Universität Hamburg

Free-Electron Laser

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- Motivation & Basics
- Technology
- Results

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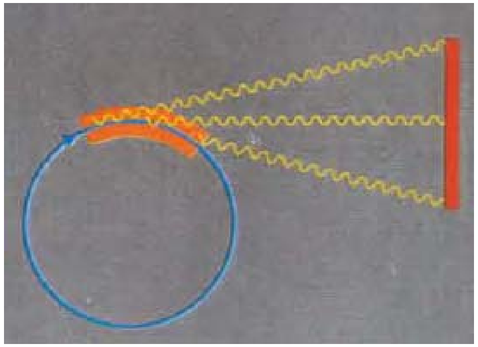
Electron Accelerators as Light Sources

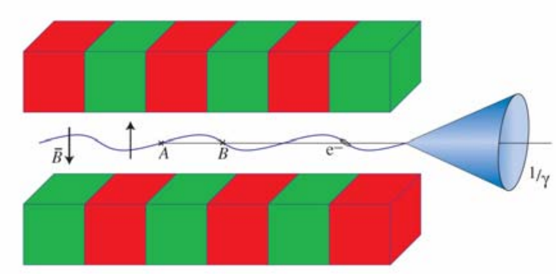
a)



Electron storage ring with bending magnets:

- continuous spectrum
- wide angular distribution

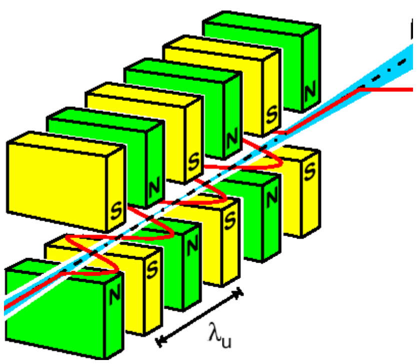
b)



Undulator radiation:

- (almost) monochromatic
- narrow angular distribution

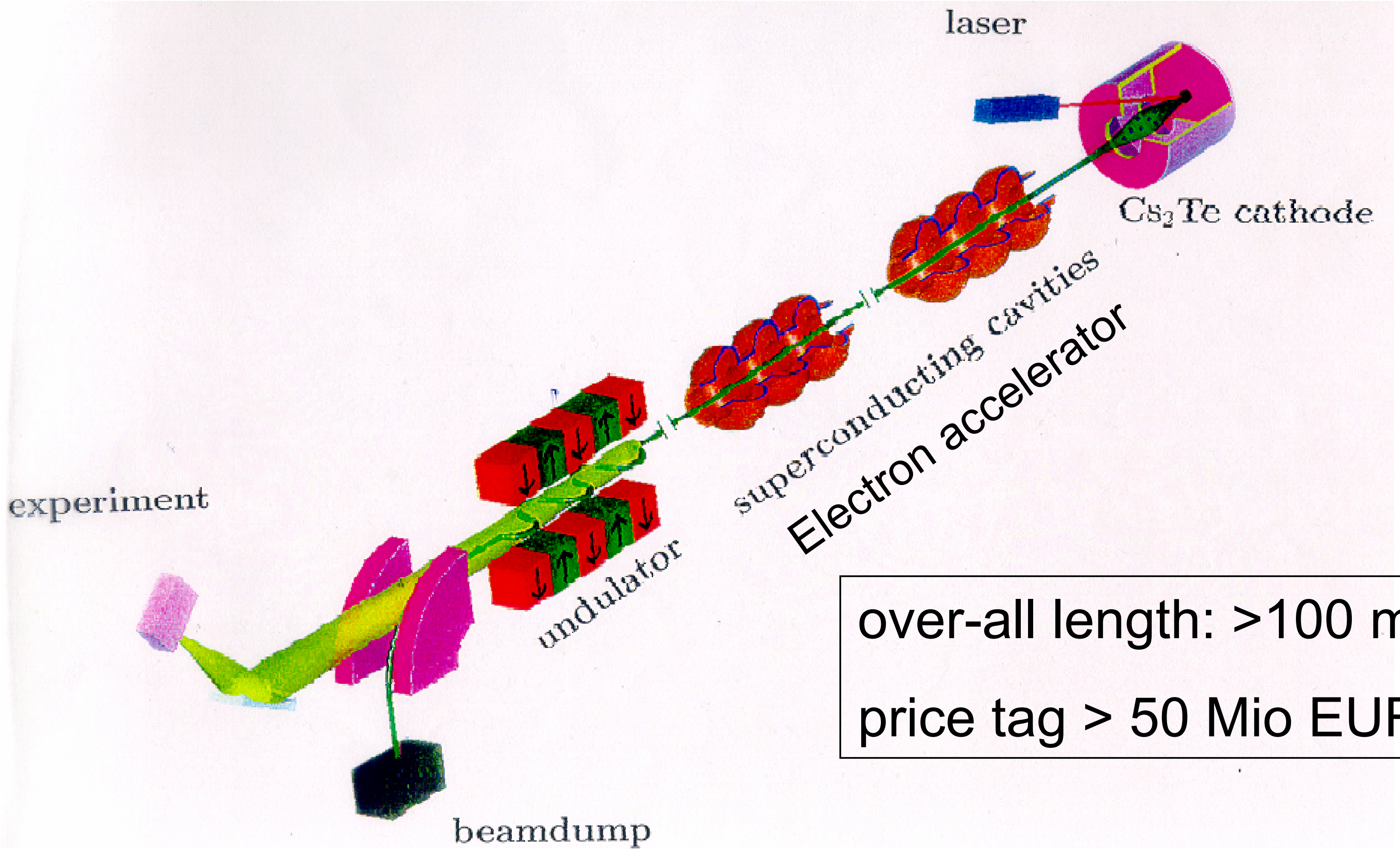
c)



Free-Electron Laser (FEL):

- narrow spectral line
- transverse coherence
- powerful: $I_N = N^2 \cdot I_1$

Schematic of a high-gain Free-Electron Laser (FEL)



over-all length: >100 m

price tag > 50 Mio EUR

Why SASE FELs?

SASE = Self-Amplified Spontaneous Emission

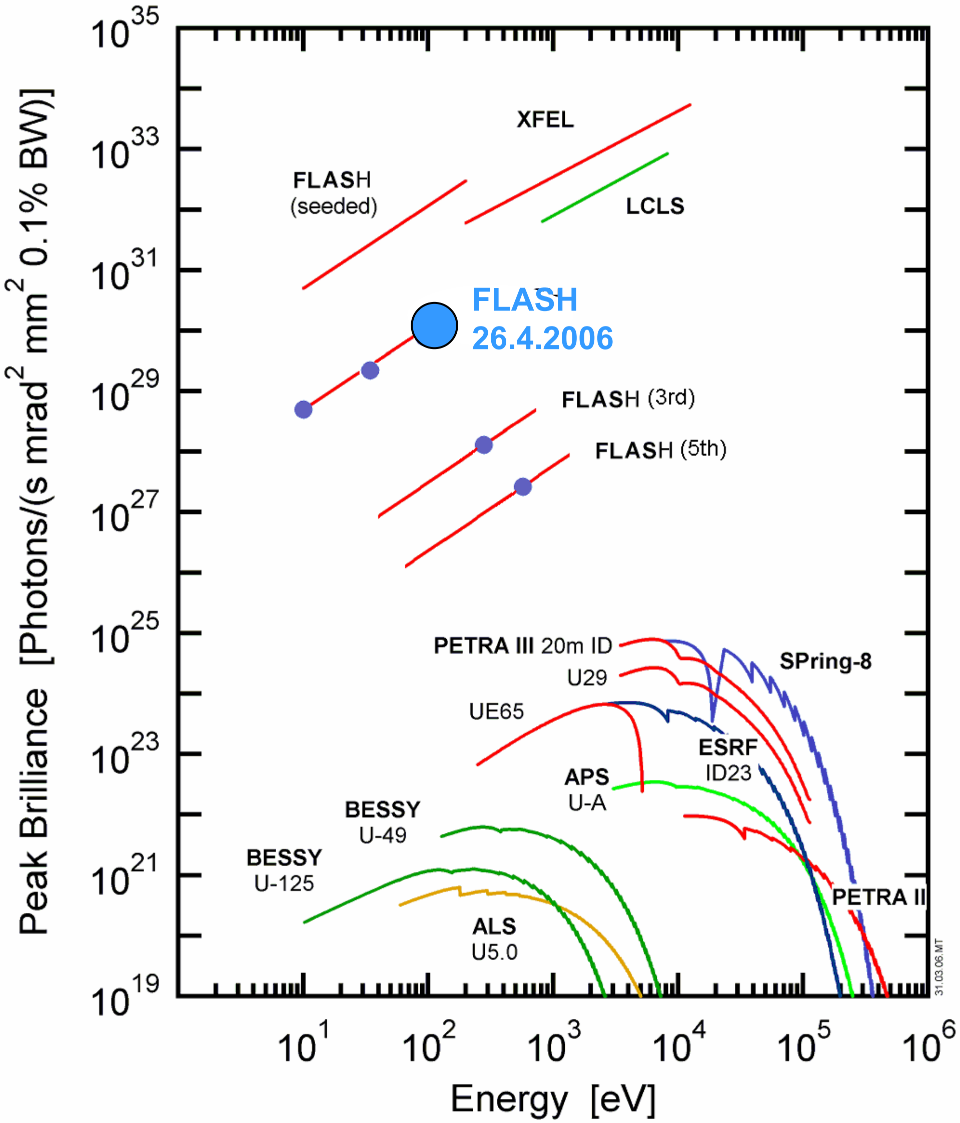
Brilliance:

No. of photons

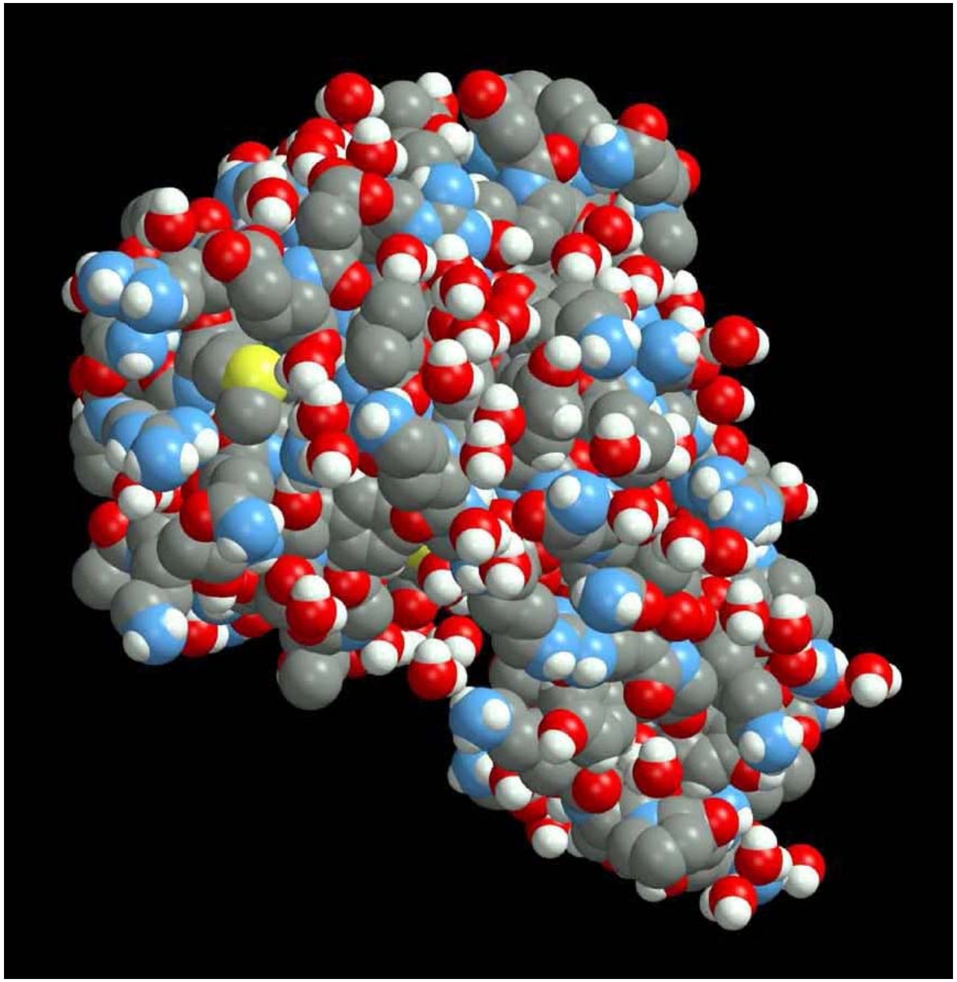
- per second
- per cross section of the radiating source
- per opening angle of radiation

This is the figure of merit for all experiments involving

- **diffraction**
- **very fast processes**



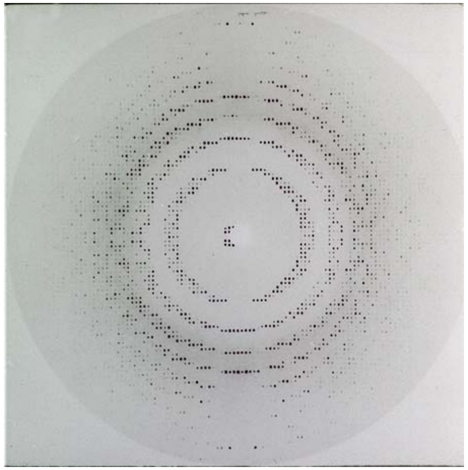
Why SASE FELs?



LYSOZYME , MW=19,806

State of the art:
Structure of biological macromolecule

reconstructed from diffraction pattern of protein crystal:



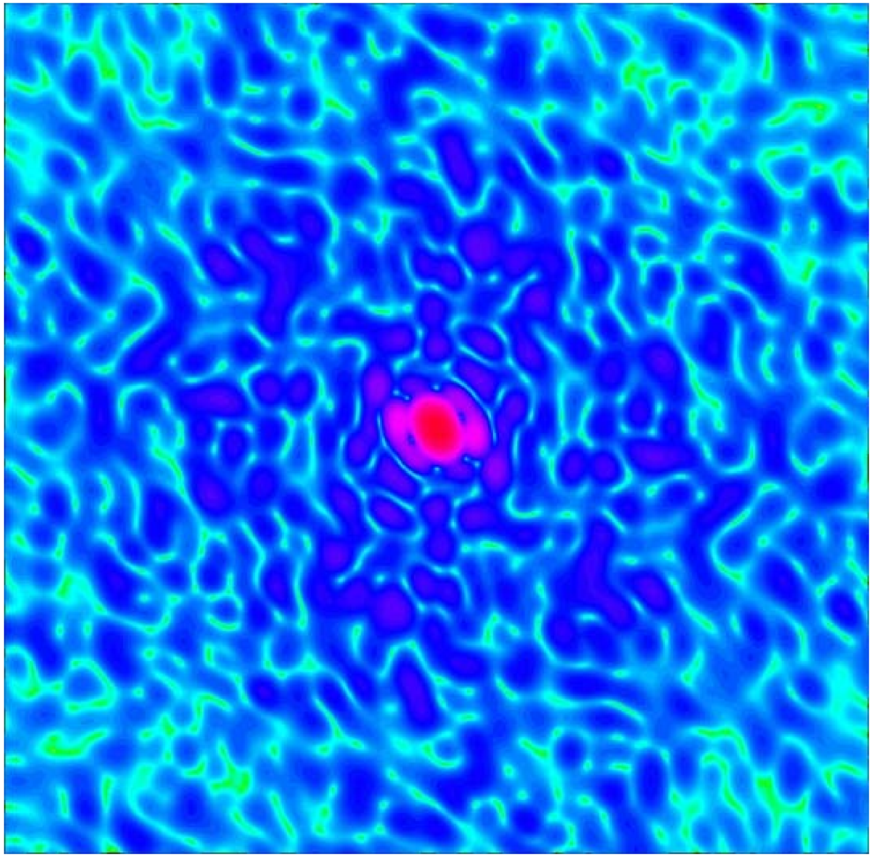
Needs ≈10^{15} samples

Crystallized → not in life environment

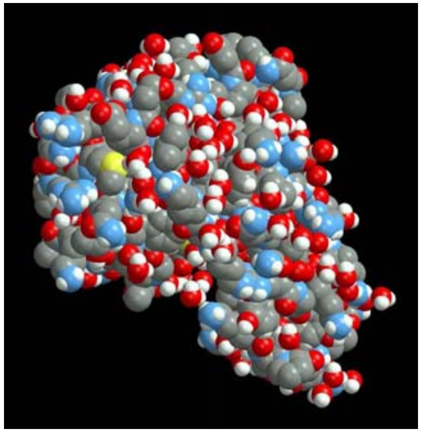
The crystal lattice imposes restrictions on molecular motion

Images courtesy Janos Hajdu

Why SASE FELs?



courtesy Janos Hajdu



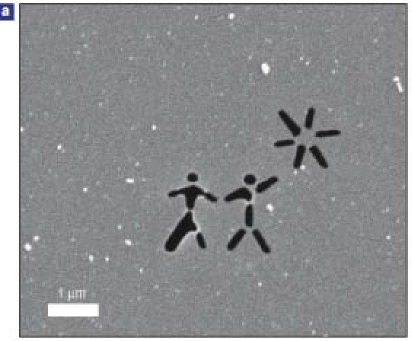
SINGLE MACROMOLECULE,
Planar section, simulated image

Resol. does not depend on sample quality

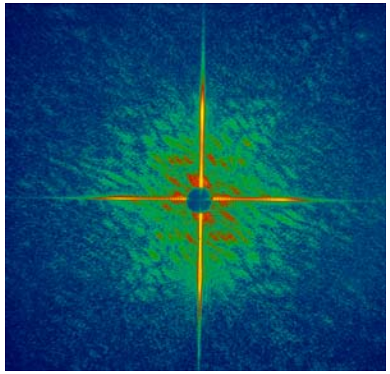
Needs very high radiation power @ $\lambda \approx 1$Å

Can see dynamics if pulse length < 100 fs

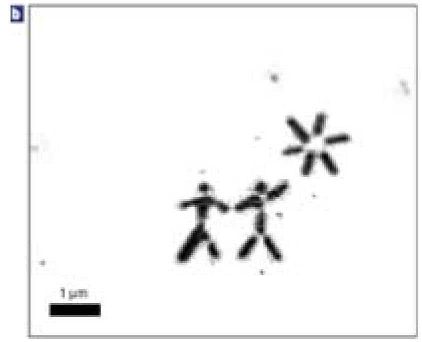
Why SASE FELs?



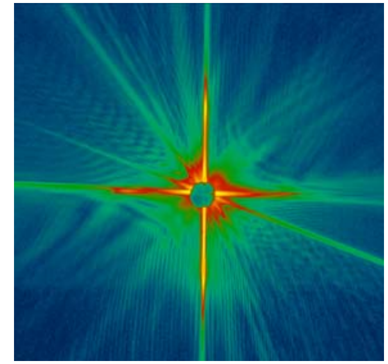
Object



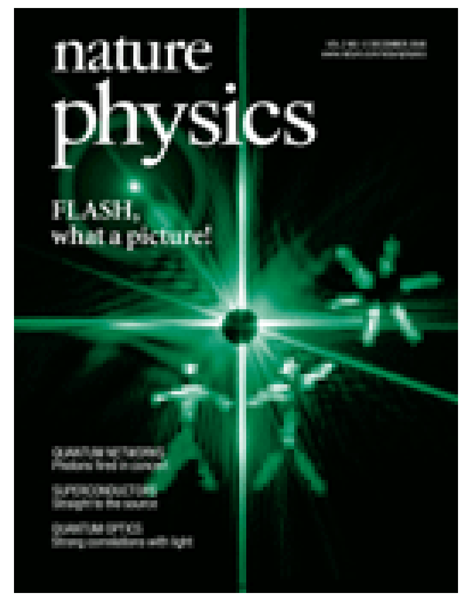
Single pulse diffraction reveals structure before radiation damage occurs



Reconstructed from diffraction pattern



2nd pulse: object destroyed



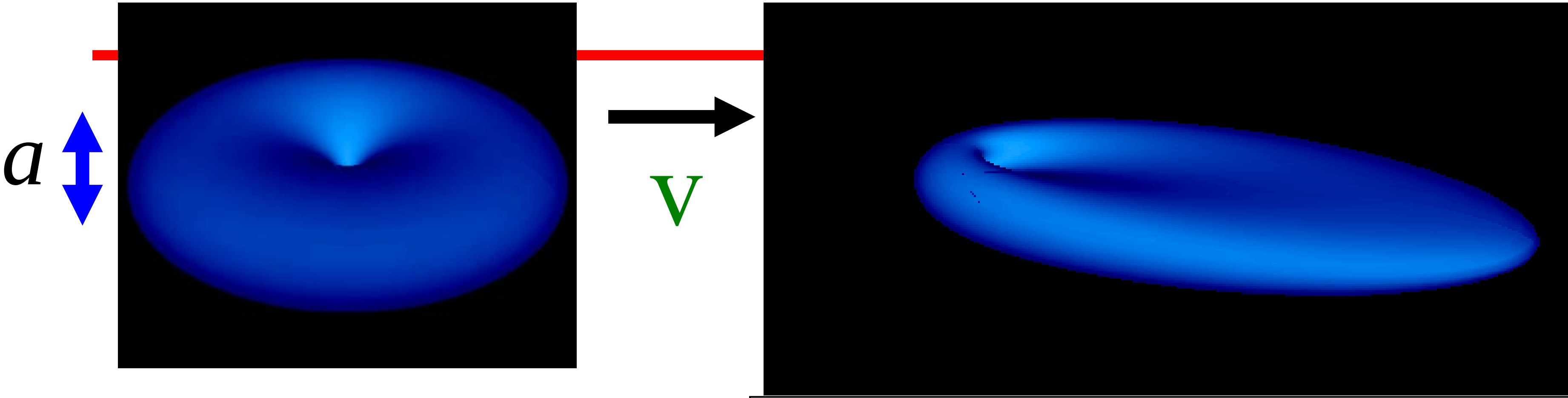
Why SASE FELs?

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

These are, typically, laser properties.
For wavelengths below ~100 nm: SASE FELs.

Basics: 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

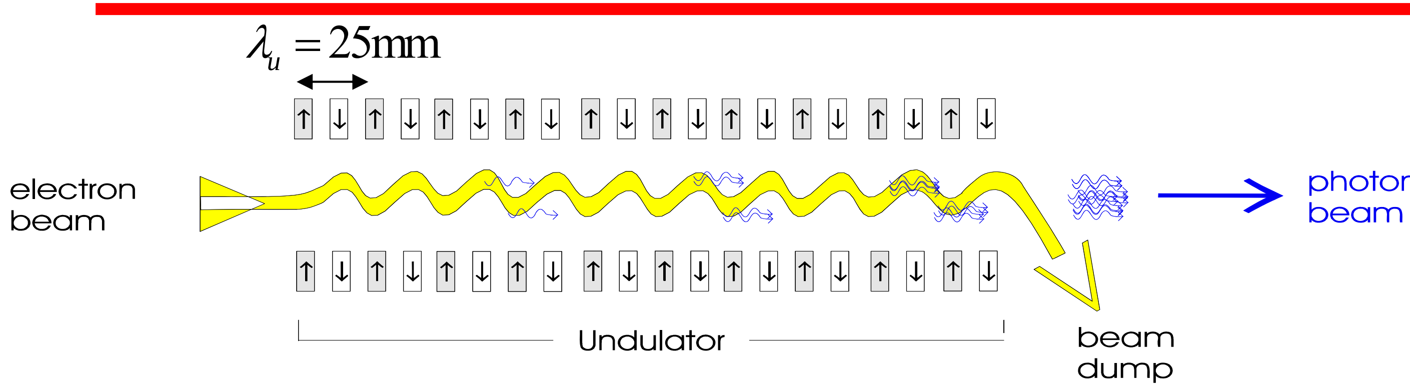
$$\gamma = \frac{E}{m_0 c^2}$$

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

We gain a factor of γ^4 in power!

note the quadratic dependence on charge!

Undulator Radiation



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

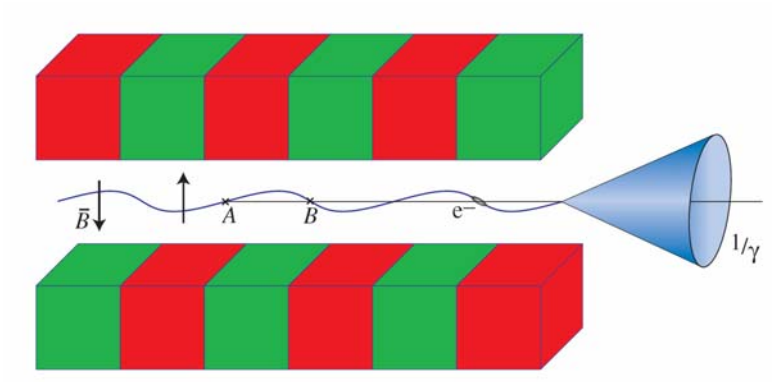
1) Moving coordinate system (*):

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

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

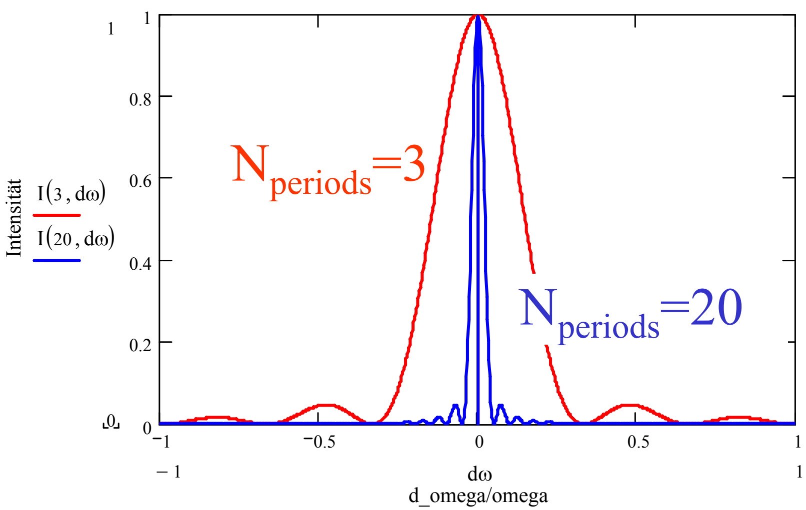
$$\lambda_{lab} = \frac{\lambda_u^*}{\gamma(1+\beta)} \approx \frac{\lambda_u}{2\gamma^2}$$

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



Undulator radiation is emitted into narrow cone:

Opening angle $\approx \dfrac{K}{\gamma}$



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!

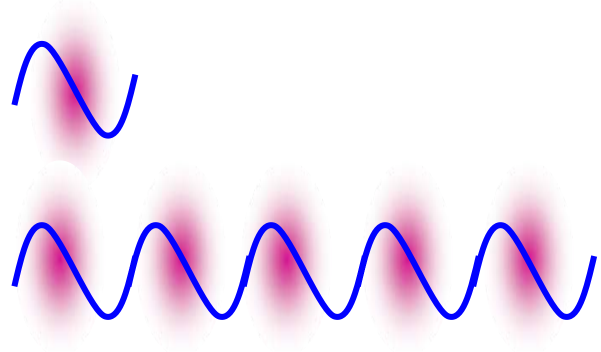
If Q consists of many particles, this requires that all charges are concentrated within distance λ !

→ FREE-ELECTRON LASER

→ desired: bunch length < wavelength

OR (even better)

Density modulation at desired wavelength



→ Potential gain in power: $N_e \sim 10^6$!!

FEL Basics

Idea:

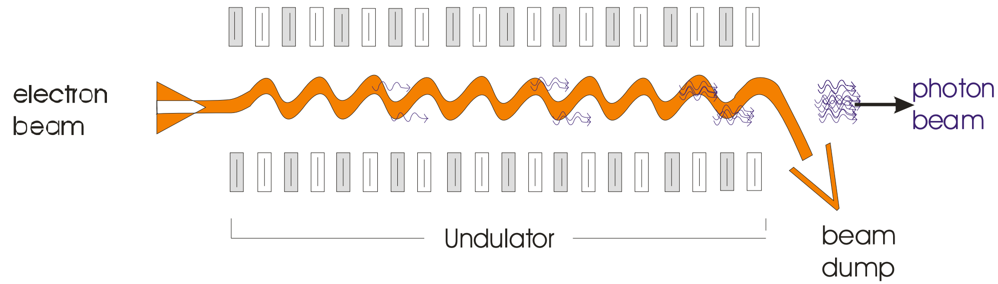
Start with an electron bunch much longer than the desired wavelength
and find a mechanism that cuts the beam into equally spaced pieces automatically

Free-Electron Laser (Motz 1950, Phillips ~1960, Madey 1970)

Special version: starting from noise (no input needed)
Single pass saturation (no mirrors needed)

Self-Amplified Spontaneous Emission (SASE)

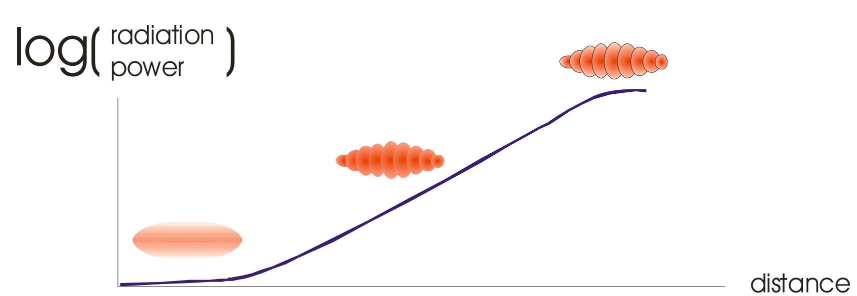
(Kondratenko, Saldin 1980)
(Bonifacio, Pellegrini 1984)



Resonance wavelength:

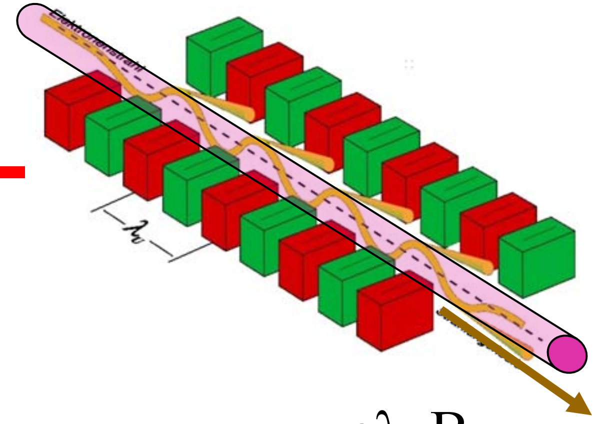
$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Undulator parameter ≈ 1



Coherent motion is all we need !!

Basic theory of FELs



Step 1: Energy modulation

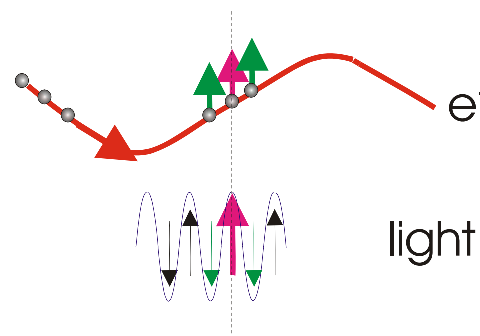
A: Electron travels on sine-like trajectory

$$v_x(z) = c\frac{K}{\gamma}\cos\left(\frac{2\pi}{\lambda_u}z\right)$$, with undulator parameter: $$K = \frac{e\lambda_u B}{2\pi m_e c}$$

B: External electromagnetic wave moving parallel to electron beam:

$$E_x(z,t) = E_0\cos(k_L z - \omega_L t)$$

Change of energy W in presence of electric field:



$$\frac{dW}{dz} = \frac{q}{v_z}\vec{v}\vec{E} = -\frac{qE_0 K}{\gamma\beta_z}\sin\Psi,$$

with the ponderomotive phase: $\boxed{\Psi = (k_u + k_L)z - \omega_L t + \varphi_0}$

Note: $\cos\alpha\cdot\cos\beta = \frac{1}{2}\cos(\alpha+\beta) + \cancel{\frac{1}{2}\cos(\alpha-\beta)} = \frac{1}{2}\sin(\alpha+\beta+\pi/2)$

Basic FEL theory

$$\boxed{\frac{dW}{dz} = -\frac{qE_0 K}{\gamma\beta_z}\sin\Psi}$$

$$\Psi = \left(k_u + k_L\right)z - \omega_L t + \varphi_0$$

The energy *dW* is taken from or transferred to the radiation field.
For most frequencies, *dW/dz* oscillates very rapidly.

Continuous energy transfer ?

Yes, if Ψ constant.

$$\rightarrow \quad \frac{d\Psi}{dz} = 0 \; ! \quad \rightarrow \quad \mathrm{k_u} + k_L - \frac{k_L}{\beta_z} = 0$$

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

Note: Same equation as for wavelength of undulator radiation.

→ Energy modulation inside electron bunch <u>at optical wavelength !</u>

Basic FEL theory

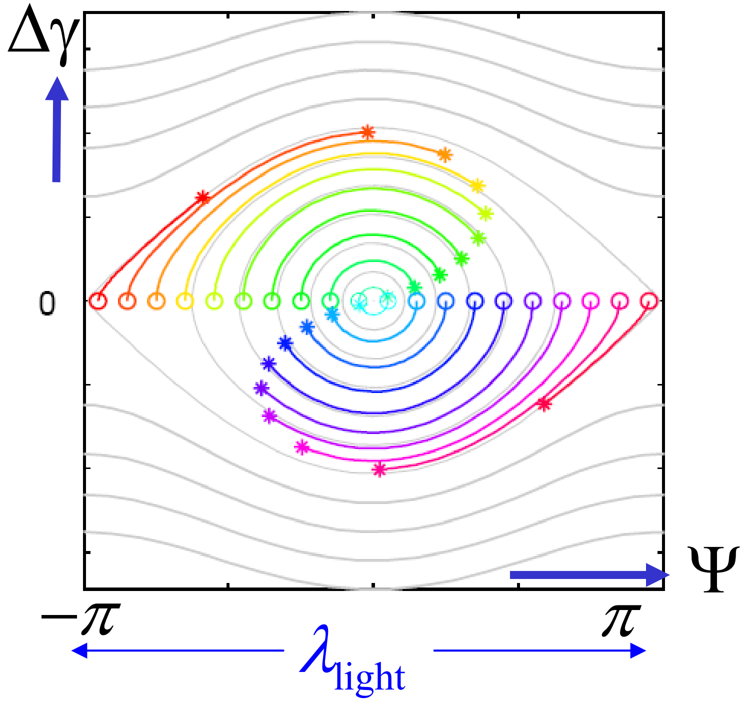
Step 2: Current modulation

Energy modulation by $\Delta\gamma$ leads to change of Phase Ψ:

$$\boxed{\frac{d\Psi}{dz} = k_u \frac{2}{\gamma_{res}} \Delta\gamma}$$

Combined with Step 1: $\frac{dW}{dz} = -\frac{qE_0 K}{\gamma\beta_z} \sin\Psi$ yields

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

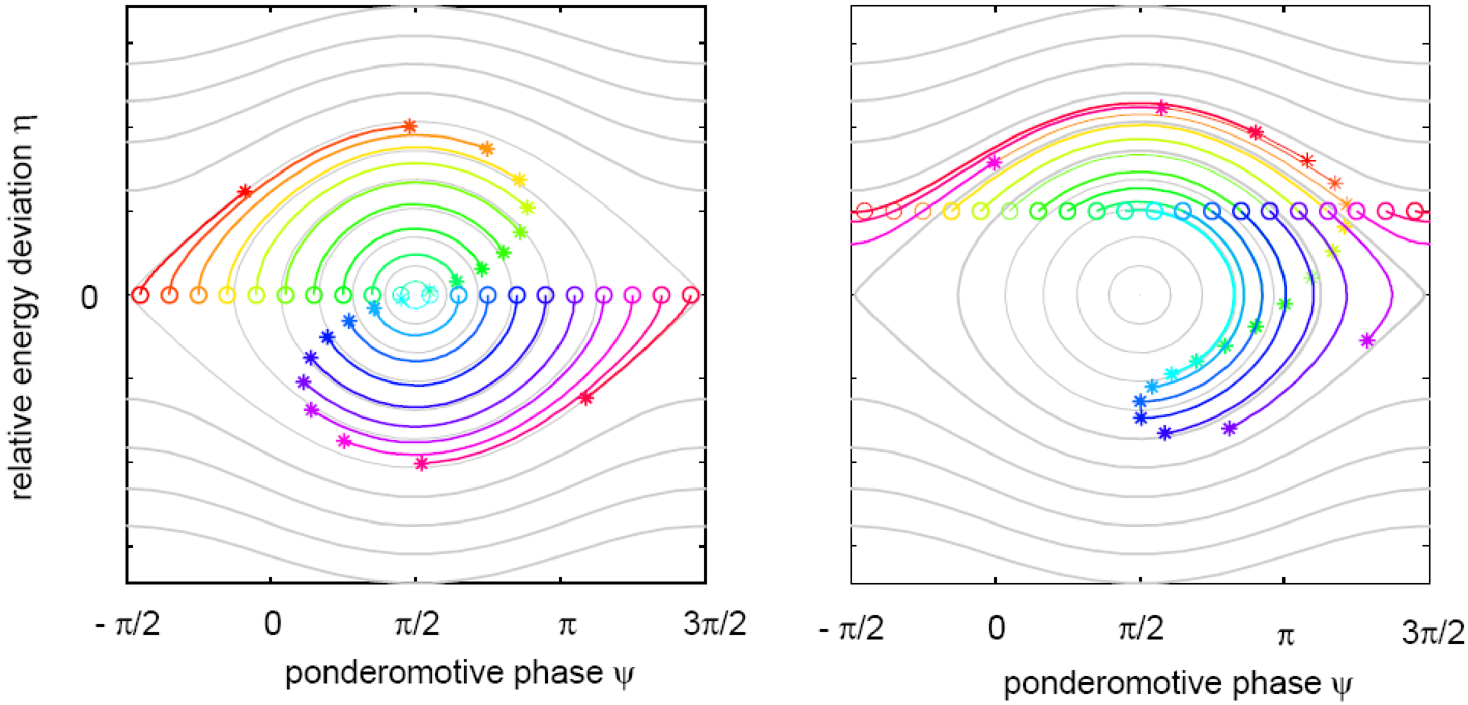


like synchrotron oscillation

-- but at spatial period λ_{light}

→ current modulation !!

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



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

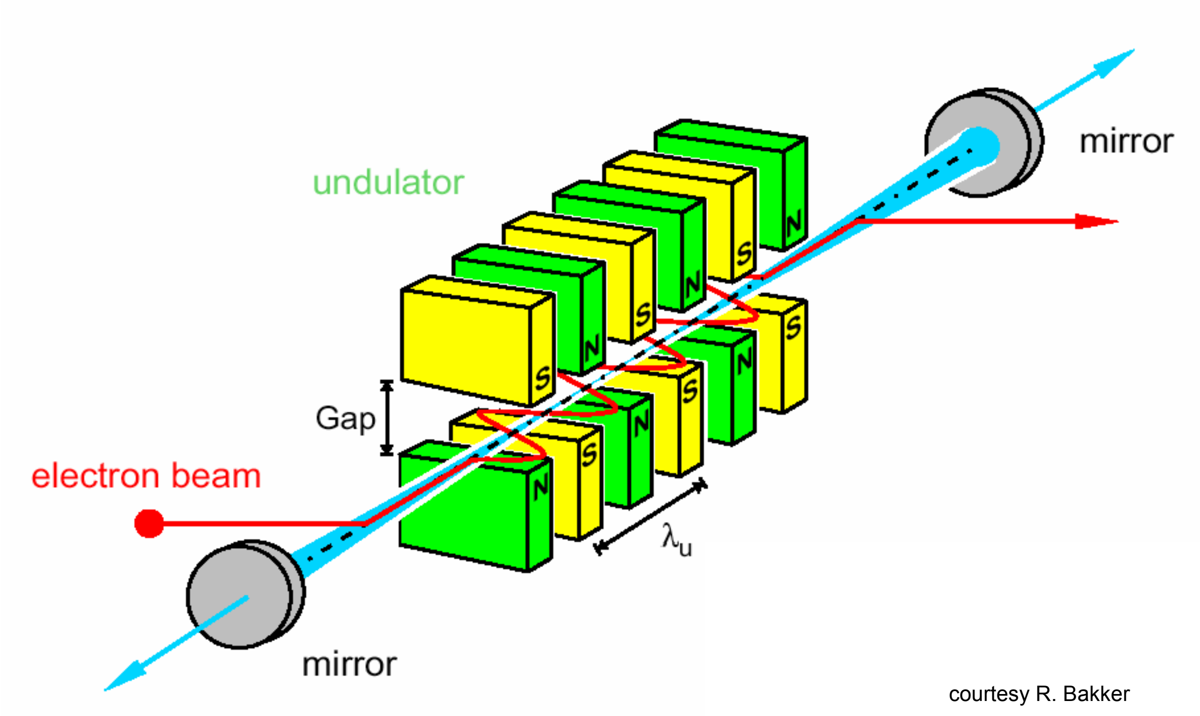
$$G_i = \frac{\text{gain of field energy produced by electron } i}{\text{total field energy}} \rightarrow \text{ requires solution of pendulum equation for } \gamma(z).$$

Real beam may have well defined energy, but all phases are equally probable!

→ Need to average gain for fixed energy Δγ over all phases

The “low gain” FEL

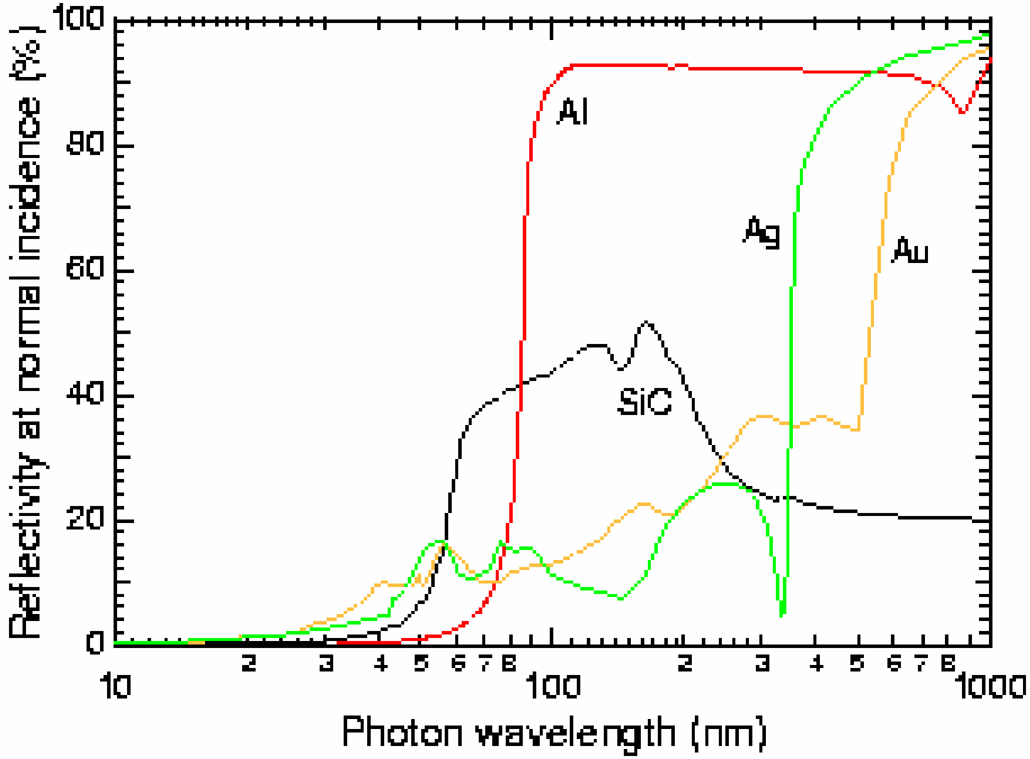
For many FELs, it is sufficient to have only a few % power gain (low gain FEL). Using a pair of mirrors, one can multiply the gain, if on each round trip of radiation there is a fresh electron bunch available.
After N round trips, $G_{total} = G^N$, which can be a very big number.



courtesy R. Bakker

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

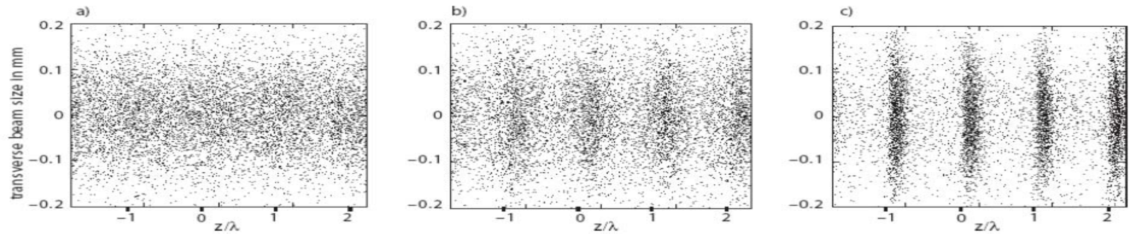
Very nice scheme.
But what if we want wavelength < approx. 100nm where no good mirrors exist?



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

High gain FEL =

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



Step 3: Radiation

Current modulation j_{Light} drives radiation of light:

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

Approximation: field growth slow compared to $1/\omega_{Light}$

$$\boxed{\frac{dE_{Light}}{dz} \approx \text{const} \cdot j_{modulation}}$$

System of Diff. Eqs. defines **High Gain FEL:**

(To be solved numerically for given distribution of electrons)

$$\frac{d}{dz}\begin{pmatrix}\Delta\gamma \\ \psi \\ E_{Light}\end{pmatrix} = \begin{pmatrix} -\dfrac{qE_{Light}K}{m_e c^2 \gamma_{res}^2}\,\mathbf{sin}\,\Psi \\ k_u \dfrac{2}{\gamma_{res}}\Delta\gamma \\ \text{const}\cdot j_{modulation}\end{pmatrix}$$

Energy modulation

Density modulation

Radiation

Analytical Theory of High-gain FEL

Ansatz: $\mathrm{j(z)} = \mathrm{j}_0 + j_1(z)\cos(\Psi + \psi_0)$

i.e. we assume a density modulation at the optical wavelength

Maxwell Eq. combined with Vlasov Eq. results in a linear integro-differential equation for the (complex) electric field amplitude **E(z)** growing with z.

Most simple case: All electrons on resonance energy →

$$\boxed{\frac{\mathrm{d}^3\mathbf{E}}{dz^3} = i\Gamma^3\mathbf{E}} \quad . \quad \text{Ansatz:} \quad \mathbf{E} = A\,\mathbf{exp}(\Lambda z) \quad \rightarrow \quad \Lambda^3 = i\Gamma^3$$

$$\Rightarrow \Lambda_1 = -i\Gamma; \quad \Lambda_2 = \frac{i+\sqrt{3}}{2}\Gamma; \quad \Lambda_3 = \frac{i-\sqrt{3}}{2}\Gamma$$

Abbreviation:

Gain Factor: $\Gamma = \left(\dfrac{\pi j_0 K^2 (1+K^2)\omega_L}{I_A c \gamma^5}\right)^{1/3}$

Alven current: $\mathrm{I_A} = 17\ \mathrm{kA}$

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

All contributions to solution oscillate or vanish, except for:

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:

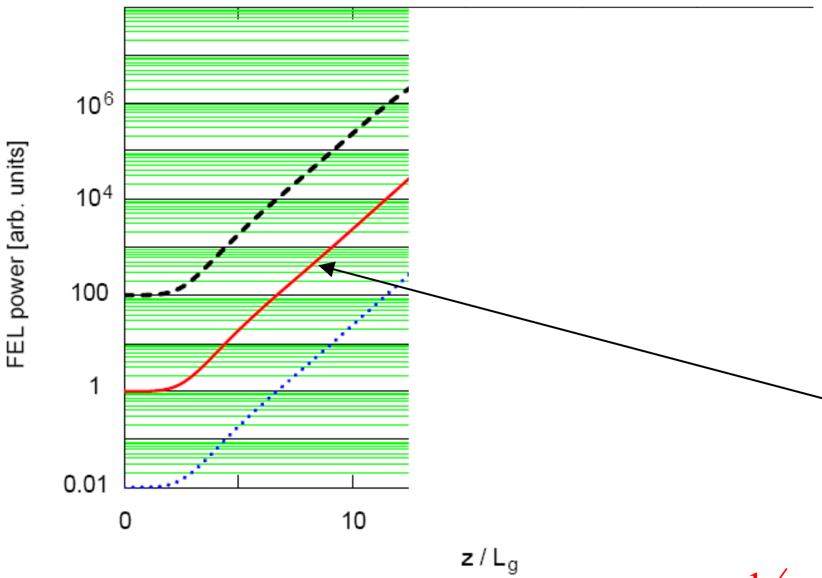
Example: Unmodulated electron beam and e.m. wave at the entrance:

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

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

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

Theory: High-gain FEL



Evolution of radiation power:

$$P_{rad} \propto |\mathbf{E}(z)|^2 \quad \text{with} \quad \mathbf{E}(z) = \frac{1}{3} E_{in} \exp\left(\frac{i + \sqrt{3}}{2} \Gamma z\right)$$

$z >> \Gamma^{-1}$: exponential growth:

$$\boxed{P_{rad} = \frac{1}{9} P_{in} \exp\left(\frac{z}{L_G}\right)} \qquad L_G = \frac{1}{\sqrt{3}} \left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \cdot \hat{I} \cdot K^2} \right)^{1/3}$$

$$L_G \propto (\text{current density})^{-1/3} \qquad \rho_{FEL} = \frac{1}{4\pi\sqrt{3}} \frac{\lambda_u}{L_G} \approx 10^{-4} \ldots 10^{-2}$$

1. Expect exponential gain with e-folding length L_G
   Major additional assumption: Orbit is perfectly straight

2. Gain should saturate when modulation is complete

Why is such a device called a laser?

1. Emission of photons is stimulated by the presence of the electromagnetic field inside the undulator

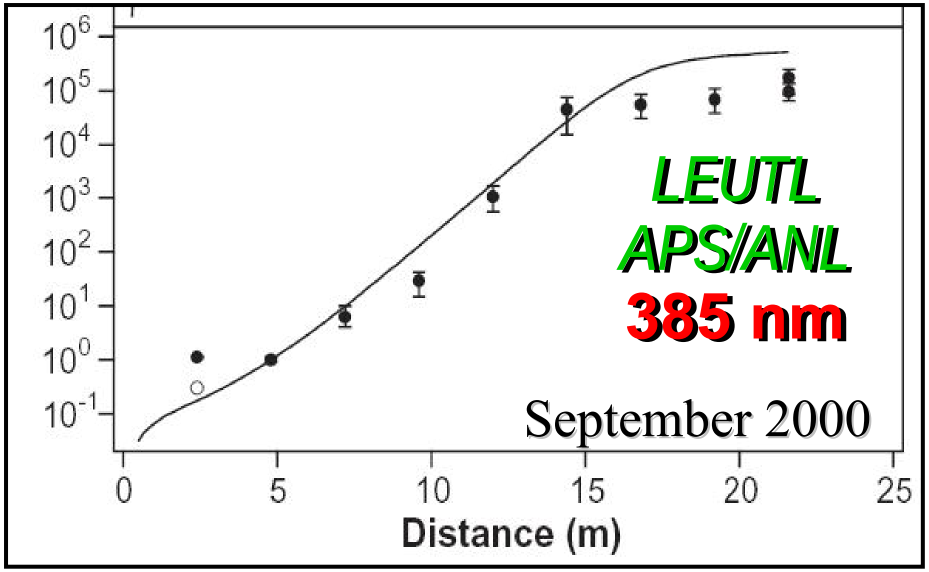
   - electron beam takes the role of active medium

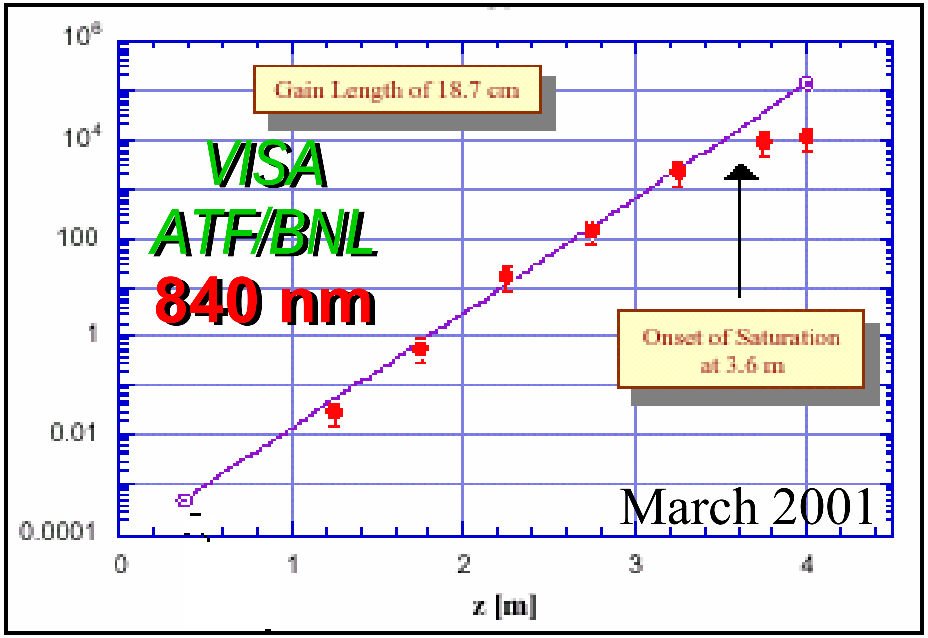
2. Radiation properties are typical for lasers

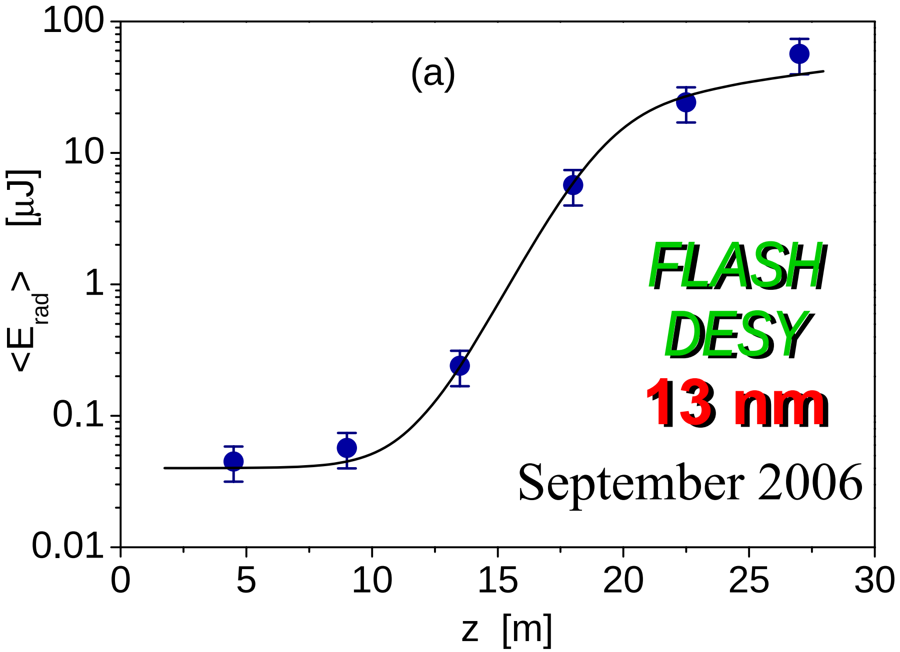
What do we observe ?

High-Gain FELs: State of the art

All observations agree with theor. expectations/ computer models

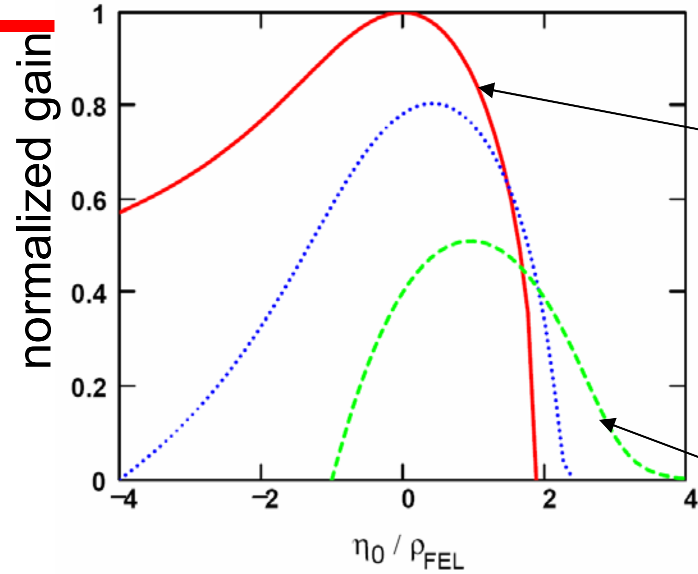






Bandwidth

Gain drops vs.
momentum error $\eta = dp/p$:
(momentum spread σ_η)



$\sigma_\eta = 0$

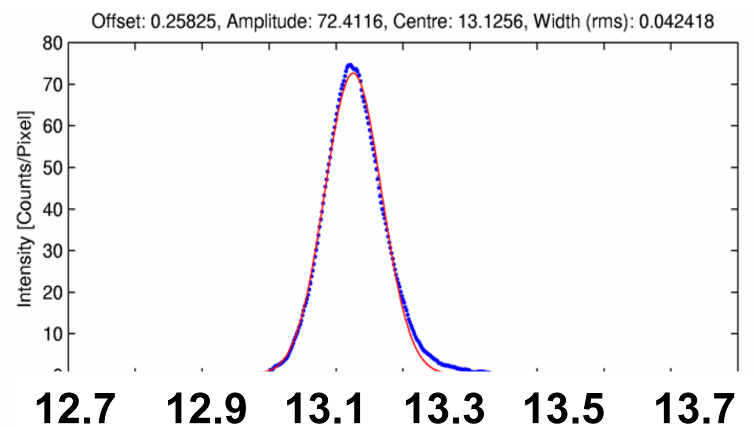
$\sigma_\eta = 0.5\rho_{FEL}$

$\sigma_\eta = 1.0\rho_{FEL}$

FEL is a narrow band amplifier !

FLASH experiment:

Bandwidth agrees with theory



Wavelength [nm]
(1000 shots)

Start-up from noise

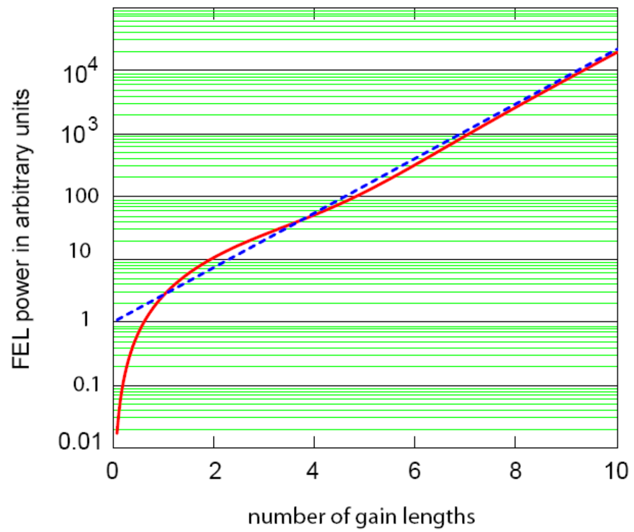
FEL can also start from initial density modulation given by noise.

Equivalent: starting from spontaneous undulator radiation.

Self-Amplified Spontaneous Radiation

SASE

Very robust mode of operation !

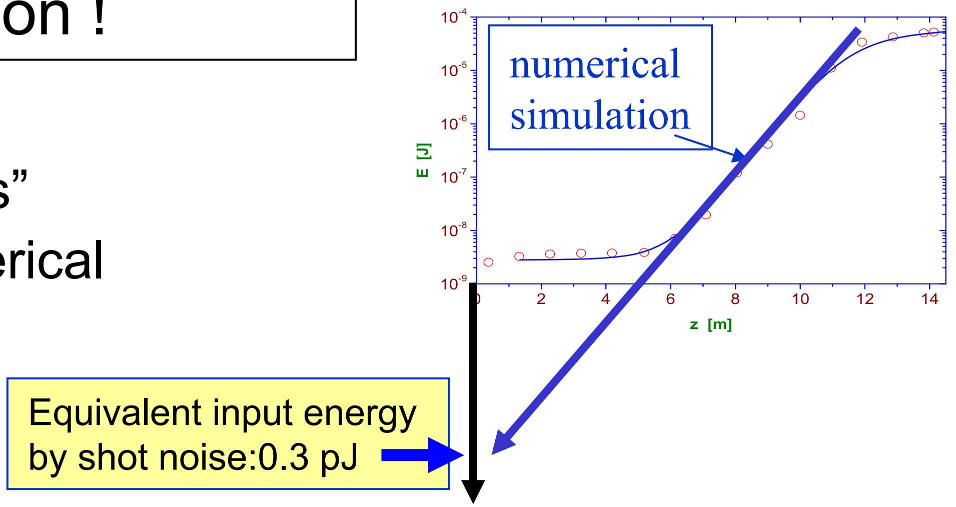


Theory must model shot noise.

Predicts effectiv “initial conditions”

Critical bench mark test for numerical FEL codes, e.g.

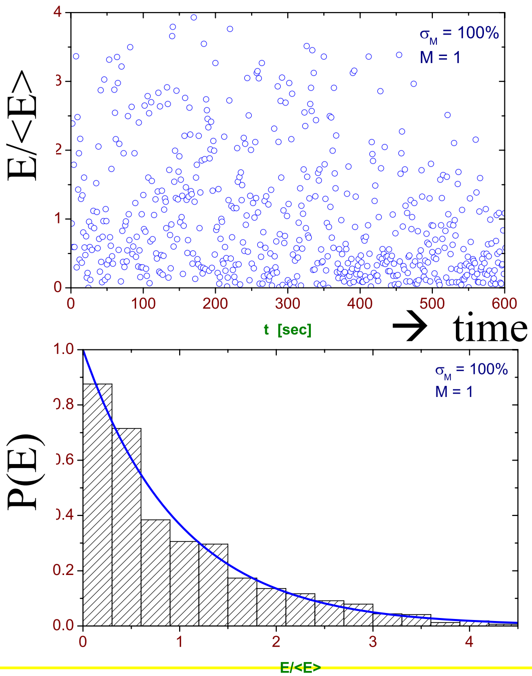
GENESIS (Reiche)



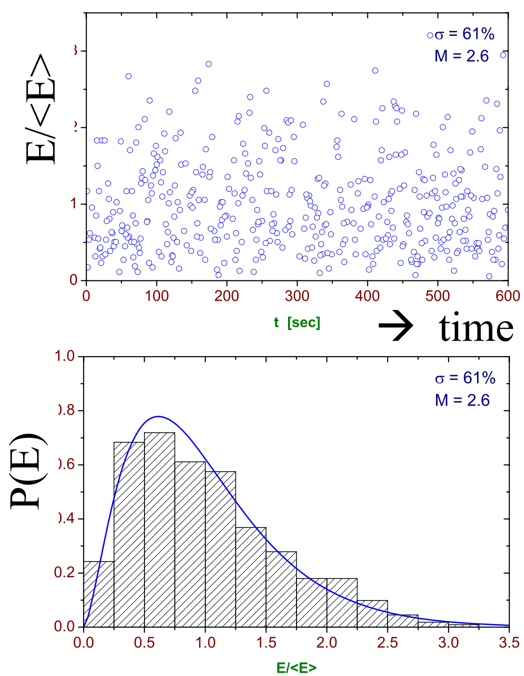
Start-up from noise

SASE output will fluctuate from pulse to pulse,
-- just as ANY part of spontaneous synchrotron radiation does !
Remember: FEL is just an amplifier !

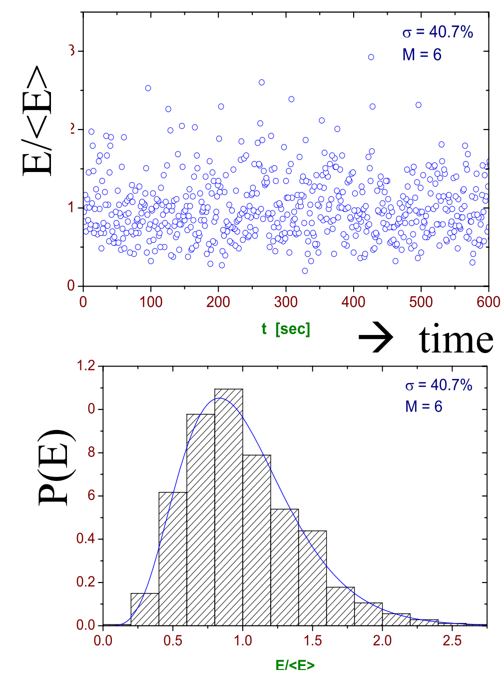
single Mode
(after monochromator slit)



short pulses
M=2.6 modes



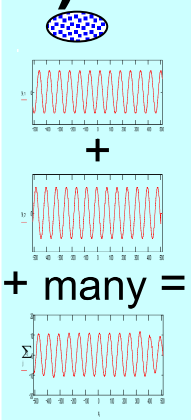
long pulses
M=6 modes



Start-up from noise

Simple 1D model: Superposition of many wavetrains with random phases

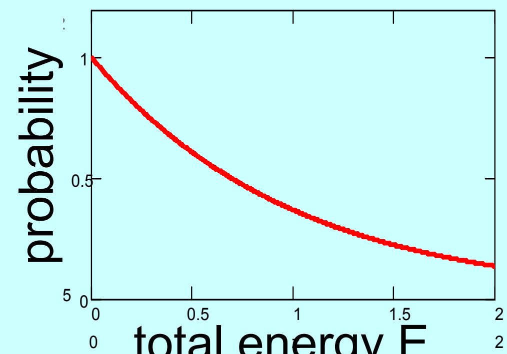
A) Short bunch << wavetrain



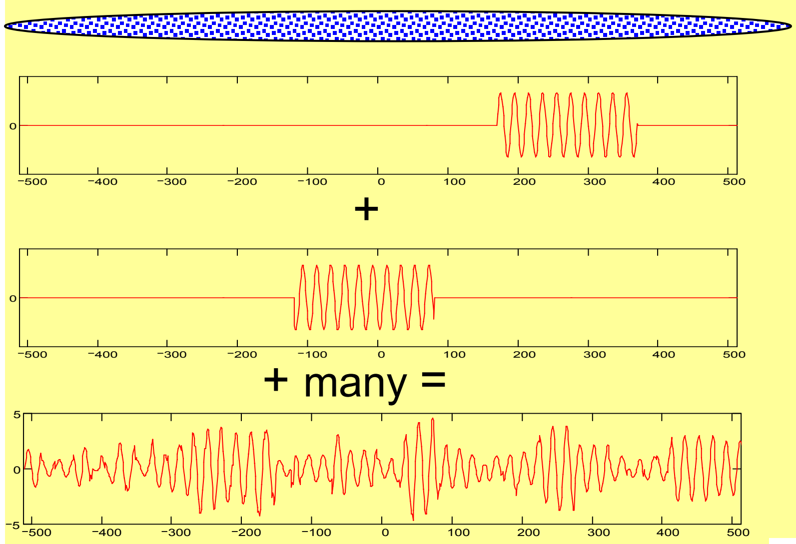
Large probability of destructive interference

"single Mode"

$$P(E)dE = \exp(-E)\,dE$$



B) Bunch length >> wavetrain: ***"many Modes"***

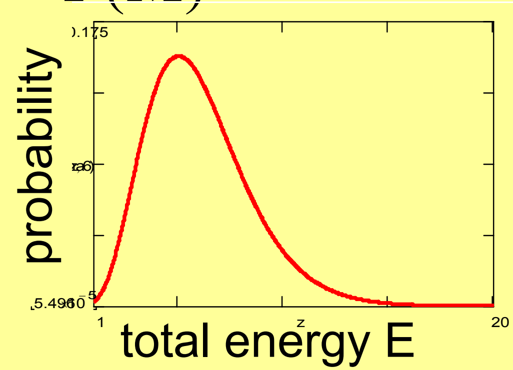


$$g_M(E)\cdot dE = \frac{1}{\Gamma(M)}(E)^{M-1}e^{-E}\cdot dE$$

Extract M from

histrogram

→ pulse length



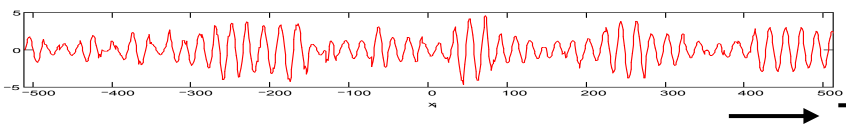
Pulse length

Time-domain measurement of pulse length:

not (yet) available for X-ray (established in the visible, FROG etc.)

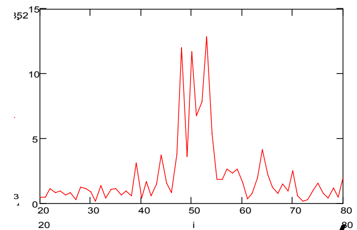
Alternative: intensity fluctuation translates into spectral fluctuation:

Width of frequency spikes ↔ length of pulse



→ T

Fourier



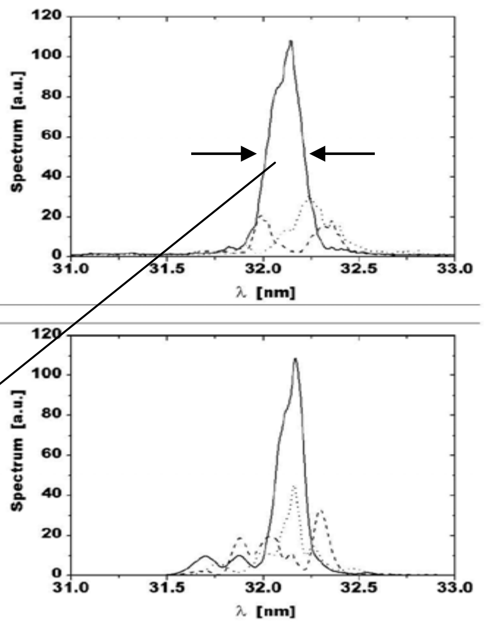
→ ω

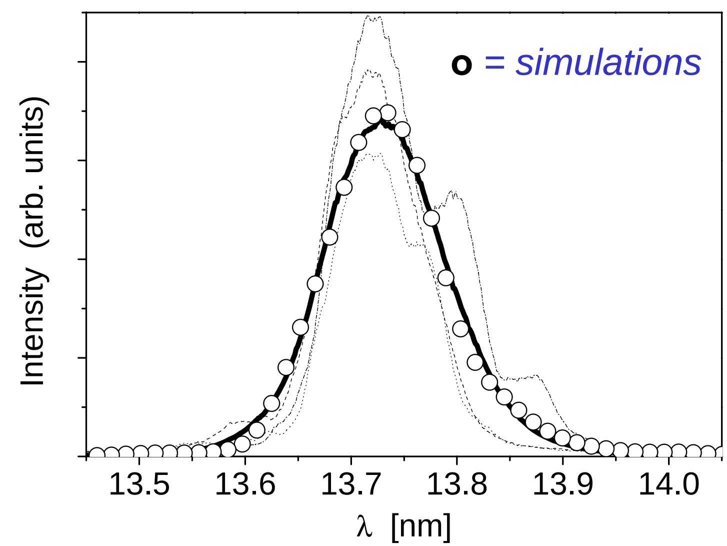
new_fund_harmonic_w.avi

3 single pulse Spectra @FLASH:

measured

predicted





~0.4% → ~25 fs pulse duration @ 32 nm

10 fs pulse duration @ 13 nm

Transverse Coherence

Emittance of a perfectly coherent ("gaussian") light beam:

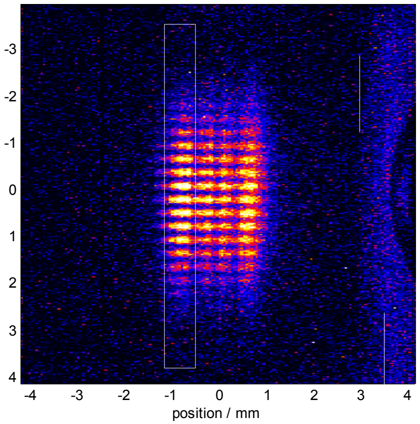
$$\varepsilon_{Light} = \sigma_r \cdot \sigma_\theta = \frac{\lambda_{Light}}{4\pi}$$

→ FEL theory predicts high transverse coherence of photon beam, if electron beam emittance:

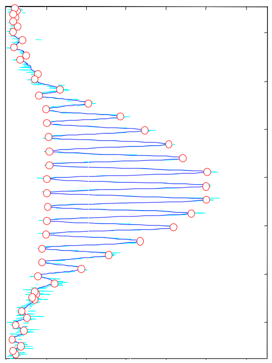
$$\boxed{\varepsilon_{electrons} < \approx \frac{\lambda_{Light}}{4\pi}}$$

Observation of interference pattern at FLASH:

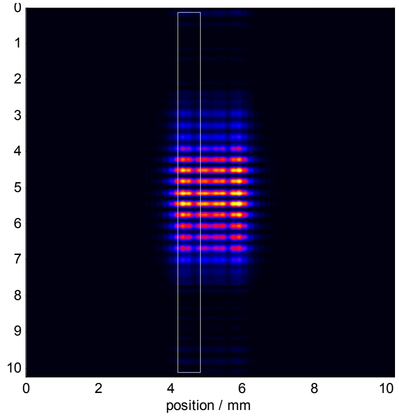
double slit



intensity modulation



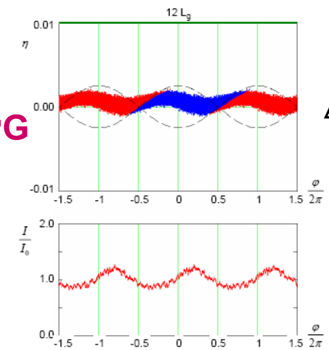
FEL simulation



Higher Harmonics

Density modulation becomes anharmonic at high gain:

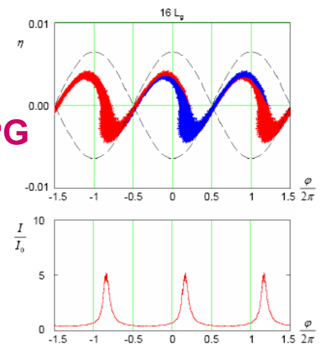
12 L_G



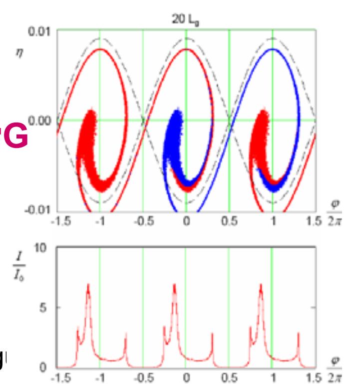
$\Delta\gamma$ / Ψ

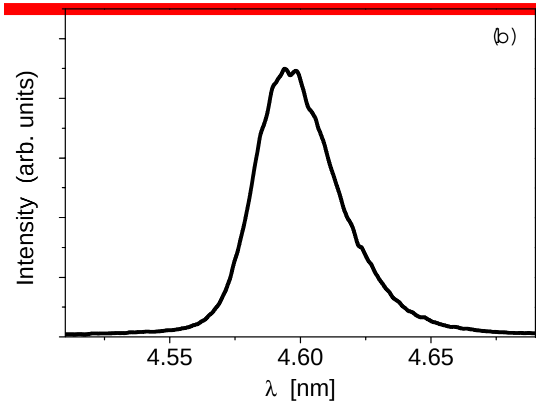
current

16 L_G

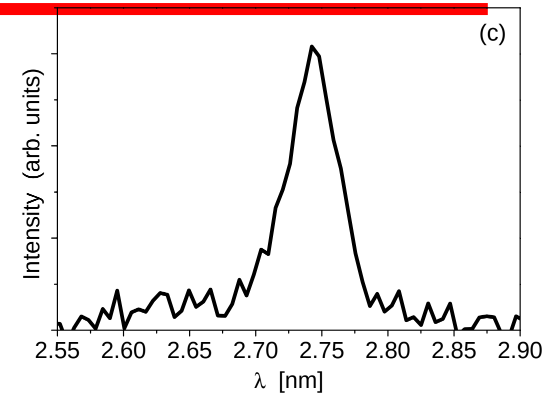


18 L_G





3^{rd} harmonics
@ 4.8 nm



5^{th} harmonics
@ 2.75 nm

new third harmonic

FLASH typical pulse energies (avg.):

Fundamental (13.8 nm):	40 μJ
3^{rd} harmonics (4.6 nm):	(0.25 ± 0.1) μJ
5^{th} harmonics (2.75 nm):	(10 ± 4) nJ

SASE FEL challenges

<u>Most electron beam parameters relevant within slices < coherence length ~1 … 10 fs</u>

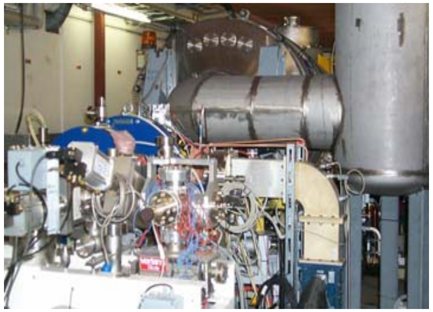
- relaxes requirements on beam specs
- complicates measurements and beam dynamics

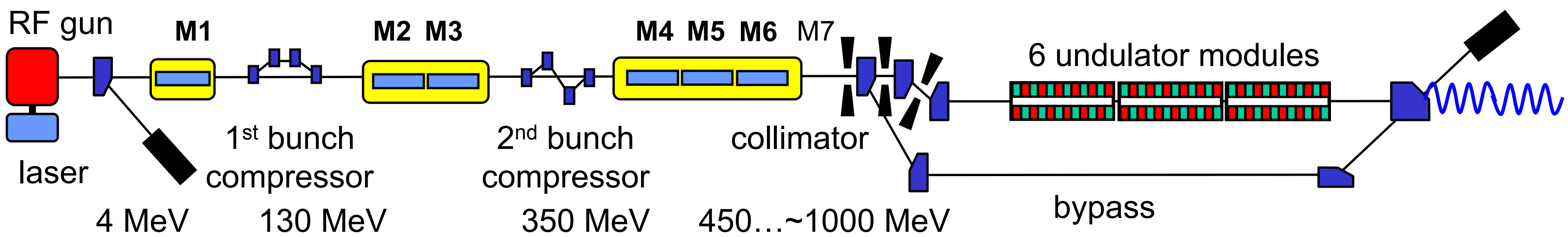
Emittance:	$\varepsilon \leq \lambda/4\pi \Leftrightarrow \sigma_r \approx 50\ \mu m$
Short Pulse length	$\sigma_s = 10 - 100$ fs
Peak current inside bunch:	$\hat{I} > 1$ kA
Energy width:	$\sigma_E/E \leq \sim 10\text{-}3$
Straight trajectory in undulator	$< 10\ \mu m$

Increasingly difficult for shorter wavelength:

longer undulator, smaller emittance, larger peak current

Present set-up of the FLASH accelerator

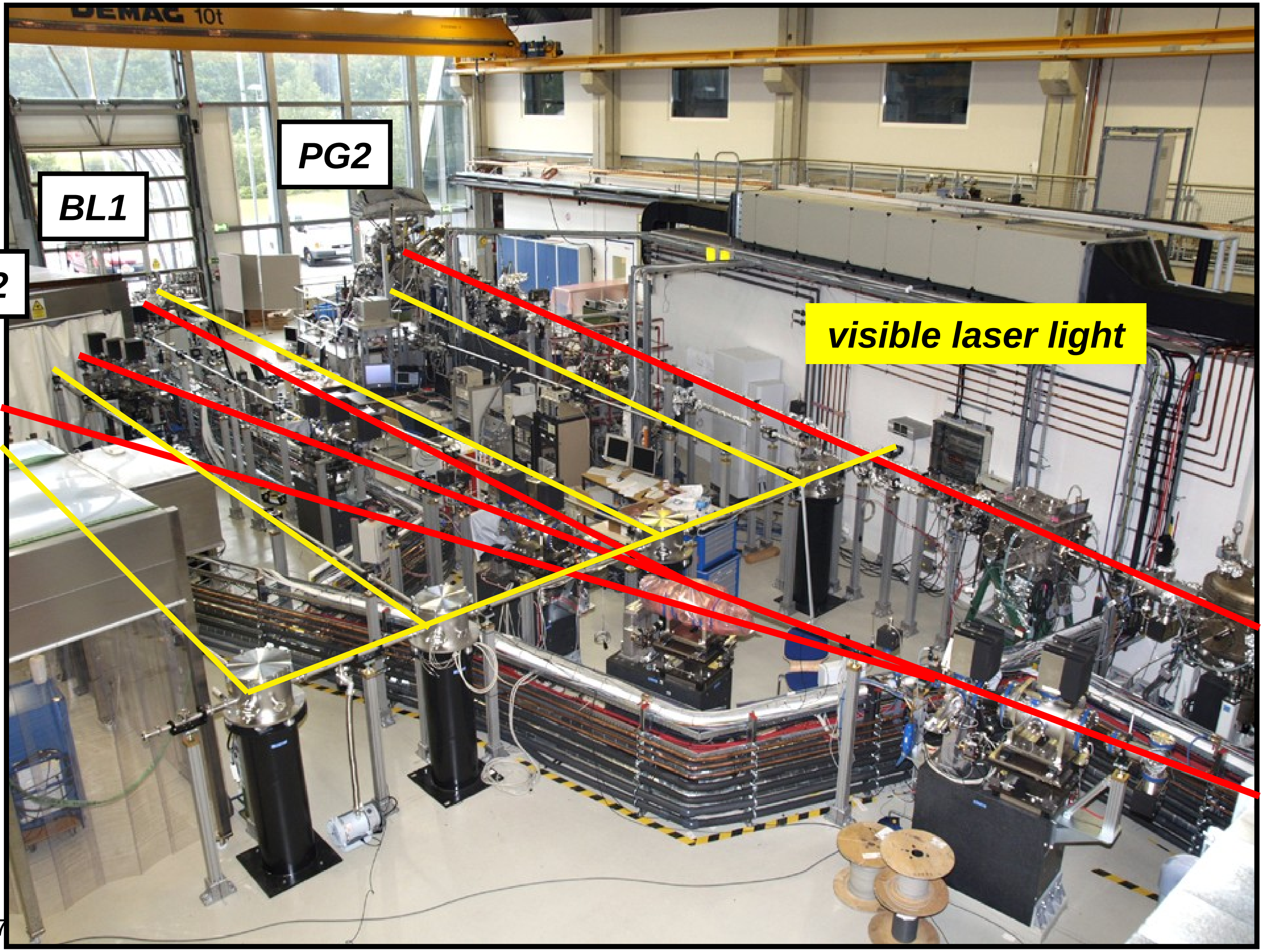


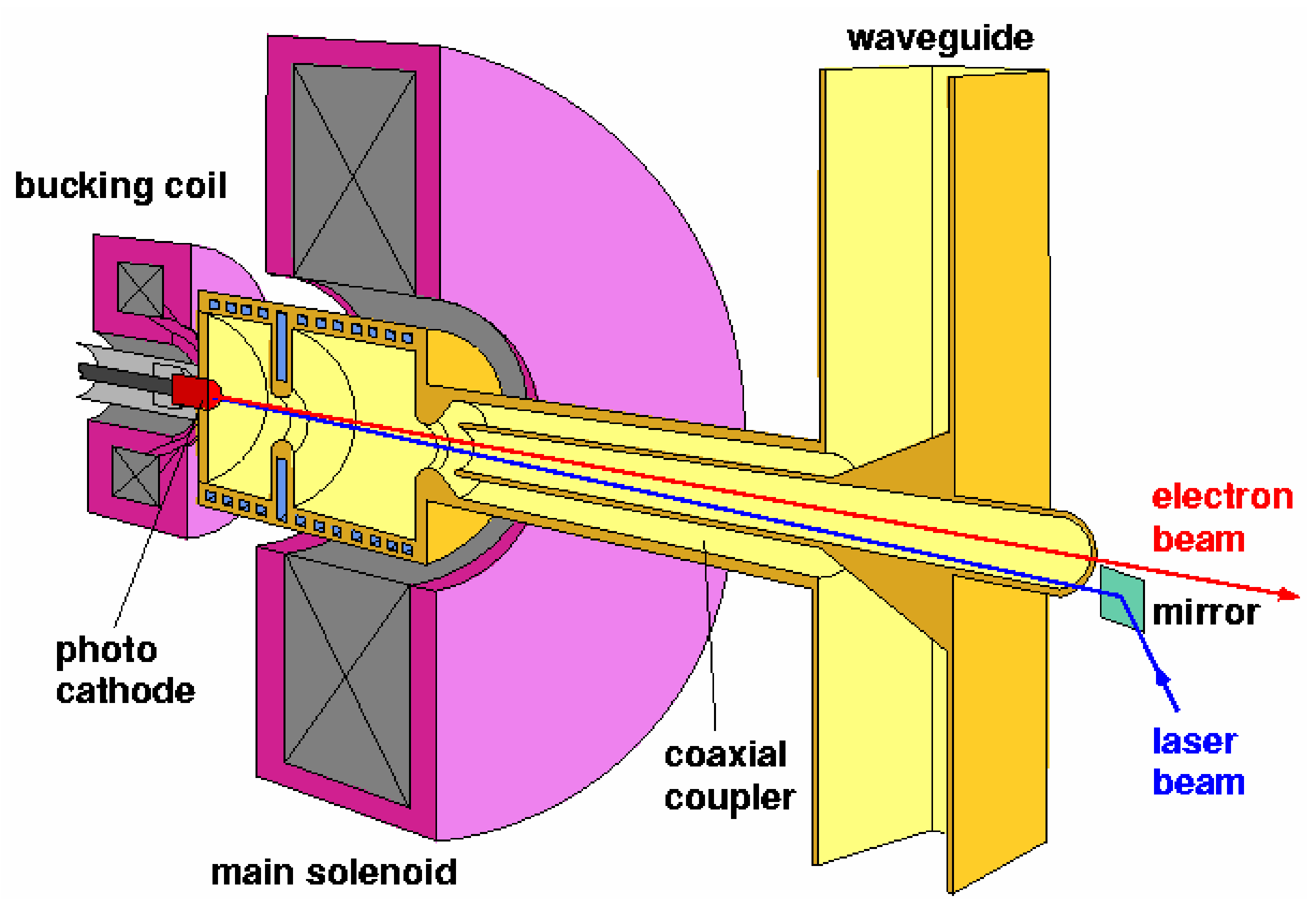


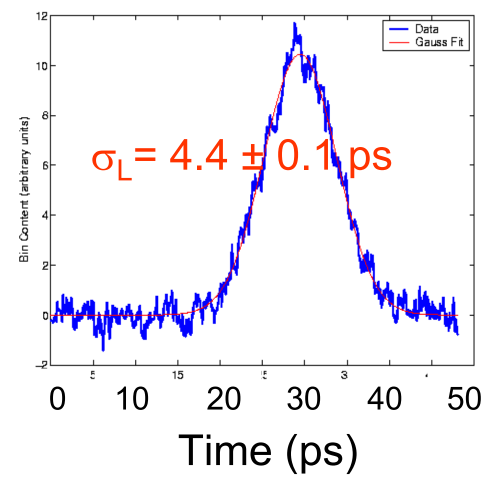

250 m

FLASH: the VUV-FEL User Facility at DESY



TESLA FEL photoinjector for small and short electron bunches

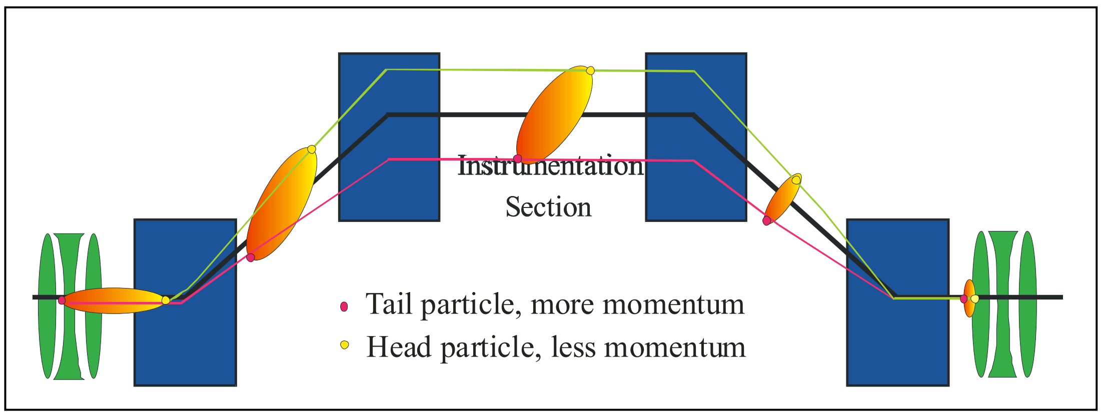




Longitudinal Bunch C

Need large peak current (> 1kA) ins

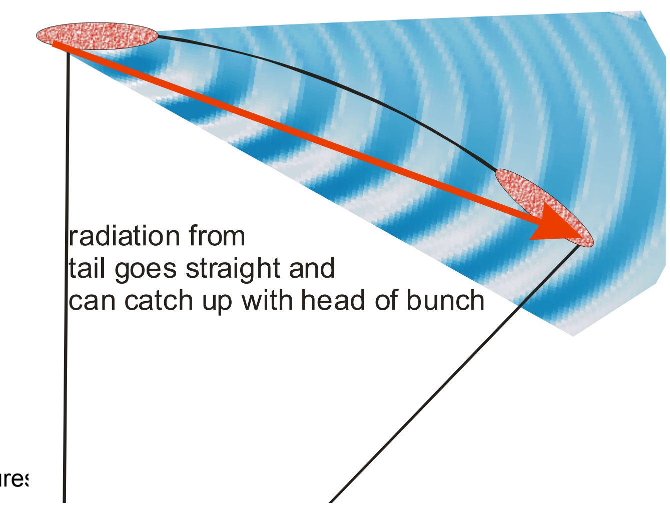
→ must compress bunches l



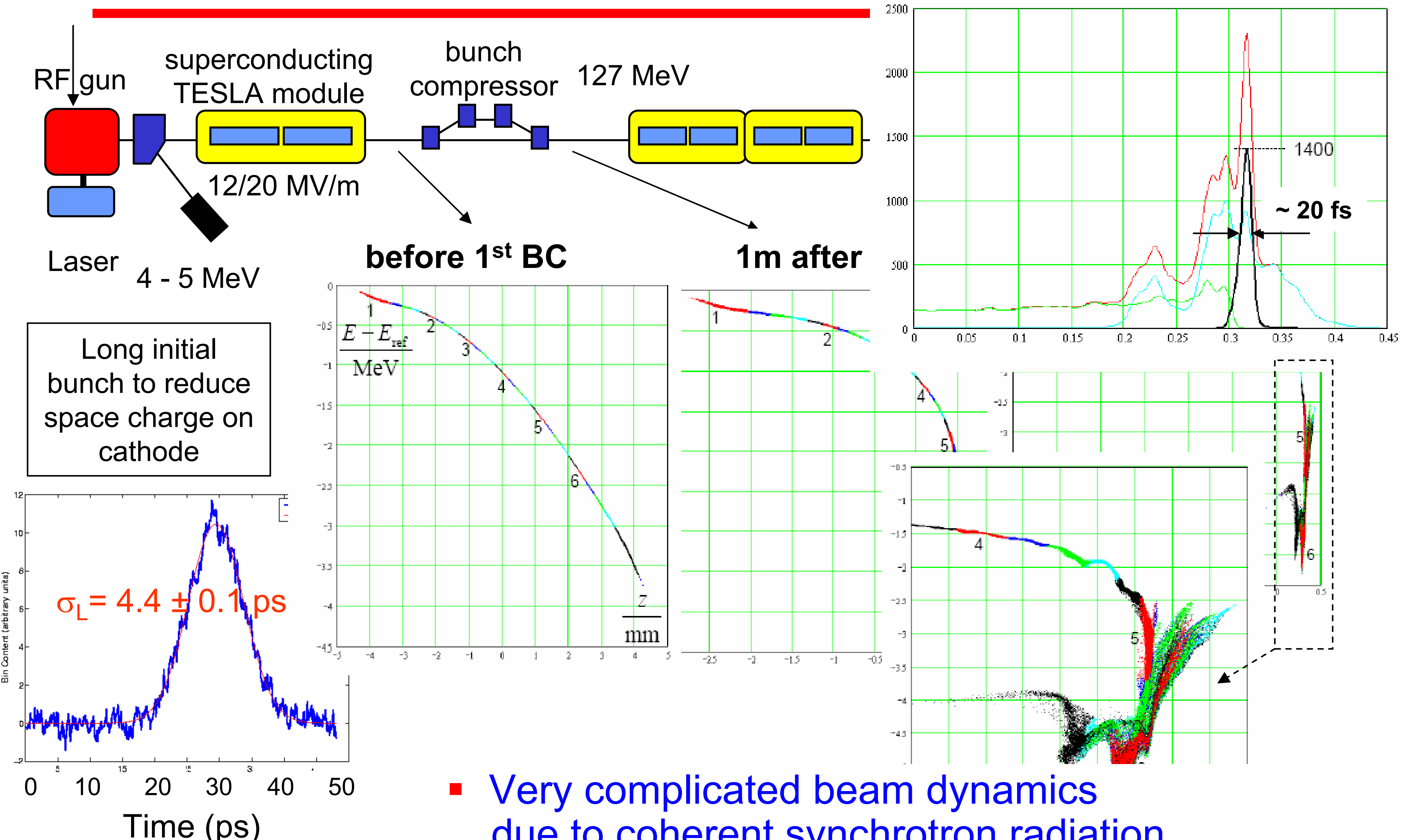
Magnetic bunch compression

Beware of
coherent synchrotron radiation (CSR)!

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



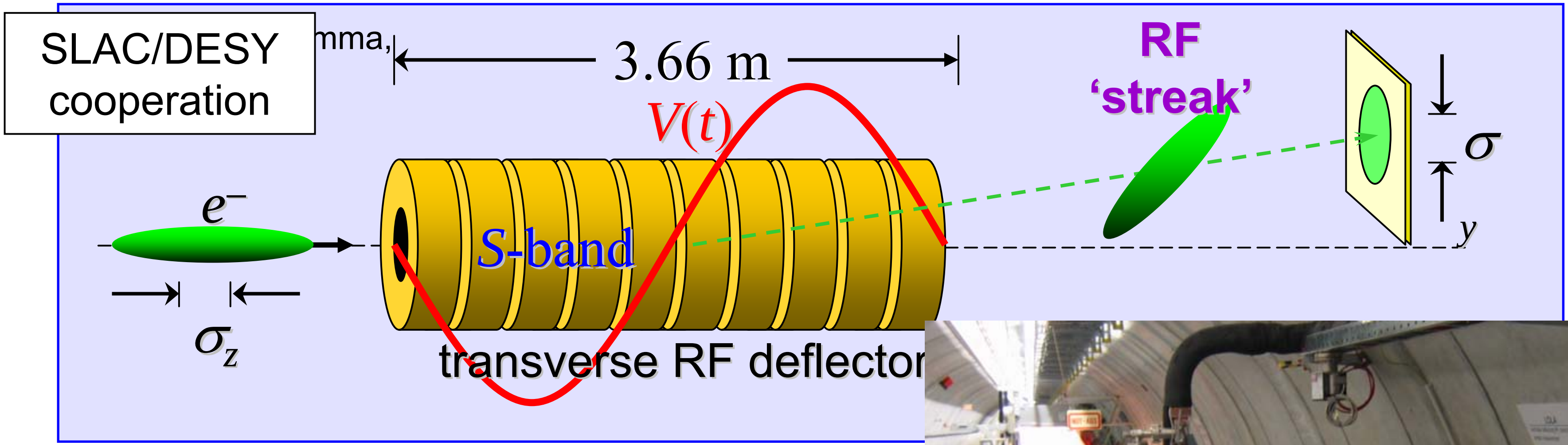
Longitudinal bunch compression

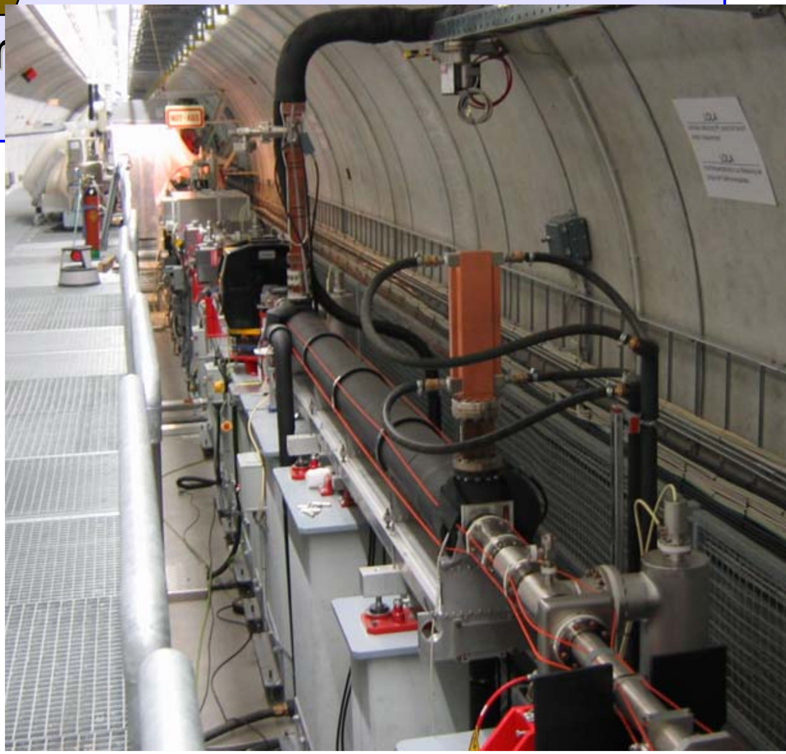


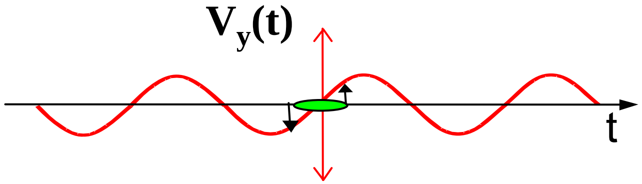
- Very complicated beam dynamics due to coherent synchrotron radiation
- Ultra-short photon pulses created ~20fs FWHM

Diagnostic Section at 130 MeV

Bunch Length with LOLA





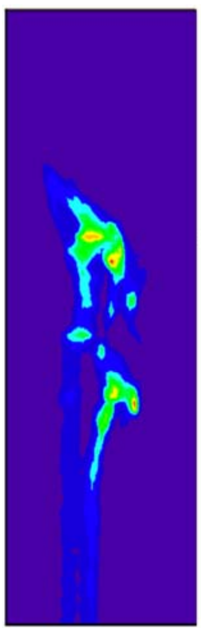


- Deflecting RF structure (S-band) from SLAC is used as a 'streak camera'
- Expected resolution < 10 um

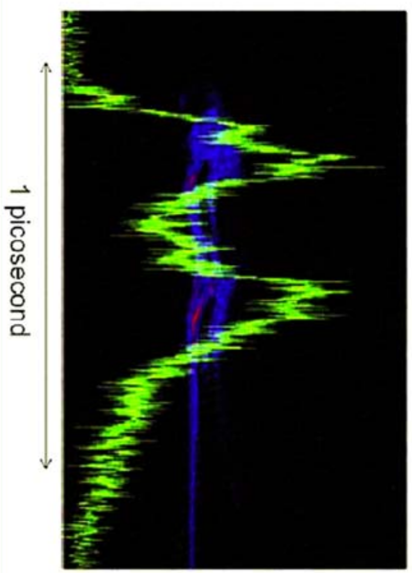
Pictures from LOLA

Three examples for different compressor settings:

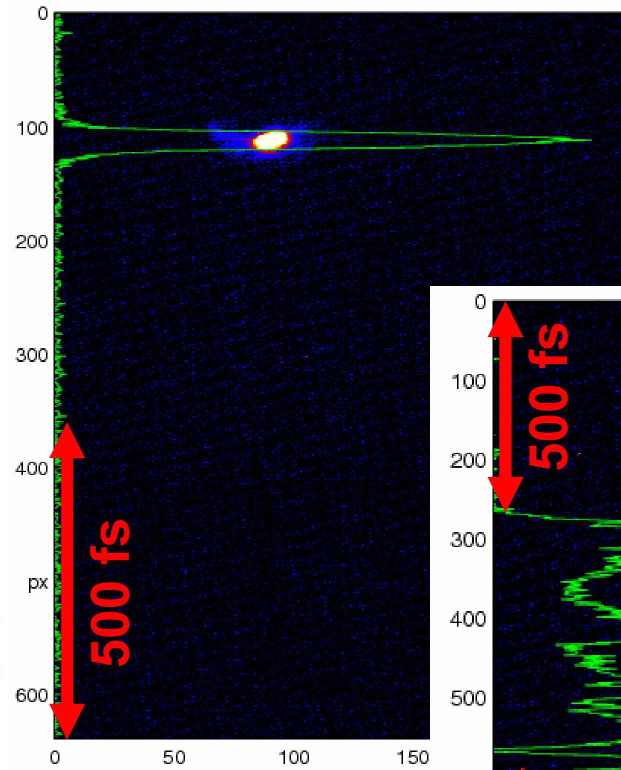
Resolution ~20 fs

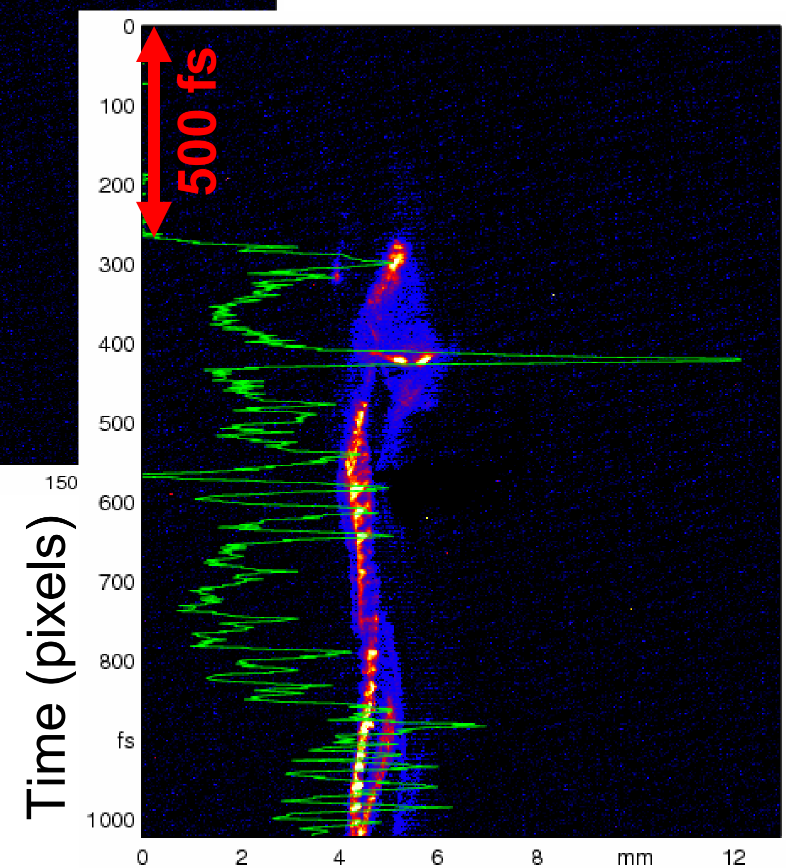


simulation



LOLA





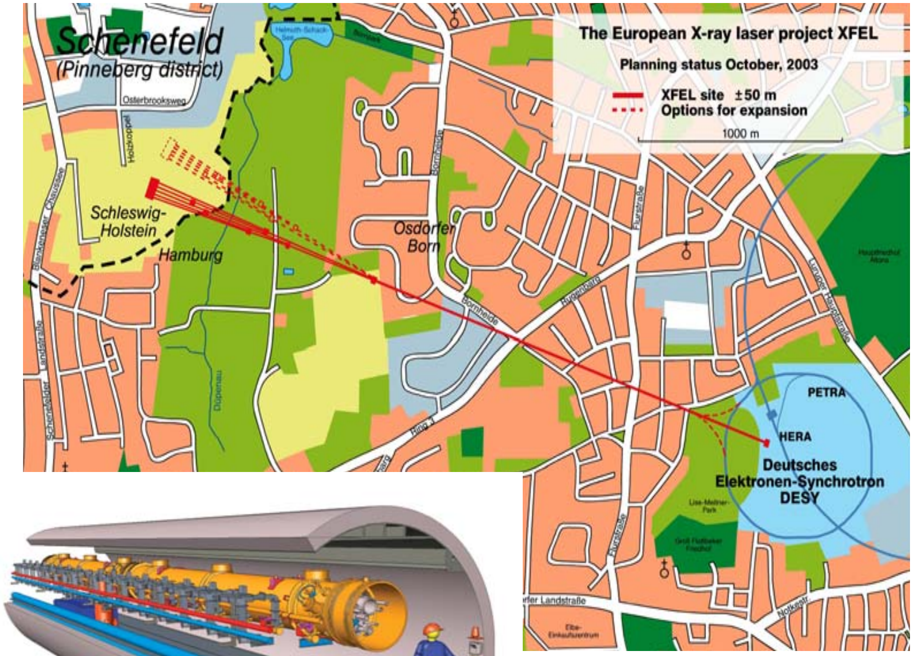
The European XFEL Project

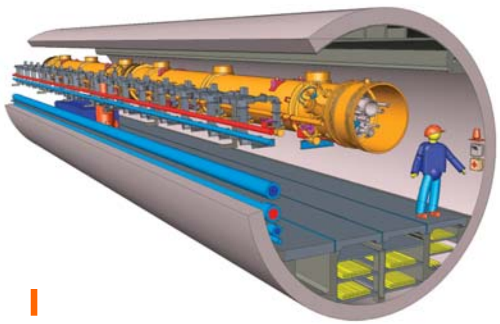
Site near DESY laboratory

- Proposal October 2002:

  X-ray FEL user facility with 20 GeV superconducting linear accelerator in TESLA technology
- Approval by German government Feb. 2003 as a European Project
- German commitment for 50% of the funding plus another expected 10% by the states Hamburg and Schleswig-Holstein, 40% from European partners
- Estimated total project cost **970 M€**

3.4km





2004 **2007** **2009: LCLS start operation (SLAC)** **2013**

preparation **construction** **beam operation**

The European XFEL

The European XFEL

XFEL Movie

Potential subjects for PhD work at FLASH/DESY, PETRA III and XFEL

1. a) Bunch Compression for the European X-ray Free-Electron Laser (XFEL) from 1 mm down to 0.025 mm rms bunch length;
2. b) Investigation of possibilities for „ultra-compression“ (< 10 μm rms bunch length) making use of a long electron beam transfer line.
3. Measurement of THz coherent synchrotron radiation at FLASH bunch compressor and infrared undulator.
4. Mechanism of halo population at the electron beam for X-ray FELs: dark currents, restgas scattering, wake fields, quantum fluctuation,….; measurements at FLASH
5. Experimental investigations on the start-up from noise at FLASH + High Gain Harmonic Generation
6. A laser-wire for measurement of submicrometer electron beam size at PETRA.
7. Start-to-end simulation and control of electron beam dynamics in the seeding version for FLASH
8. Transverse beam profile monitor based on incoherent synchrotron radiation. Important for permanent, parasitic, single bunch monitoring. Can be tested at FLASH, needed for XFEL.
9. Studies on digital electronics for electron beam position monitors with high single bunch resolution.
10. Development of an electron beam position monitor with Nanometer resolution for the XFEL.
11. Measurement of ultra-short electron bunches using an optical replica technique.
12. Synchronization of pump&probe laser with electron bunch over large distance.
13. Multi-bunch effects at FLASH incl. stability of bunch center within bunch train & feedback.
14. Design and construction of a thermionic gun for LINAC II at DESY.
15. Options for High-Gain Harmonic Generation (HGHG) at FLASH.
16. Design, construction and commissioning of a multi-bunch feedback for PETRA III.

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
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)

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The FLASH team

FLASH is a project within the TESLA Technology Collaboration

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