than $1/\Gamma$, this part of solution dominates.
Coefficients $A_{1,2,3}$ need to be determined by initial conditions:

Example: Unmodulated electron beam and e.m. wave at the entrance:

In this case: $\tilde{\mathbf{E}}(z=0) = \mathbf{E}_{ext}, \; \tilde{j}_1(z=0) = 0, \; \frac{d}{dz}\tilde{j}_1(z=0) = 0 \quad \rightarrow \quad \begin{pmatrix} \tilde{\mathbf{E}} \\ \tilde{\mathbf{E}}' \\ \tilde{\mathbf{E}}'' \end{pmatrix}_{z=0} = \begin{pmatrix} \mathbf{E}_{ext} \\ 0 \\ 0 \end{pmatrix}$

$$\tilde{\mathbf{E}}(z) = \frac{1}{3}\mathbf{E}_{ext}\left[\mathbf{exp}(-i\Gamma z) + \mathbf{exp}\left(\frac{i+\sqrt{3}}{2}\Gamma z\right) + \mathbf{exp}\left(\frac{i-\sqrt{3}}{2}\Gamma z\right)\right]$$

for $z \gg 1/\Gamma$:

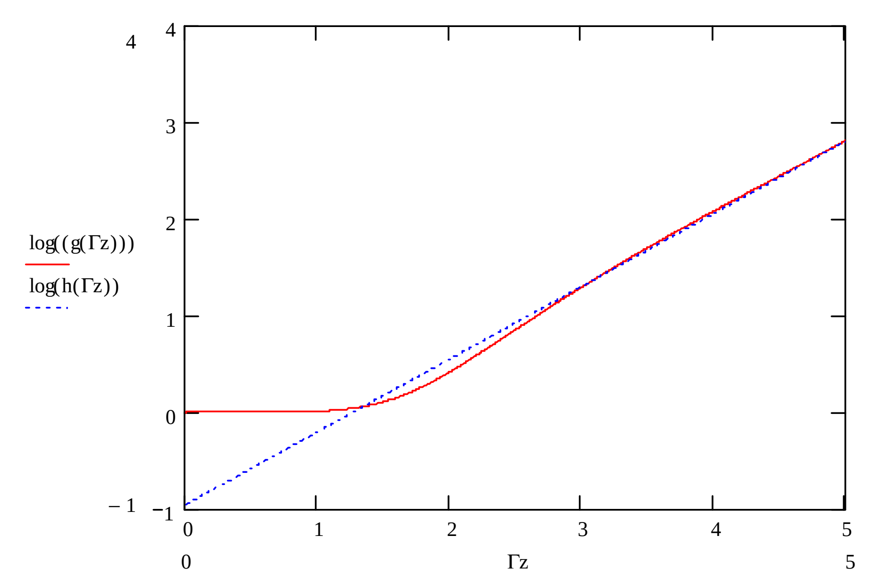
$$\tilde{\mathbf{E}}(z) = \frac{1}{3}\mathbf{E}_{ext}\,\mathbf{exp}\left(\frac{i+\sqrt{3}}{2}\Gamma z\right)$$

The power gain is given by (prove it!)

$$G = \frac{|\tilde{\mathbf{E}}|^2}{\mathbf{E}_{ext}^2} = \frac{1}{9}\left[1 + 4\cosh\frac{\sqrt{3}}{2}\Gamma z\left(\cosh\frac{\sqrt{3}}{2}\Gamma z + \cos\frac{3}{2}\Gamma z\right)\right]$$

$\rightarrow$ (for $z \gg 1/\Gamma$): $\boxed{G = \frac{1}{9}\exp\sqrt{3}\Gamma z}$

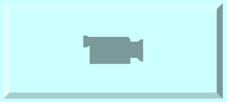
The factor 1/9 describes the coupling of the incoming e.m. field to FEL gain process



$$P_{rad} = \frac{1}{9} P_{in} \exp\left(\sqrt{3}\Gamma z\right).$$

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A c\gamma^5}{\pi j_0 K^2 (1+K^2)\omega_L}\right)^{1/3}$$ or, using $\omega_L = \frac{4\pi c\gamma^2}{\lambda_u (1+K^2)}$ and $j_0 \approx \frac{\hat{I}}{\pi\sigma_r^2}$,

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \hat{I} K^2}\right)^{1/3}$$ is called power gain length.



Bunching at SASE FEL seen in y/z coordinates

Also widely used: $\rho = \frac{\lambda_u \Gamma}{4\pi}$ "FEL-parameter"

$$\rho = \frac{1}{4\pi\sqrt{3}}\frac{\lambda_u}{L_G} = \frac{1}{4\pi\sqrt{3}}\frac{1}{N_{Gain}}$$

P_{in} = input power;
may also be spontaneous radiation from first part of the undulator.

Exponential growth of power at SASE FEL

→Self-Amplified Spontaneous Emission (SASE) mode of operation

→ Most attractive for (short) wavelengths where no mirrors and no good (= powerful and tunable) input laser are available.

Present world record w.r.t. short wavelengths (32 nm):
Power gain $P_{rad}/P_{in} = 10^6$ demonstrated at DESY

Saturation takes place after $L_{sat} = \frac{\lambda_u}{\rho} \approx 22 L_G$.

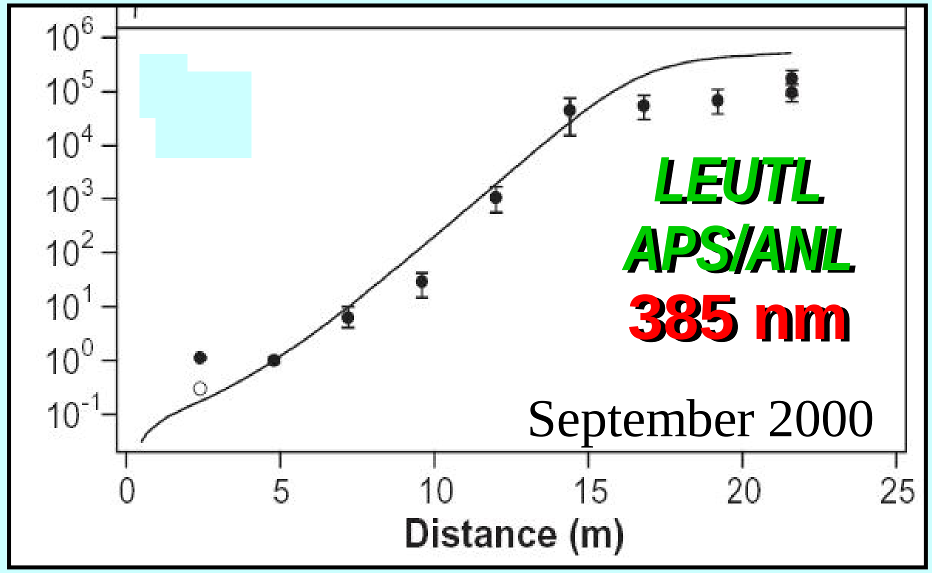
Peak power 1 GW

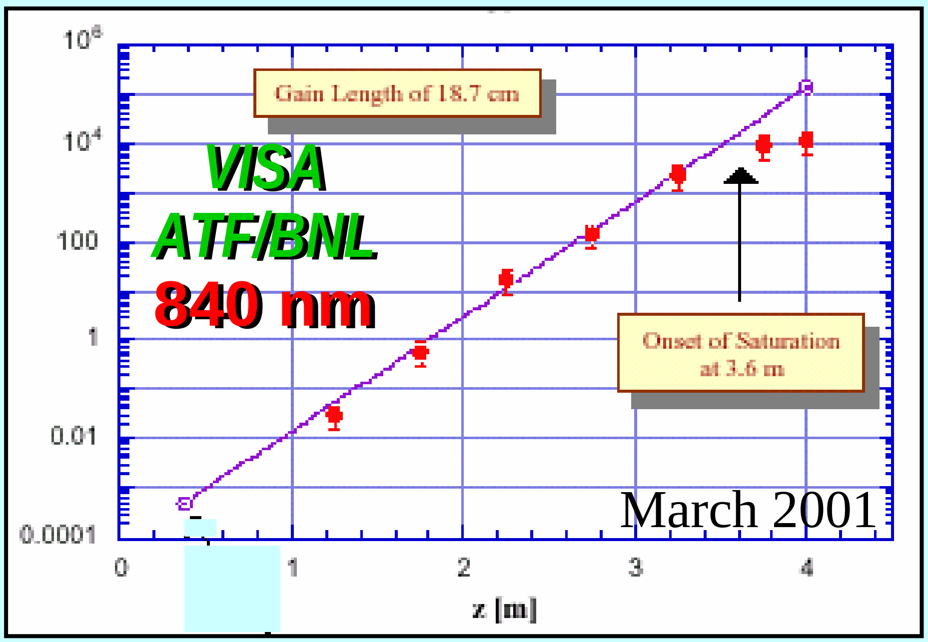
At saturation, the radiation band width is $\frac{\Delta\lambda_{rad}}{\lambda_{rad}} \approx \rho$,

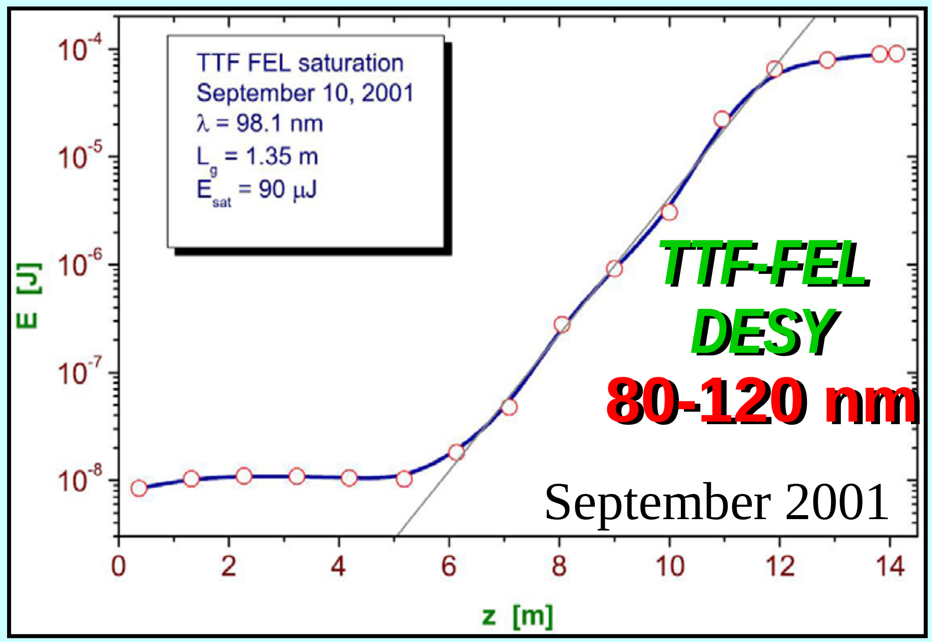
and the fraction of beam energy into (coherent!) radiation energy is also $\frac{E_{rad}}{E_0} \approx \rho$

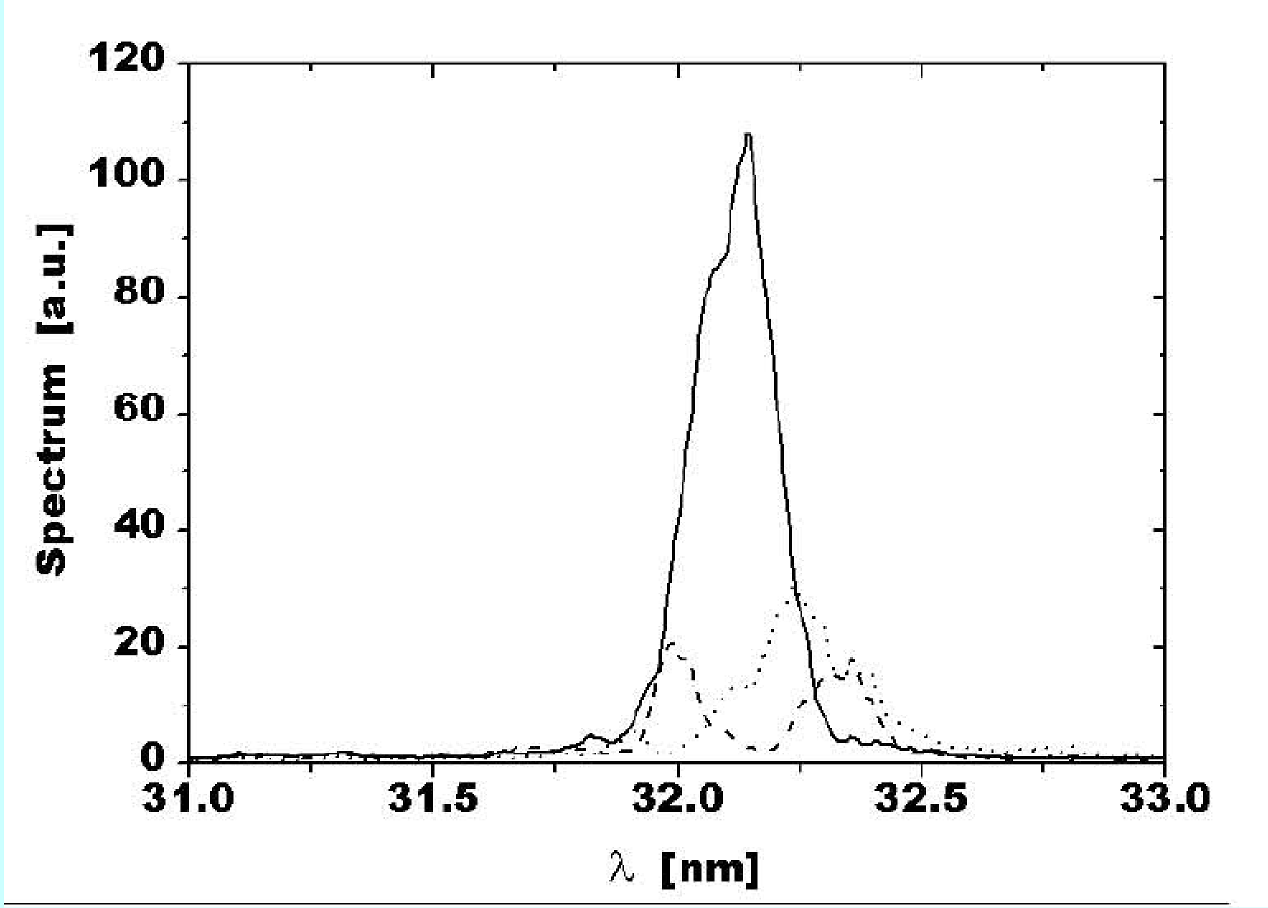
SASE FELs: State of the art

All observations agree with theor. expectations/ computer models





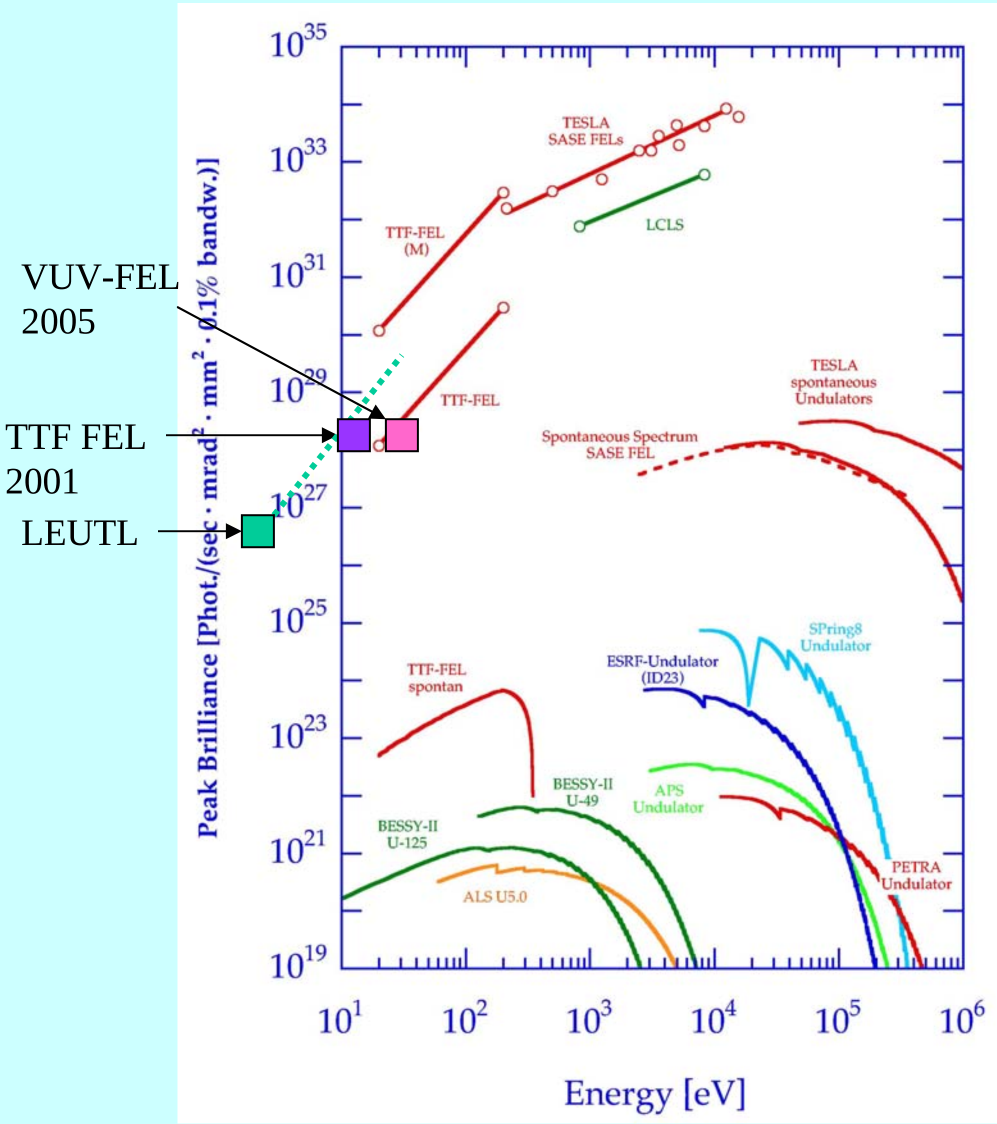




Results 2005:

FEL pulses ca. 25 fs long
with up to $E_{pulse} = 25\ \mu J$ energy.
$\rightarrow$ 1 GW peak power.

Peak brilliance



VUV FEL User Facility at DESY

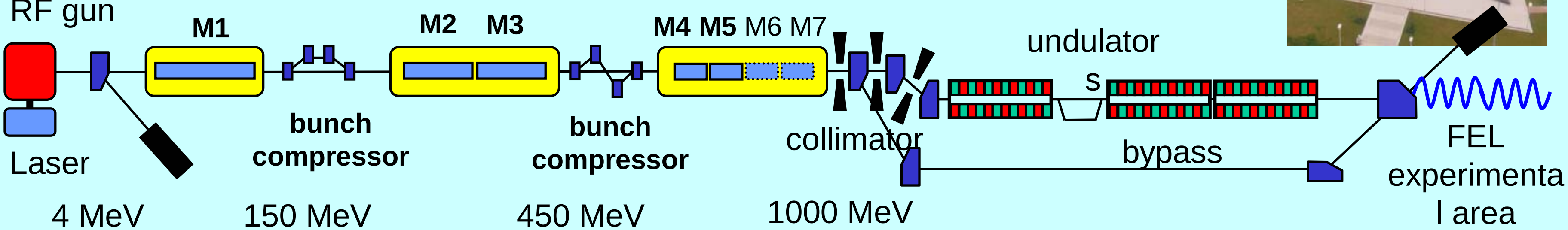
TTF FEL

VUV-FEL

experimental hall

start of user operation NOW

VUV FEL User Facility at DESY



250 m

What are the challenges?Overview

Electron beam parameters needed for Self-Amplified-Spontaneous Emission (SASE)

Energy:

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

für λ_{em}= 1 Å: E ≈ 20 GeV

Energy width:

Narrow resonance → $\sigma_E/E \leq \rho \sim 10^{-4}$

⇔ Small distortion by wakefields

⇒ super conducting linac ideal!

Straight trajectory in undulator:
ultimately < 10 μm over 100 m

Gain Length: $$L_g = \frac{1}{\sqrt{3}}\left[\frac{2mc}{\mu_0 e}\frac{\gamma^3\sigma_r^2\lambda_u}{K^2\hat{I}}\right]^{1/3}$$

Beam size:

σ_r ≈ 40 μm ⇔ high electron desity for maximum interaction with radiation field

Emittance $\varepsilon \leq \lambda/4\pi$

need special electron source to accelerate the beam before it explodes due to Coulomb forces

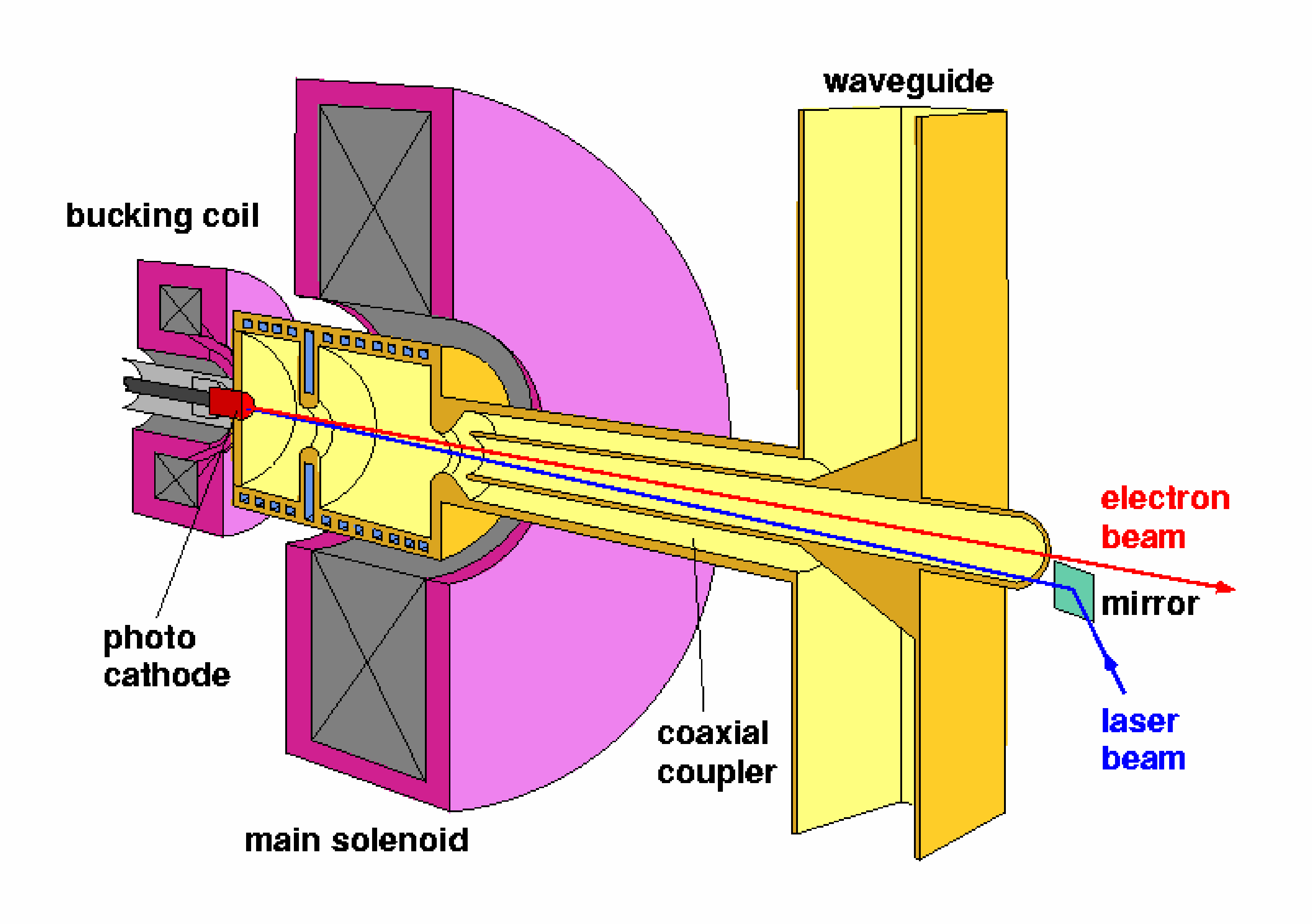
Peak current inside bunch:

$\hat{I}$ > 1 kA

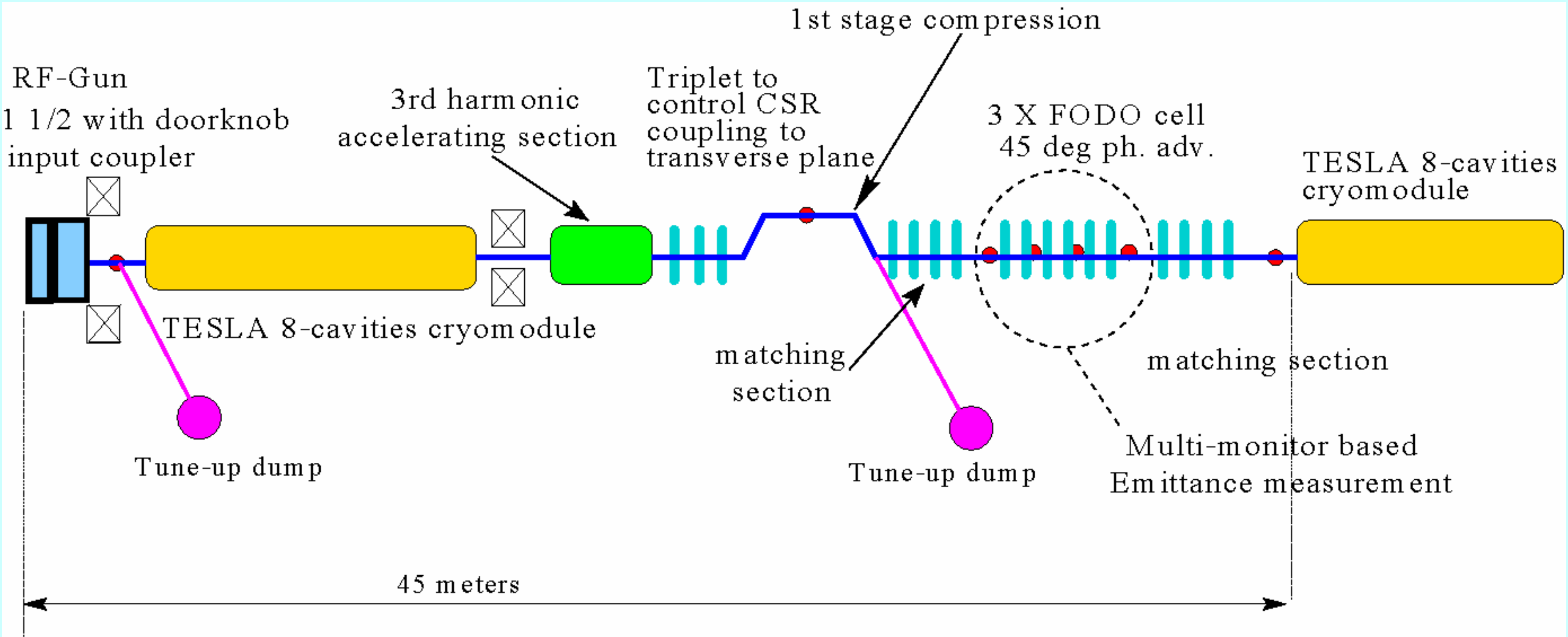
feasible only at ultrarelativistic energies, otherwise ruins emittance ⇒ bunch compressor

What are the challenges? RF gun

TESLA FEL photoinjector for small and short electron bunches

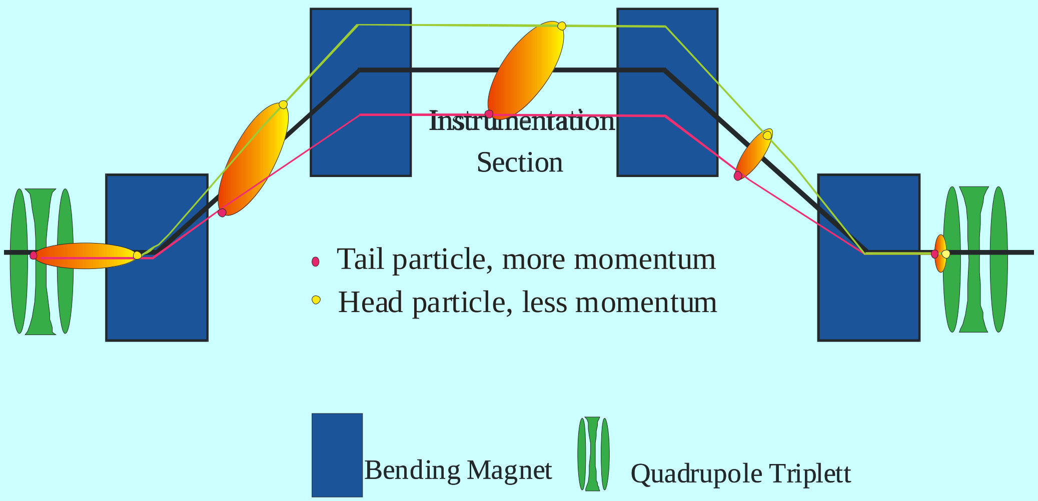


Layout of integrated injector/compressor for TTF2 and TESLA FEL



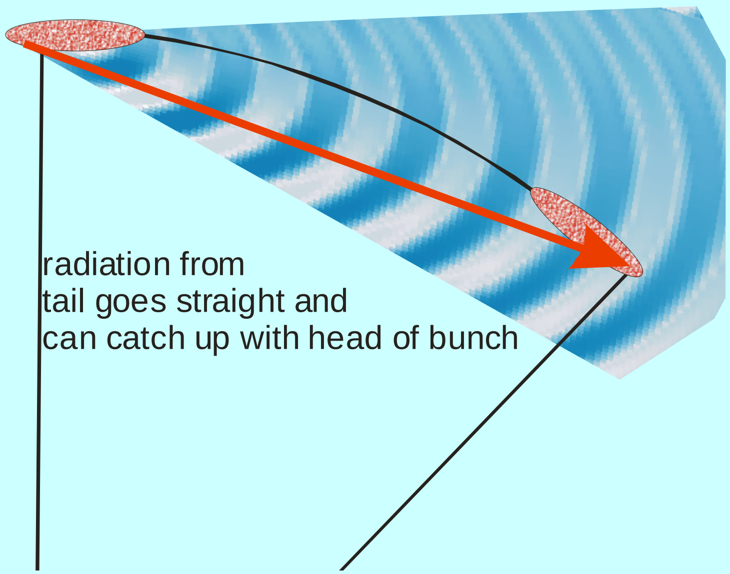
What are the challenges? Bunch compression

Magnetic bunch compression



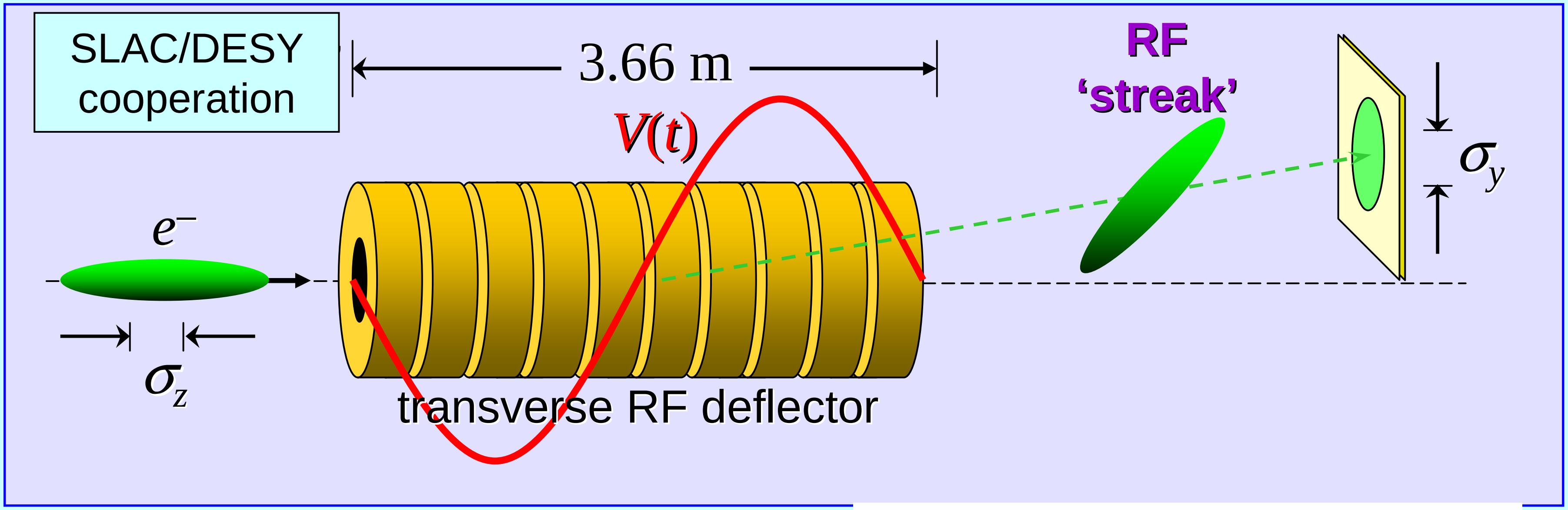
Beware of
coherent synchrotron radiation (CSR)

very powerful microwave radiation
with λ >~ bunch length if
bunch length << size of vacuum chamber

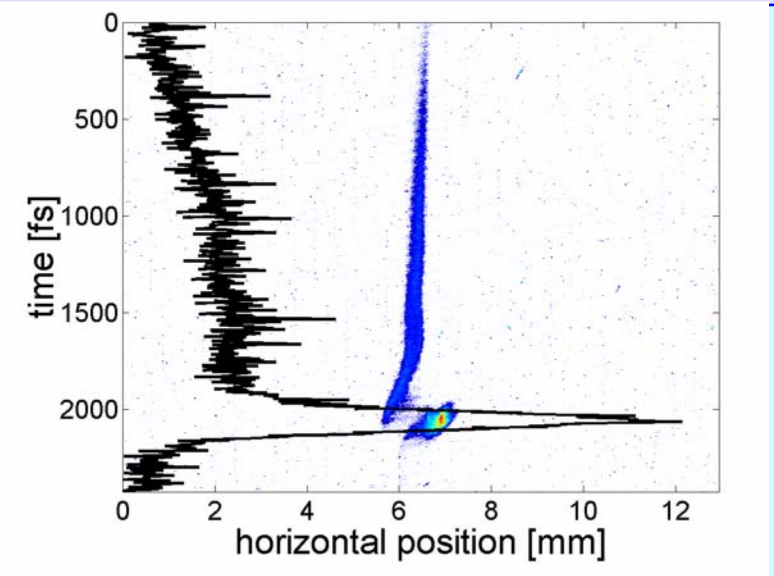


Beam dynamics simulation must take into account combined space charge and e.m. radiation in near-field. e.g.: TRAFIC4 by A. Kabel/SLAC

How to measure 100 μm bunch length ?



Deflecting RF structure from SLAC is used as an oscilloscope

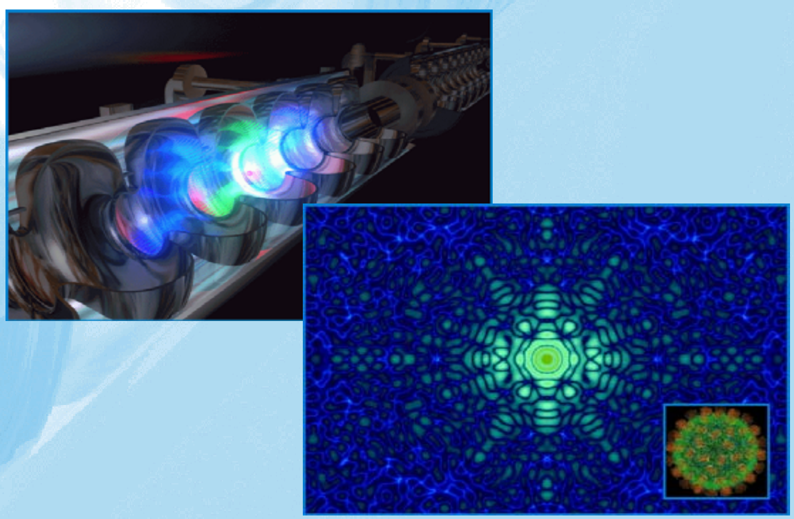


TESLA XFEL

First Stage of the X-Ray Laser Laboratory

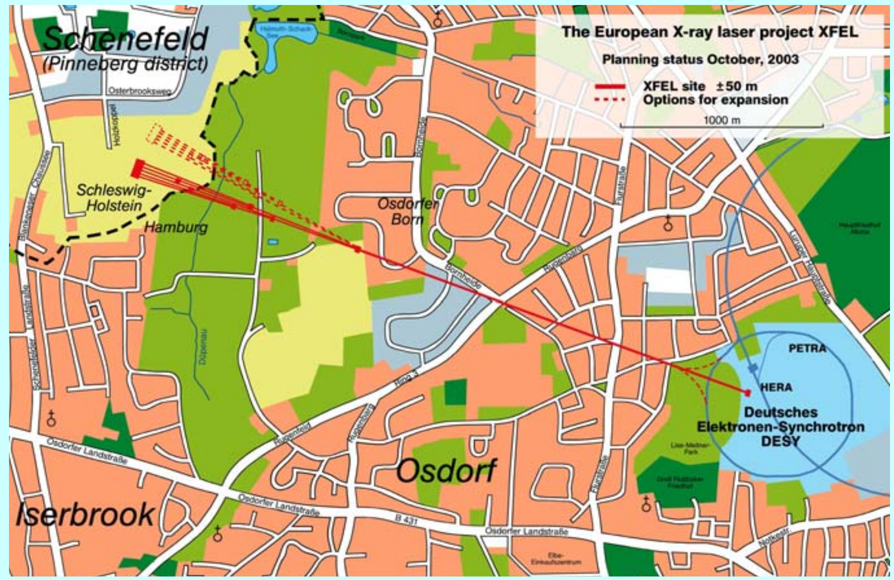
Technical Design Report

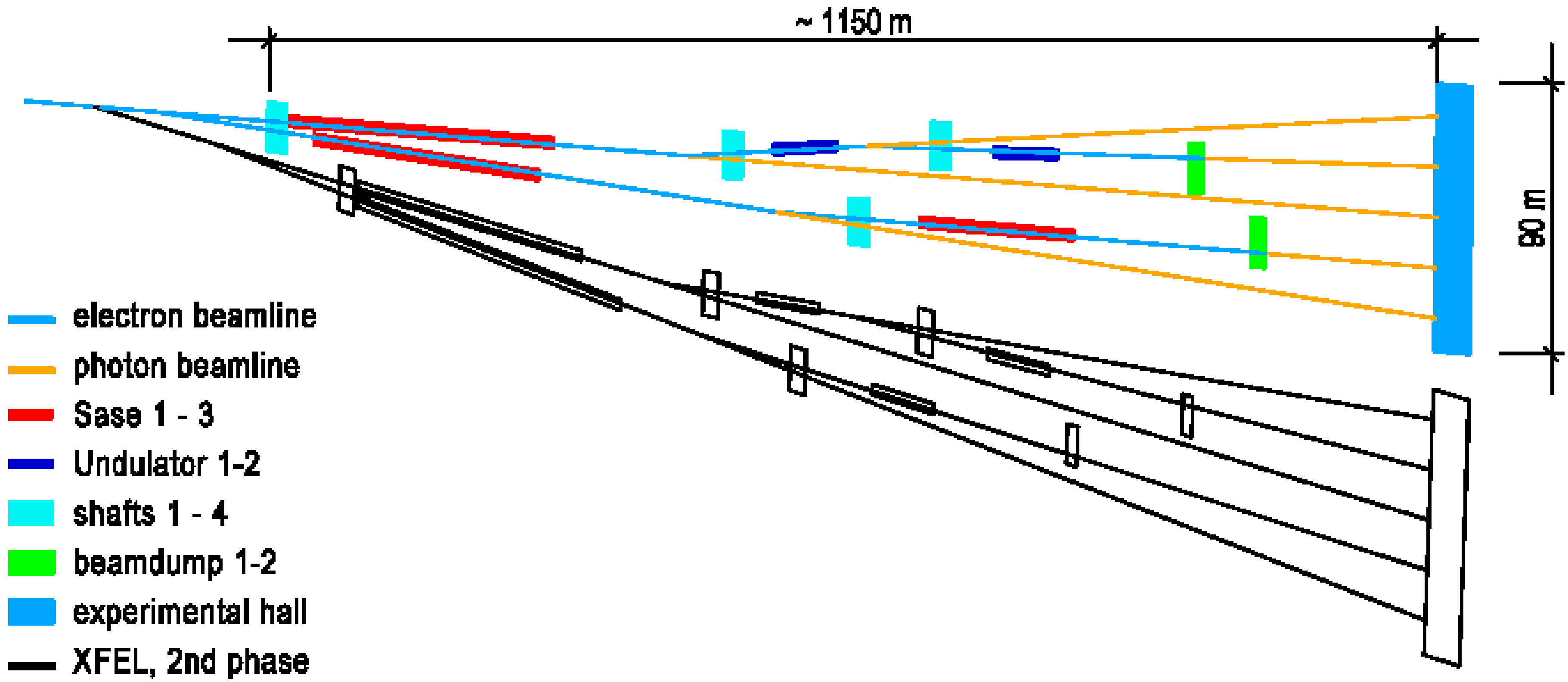
Supplement



October 2002

Over-all layout of the European XFEL at DESY





Phase 1:	Phase 2:
20 GeV s.c. accelerator 10 experimental stations	2 more FELs 3 more undulators for spont. rad. 10 more experimental stations

Bundesministerium
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und Forschung

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Presse-
mitteilung

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- A new free electron laser is to be built at the DESY research centre in Hamburg. In view of the locational advantage, Germany is prepared to cover half of the investment costs amounting to €673 million. Talks on European cooperation will soon start so that it will be possible to take a decision on construction within about two years.The construction period will be approximately six years.

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References:

Low gain FELs:

1. K. Wille: Introduction to accelerator physics

2. J.B. Murphy, C. Pellegrini:
   Introduction to FEL physics in: Laser Handbook Vol. 6 (North Holland)

High gain FELs:

3. E. Saldin, E. Schneidmiller, M. Yurkov: The Physics of FELs, Springer Verlag

4. J.B. Murphy, C. Pellegrini, in: Laser Handbook Vol. 6:
   Introduction to the physics of the FEL

5. S. Reiche/UCLA: GENESIS1.3, available via internet

6. L. Gianessi: PERSEO (MATHCAD package) c/o gianessi@frascati.enea.it

Radiation code:

T. Shintake, SPring8: http://www-xfel.spring8.or.jp

Potential subjects for PhD work related to FELs

1. a) Bunch Compression for the European X-ray Free-Electron Laser from 1 mm down to 0.025 mm rms bunch length, including options for „ultra-compression“ (< 10 µm rms bunch length) making use of wake fields.
2. Nonlinear collimator for high energy electrons (for Linear Collider and XFEL; possibly test at SLAC)
3. Measurement and analysis of THz coherent undulator radiation at the VUV-FEL.
4. Mechanism of halo population at the electron beam for X-ray FELs: dark currents, restgas scattering, wake fields, quantum fluctuation,….; measurements at TTF
5. Experimental investigations on the start-up from noise at a VUV-FEL + High Gain Harmonic Generation; dependence on electron beam parameters
6. Investigation on emittance limitations in PETRA III (impact of orbit and spurious dispersion, beam-based alignment, space charge limits,..), including experimental studies at PETRA.
7. Design, construction and test of a laser-wire for measurement of submicrometer electron beam size.
8. Ray tracing of VUV radiation through the monochromator section of the seeding version for TTF FEL
9. 6D phase space tomography (incl. slice emittance measurements) of the electron beam at the VUV-FEL (using LOLA etc.).
10. Transverse beam profile monitor based on incoherent synchrotron radiation. Important for permanent, parasitic, single bunch monitoring. Could be tested after BC3 at VUVFEL.
11. Studies on digital electronics for electron beam position monitors with high single bunch resolution
12. Development of a electron beam position monitor with Sub-Micrometer resolution for the XFEL.
13. Measurement of ultra-short electron bunches using an optical replica technique (collab. Univ. Stockholm)
14. Synchronization of pump&probe laser with electron bunch over large distance; phase monitor, noise models
15. Feedback systems at VUV-FEL and XFEL + FEL stability issues incl. hardware analysis
16. A Photoinjector for the LINAC2 at DESY.
17. Start-to-end electron beam dynamics simulation for the European XFEL.

At electron gun test stand PITZ in DESY Zeuthen:

1. Theoretical studies on electron beam dynamics in the vicinity of the photocathode
2. Design, construction and test of a flat beam electron gun (providing an external collaboration)
3. Cathodes for electron guns: new surface materials, new mechanical design (in collaboration with INFN Milano)
4. Relation between laser parameters and electron beam parameters (experiment and comparison with theory)

Diploma thesis topics:

1. Measurement of magnetic stray fields in the vicinity of pulse transformators and klystrons at TTF2.
2. Computer simulation of ground motion effects on XFEL and Linear Collider based on existing ground motion measuments.
3. Emittance measurement in the high energy section and in the undulator of the VUV-FEL using wire scanners and transition radiation.
4. Measurement of quantum efficiency of used semiconductor cathodes. (at PITZ/DESY-Zeuthen in collaboration with INFN Milano)
5. Re-write Trafic4 code
6. Transmission properties of an optical transfer channel in the near infrared to THz spectral range used for bunch length analysis at the VUV-FEL at DESY.
7. Low Level RF control for the superconducting third harmonic (3.9 GHz) buncher cavity for the VUV-FEL
8. Slice emittance measurements using a transverse deflecting mode RF cavity at the VUV-FEL.
9. Measurement of transverse beam size using synchrotron radiation in bunch compressor magnets.

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