Future Accelerators – part III

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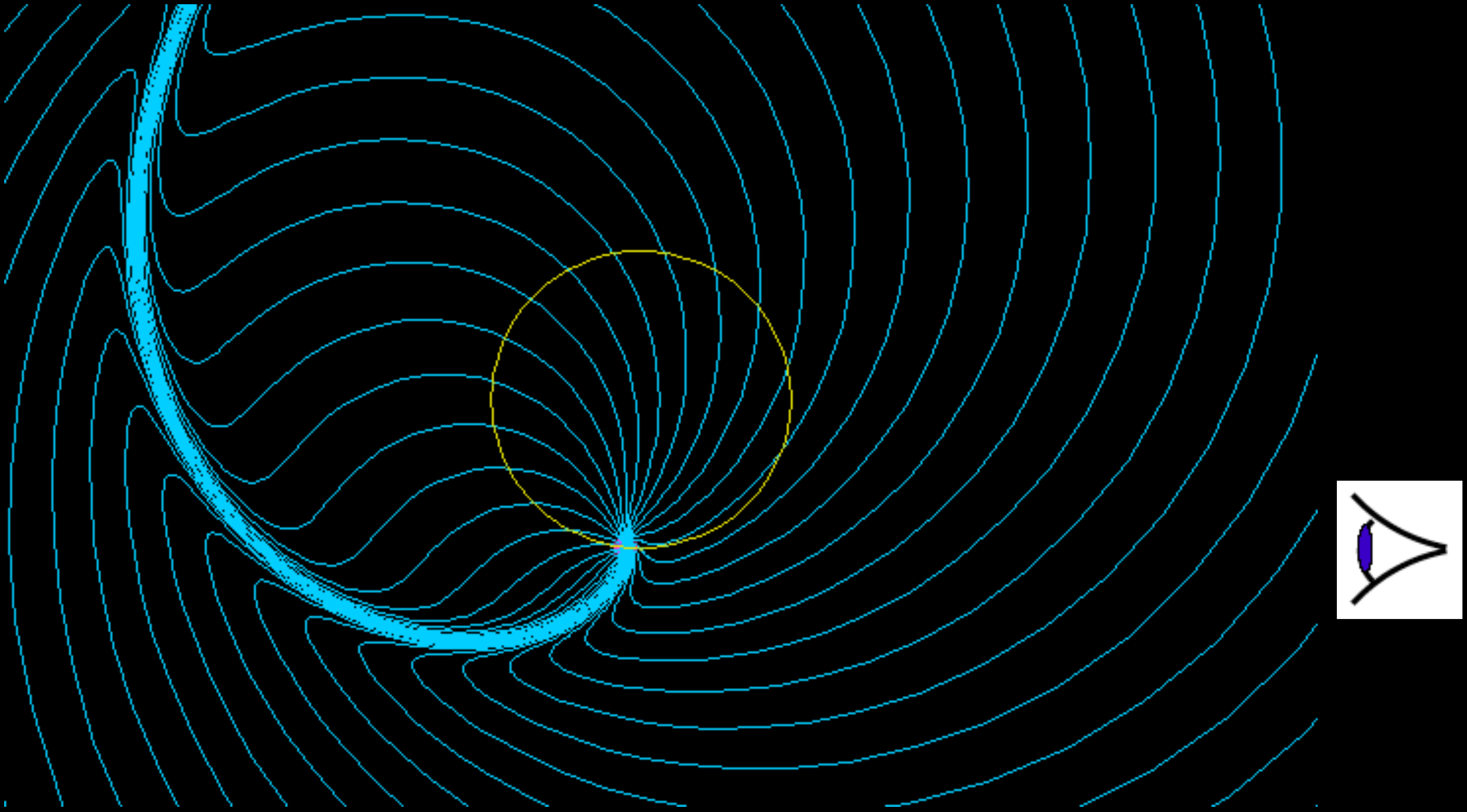
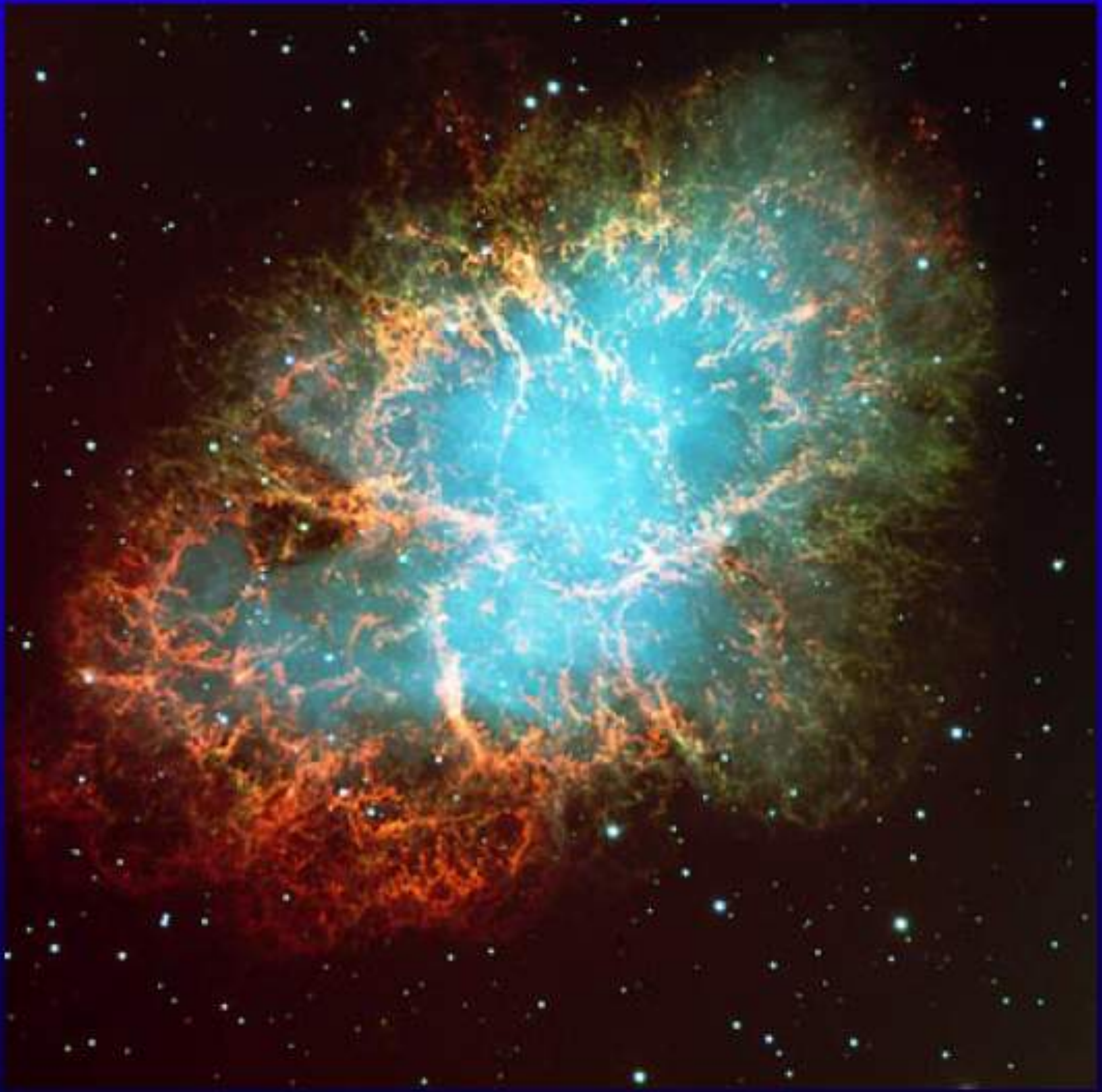
XIV ICFA School – Habana - December 2017

Charge particle in circular motion



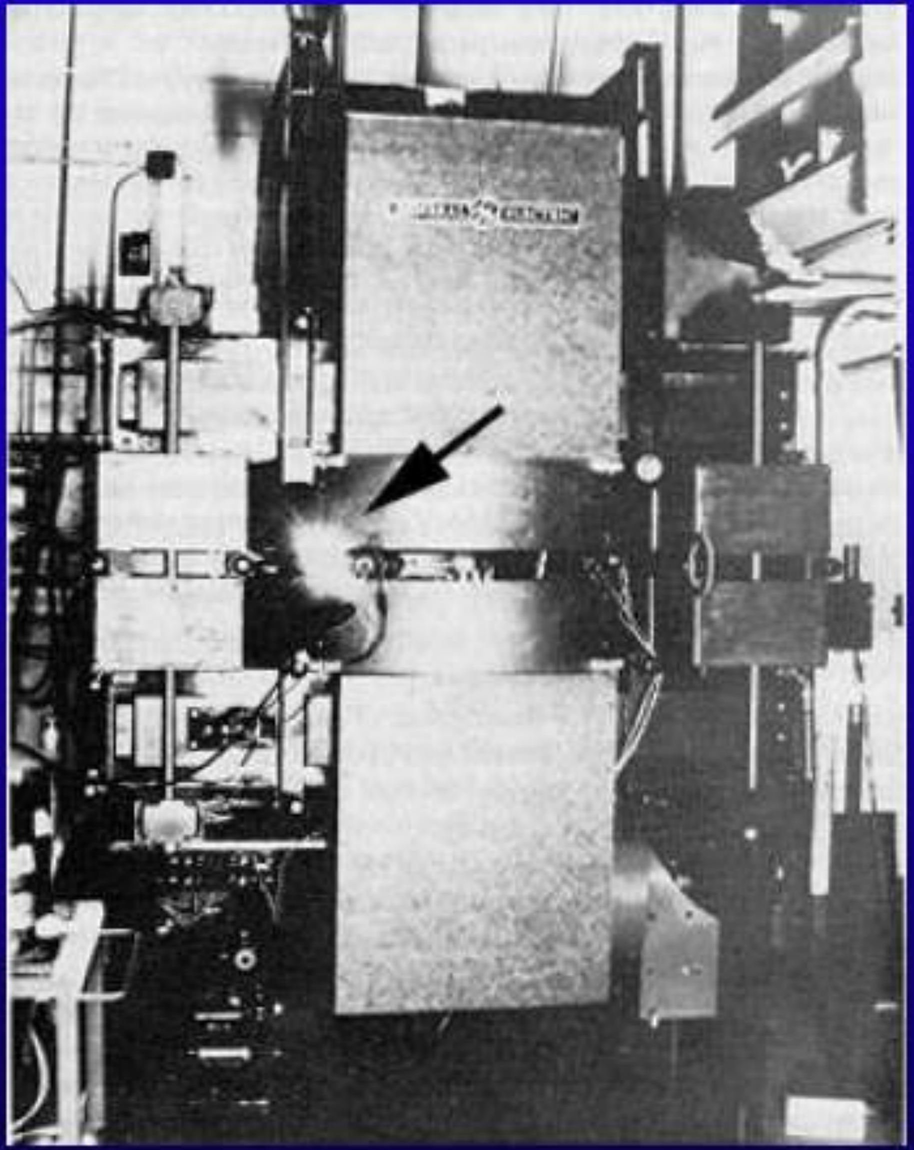
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

Crab Nebula
6000 light years away



First light observed
1054 AD

GE Synchrotron
New York State



First light observed
1947

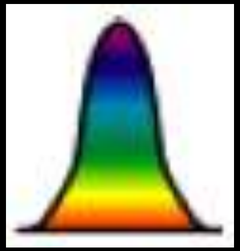
Elettra (Trieste)

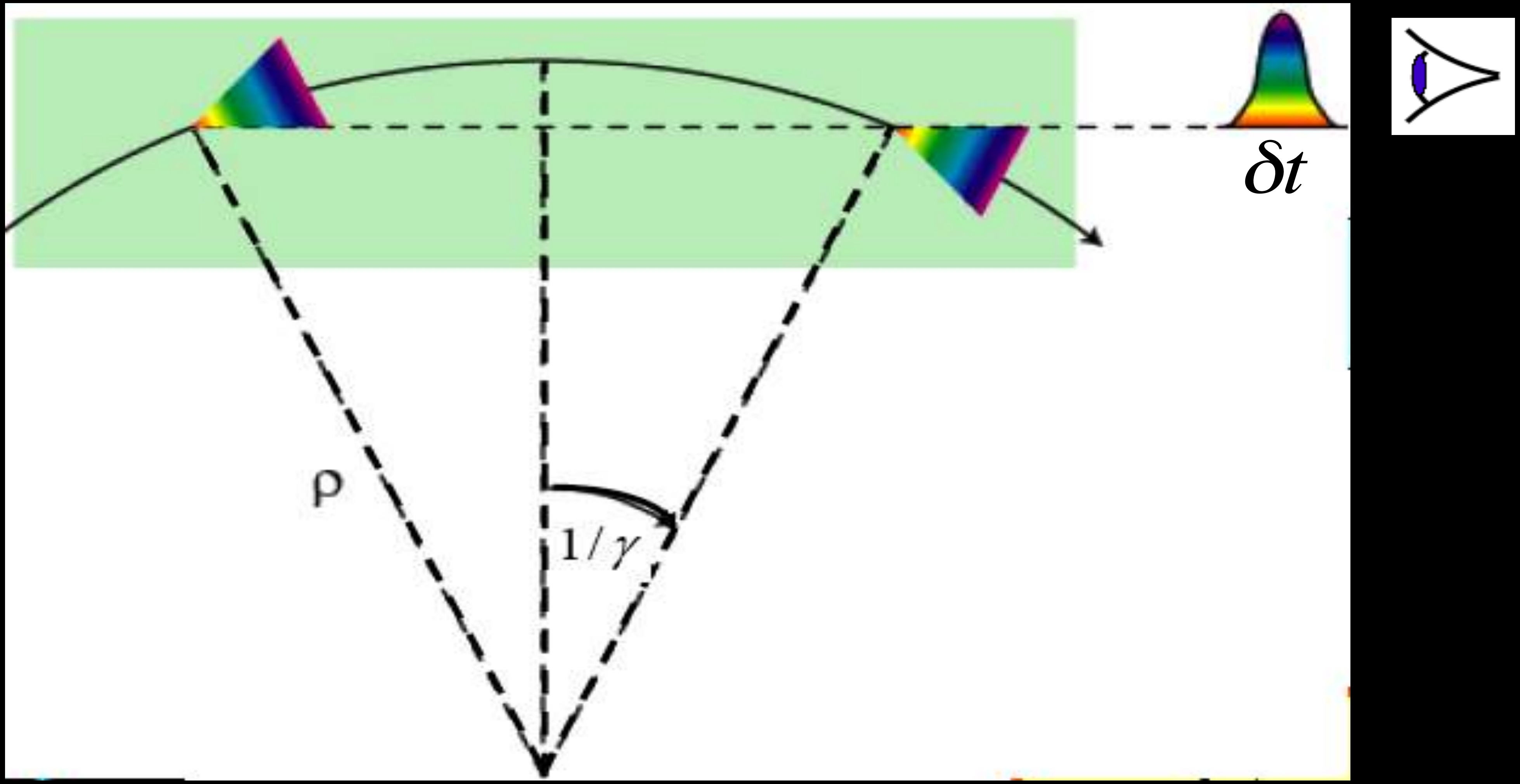
ESRF (Francia)

SLS (Svizzera)

Pulse length

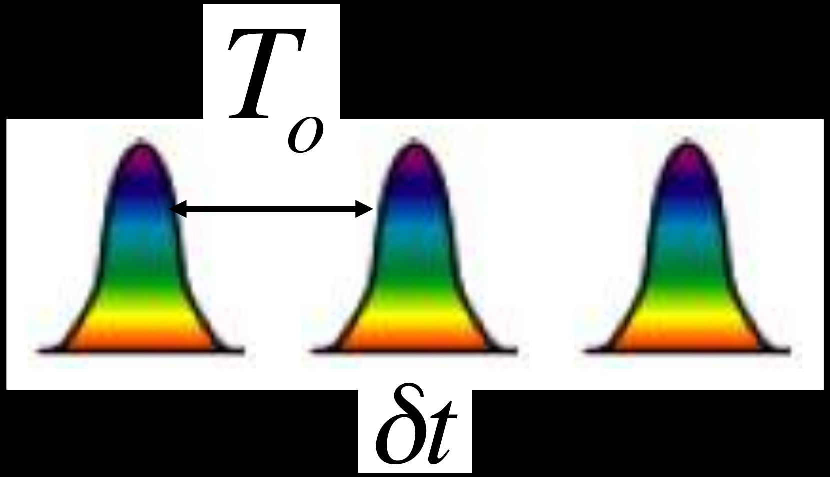
$$\delta t \approx \frac{\rho}{E^3} \approx 100\,ps$$



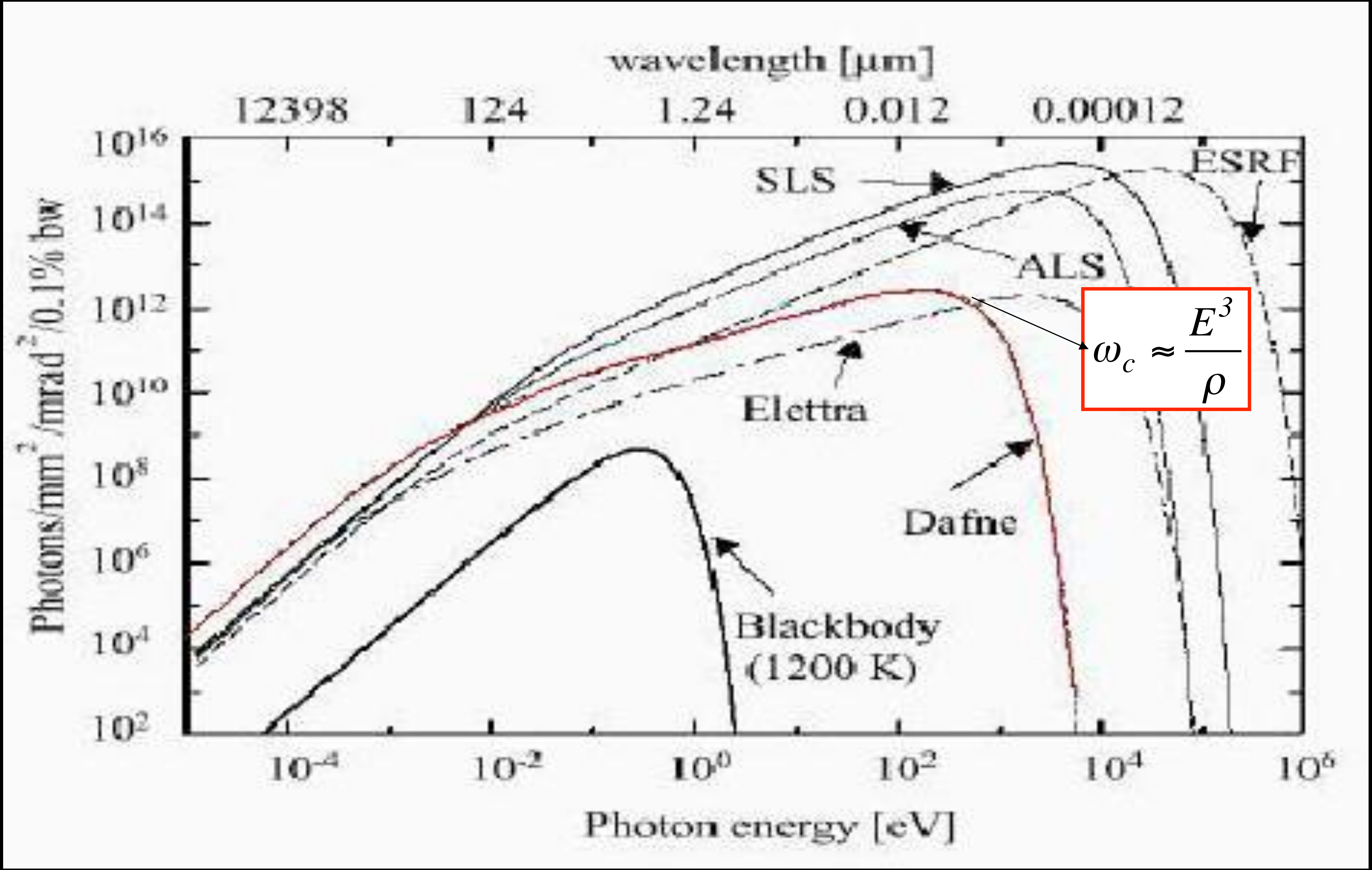


Pulse repetition rate

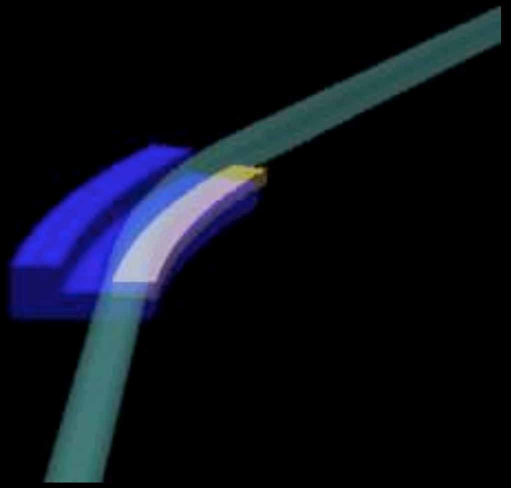
$$\omega_o = \frac{2\pi}{T_o}$$

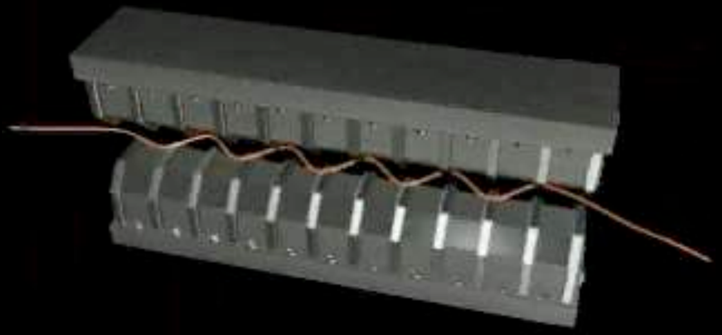


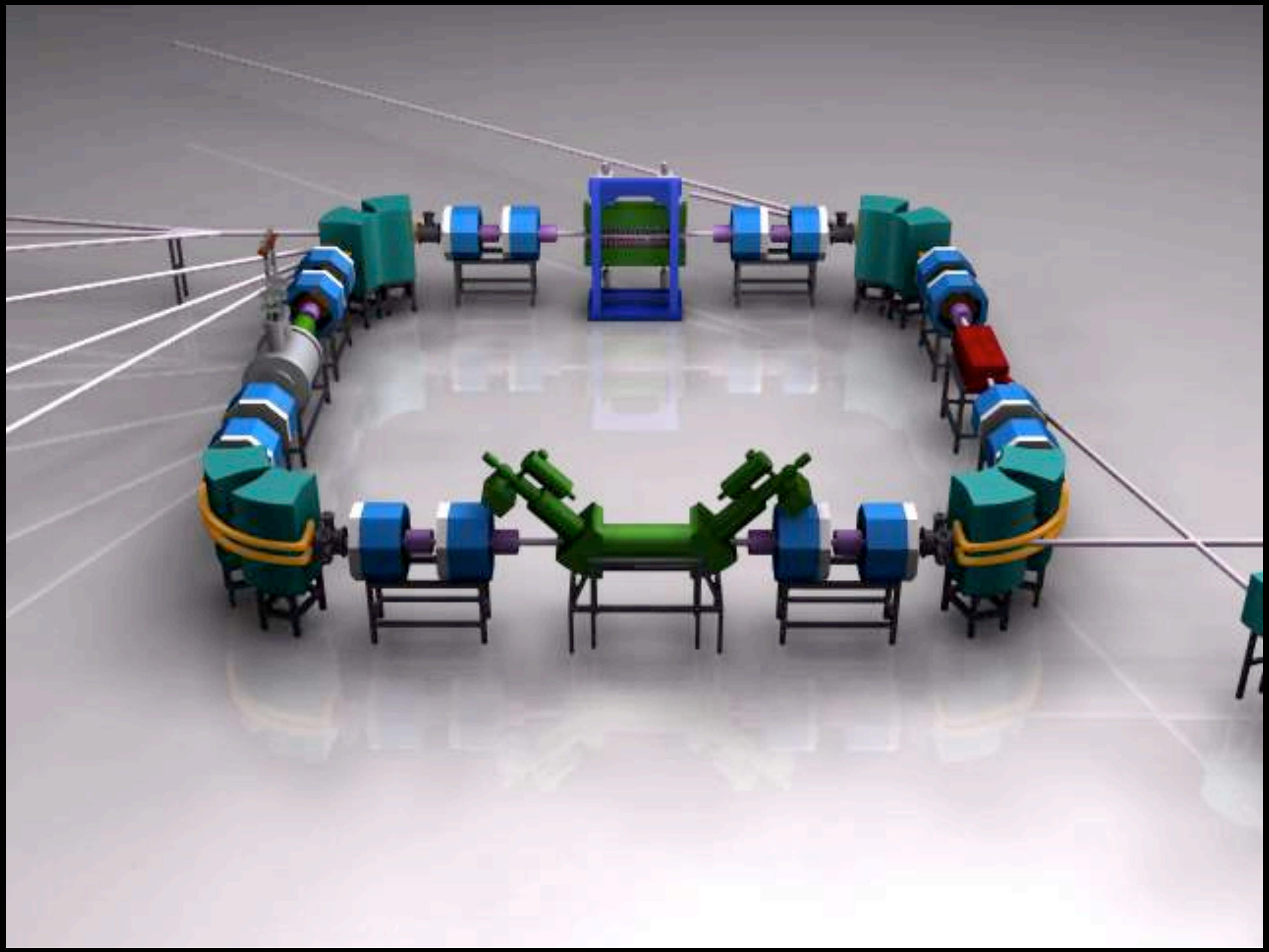
$$\langle P_s\,(\mathrm{MW})\rangle_{\mathrm{iso}} = 0.088463\,\frac{E^4\,(\mathrm{GeV})}{\rho\,(\mathrm{m})}\,I\,(\mathrm{A})\ .$$



$$\boxed{\omega_c \approx \frac{E^3}{\rho}}$$

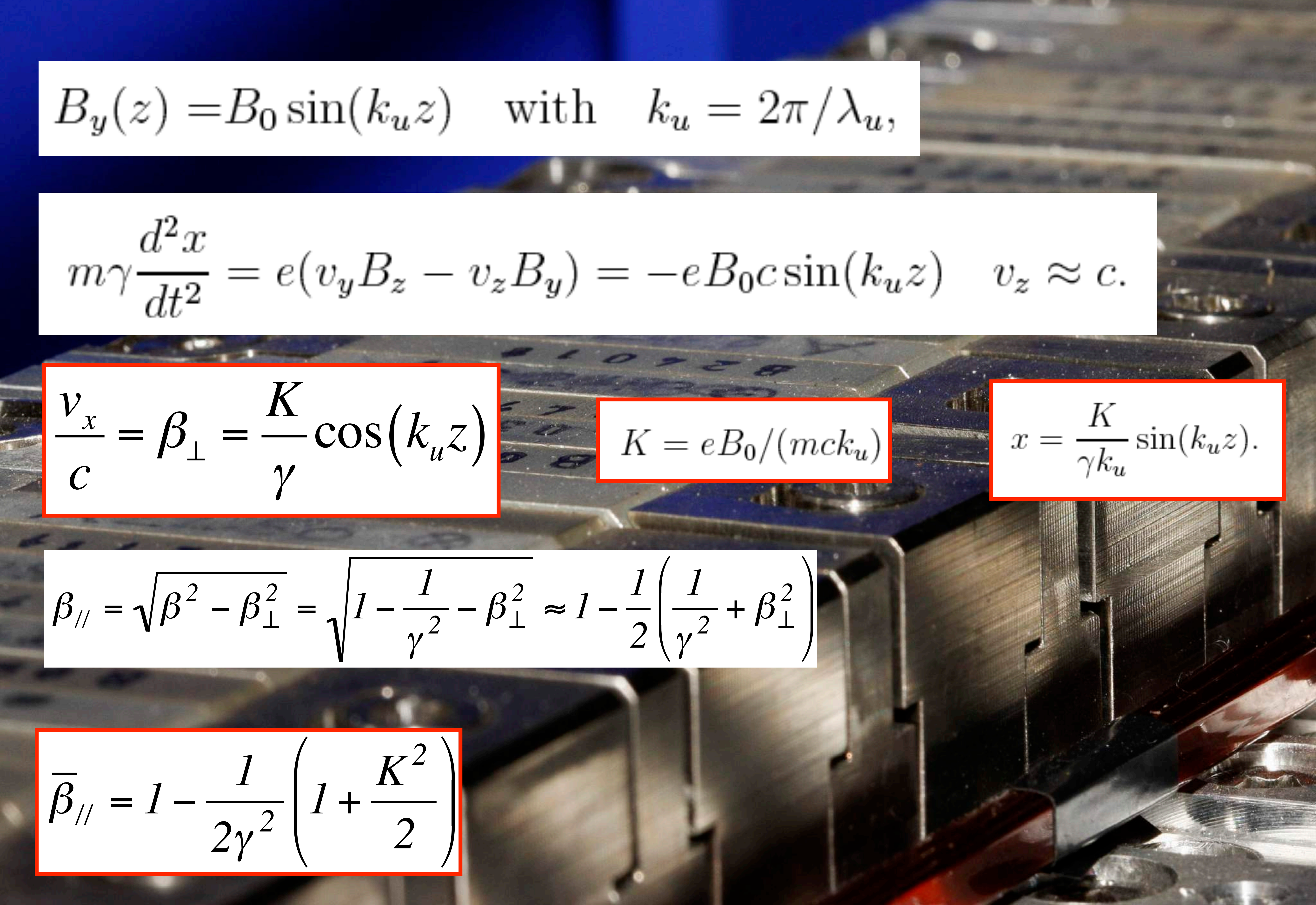







M5
M5
M6
POLI

Transverse electron motion in an Undulator:



$$B_y(z) = B_0 \sin(k_u z) \quad \text{with} \quad k_u = 2\pi/\lambda_u,$$

$$m\gamma \frac{d^2x}{dt^2} = e(v_y B_z - v_z B_y) = -eB_0 c \sin(k_u z) \quad v_z \approx c.$$

$$\boxed{\frac{v_x}{c} = \beta_\perp = \frac{K}{\gamma}\cos(k_u z)}$$

$$\boxed{K = eB_0/(mck_u)}$$

$$\boxed{x = \frac{K}{\gamma k_u}\sin(k_u z).}$$

$$\beta_{//} = \sqrt{\beta^2 - \beta_\perp^2} = \sqrt{1 - \frac{1}{\gamma^2} - \beta_\perp^2} \approx 1 - \frac{1}{2}\left(\frac{1}{\gamma^2} + \beta_\perp^2\right)$$

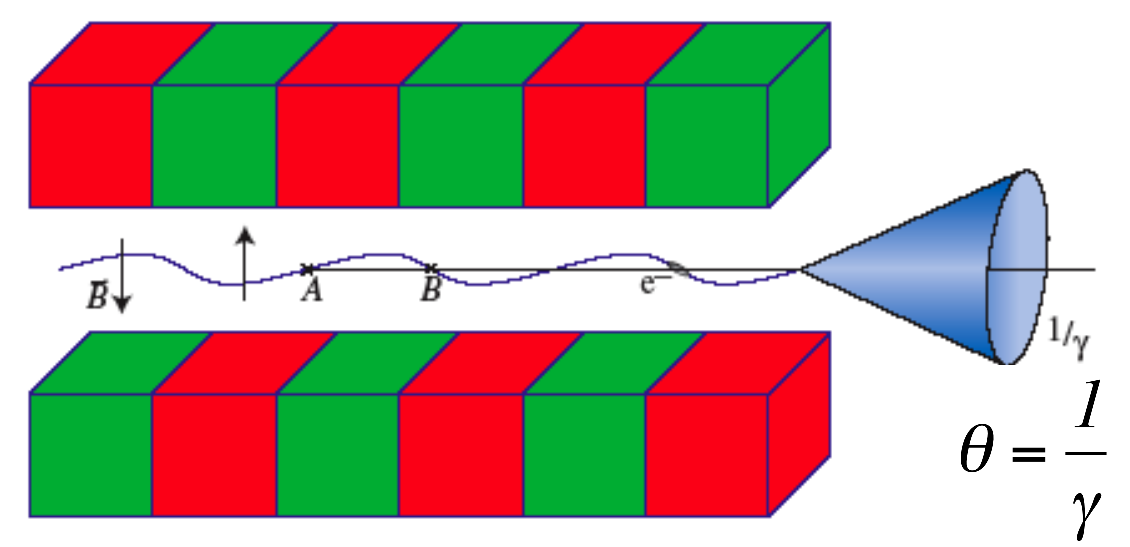
$$\boxed{\bar{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)}$$

Undulator Radiation

© DESY

$$x = \frac{K}{\gamma k_u}\sin(k_u z).$$

$$\bar{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



$$\theta = \frac{1}{\gamma}$$

$$x' = \frac{K}{\gamma}\cos\left(k_u z\right)$$

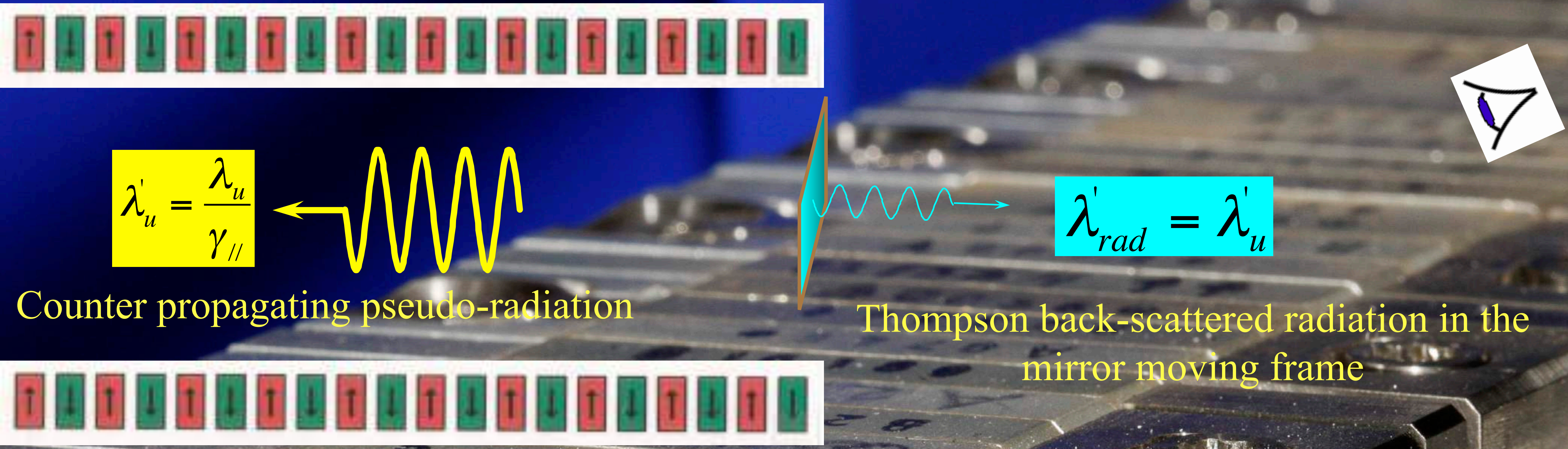
$$K = eB_0/(mck_u)$$

The electron trajectory is determined by the undulator field and the electron energy

The electron trajectory is inside the radiation cone if:

$$K \leq 1$$

Relativistic Mirrors



$$\lambda'_u = \frac{\lambda_u}{\gamma_{//}}$$

Counter propagating pseudo-radiation

$$\lambda'_{rad} = \lambda'_u$$

Thompson back-scattered radiation in the mirror moving frame

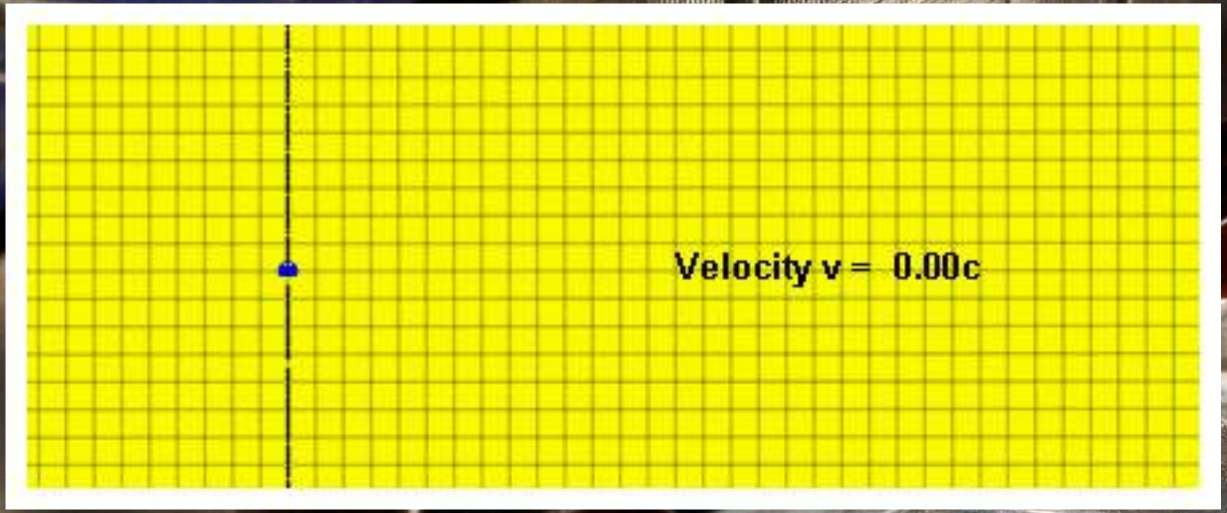
$$\lambda_{rad} = \gamma\lambda'_{rad}\left(1-\beta\cos\vartheta\right) \approx \lambda_u\left(1-\bar{\beta}_{//}\cos\vartheta\right)$$

Doppler effect in the laboratory frame

$$\bar{\beta}_{//} = 1-\frac{1}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

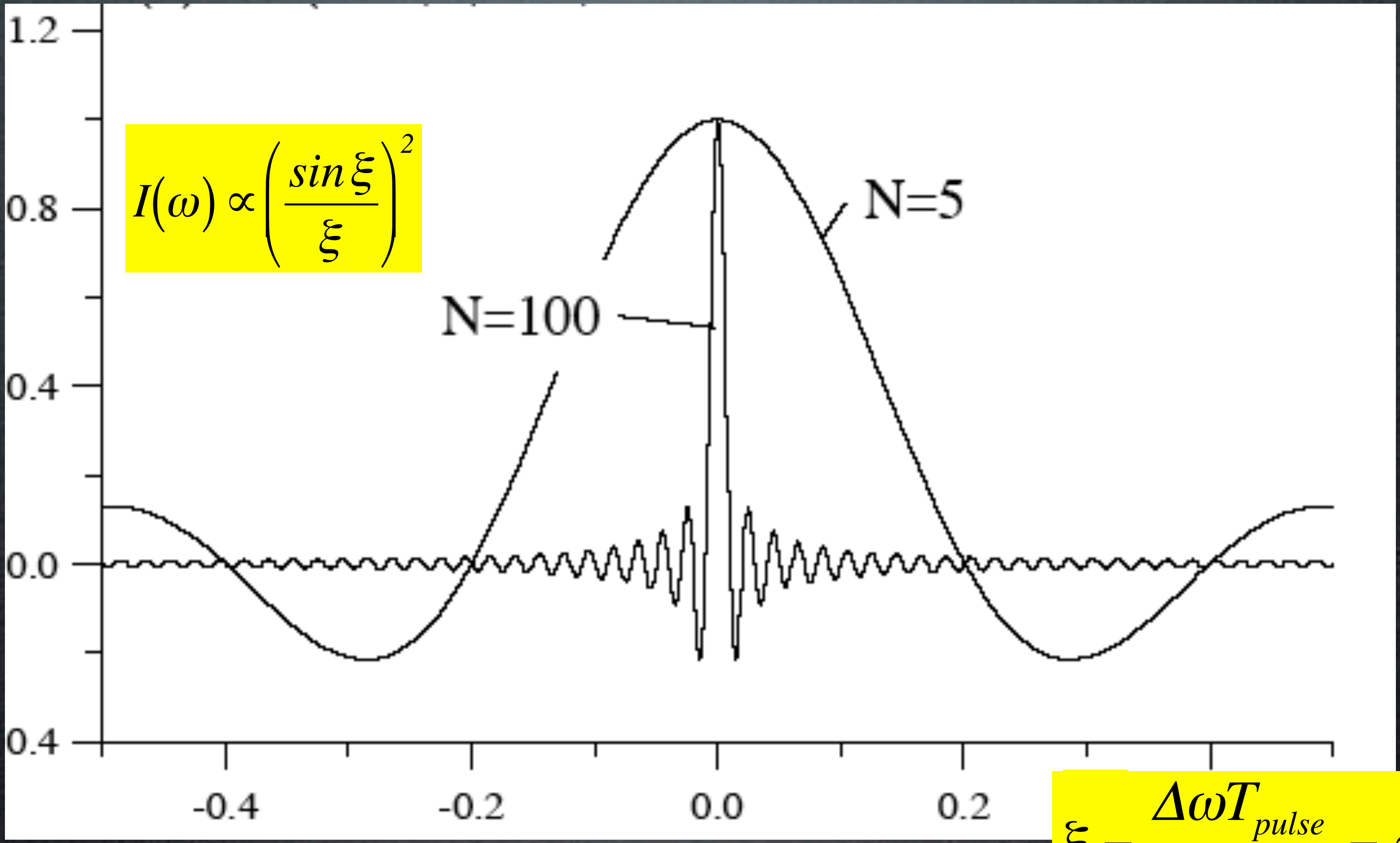
$$\cos\vartheta \approx 1-\frac{\vartheta^2}{2}$$

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\vartheta^2\right)$$



Tunability & Red Shift

Spectral Intensity



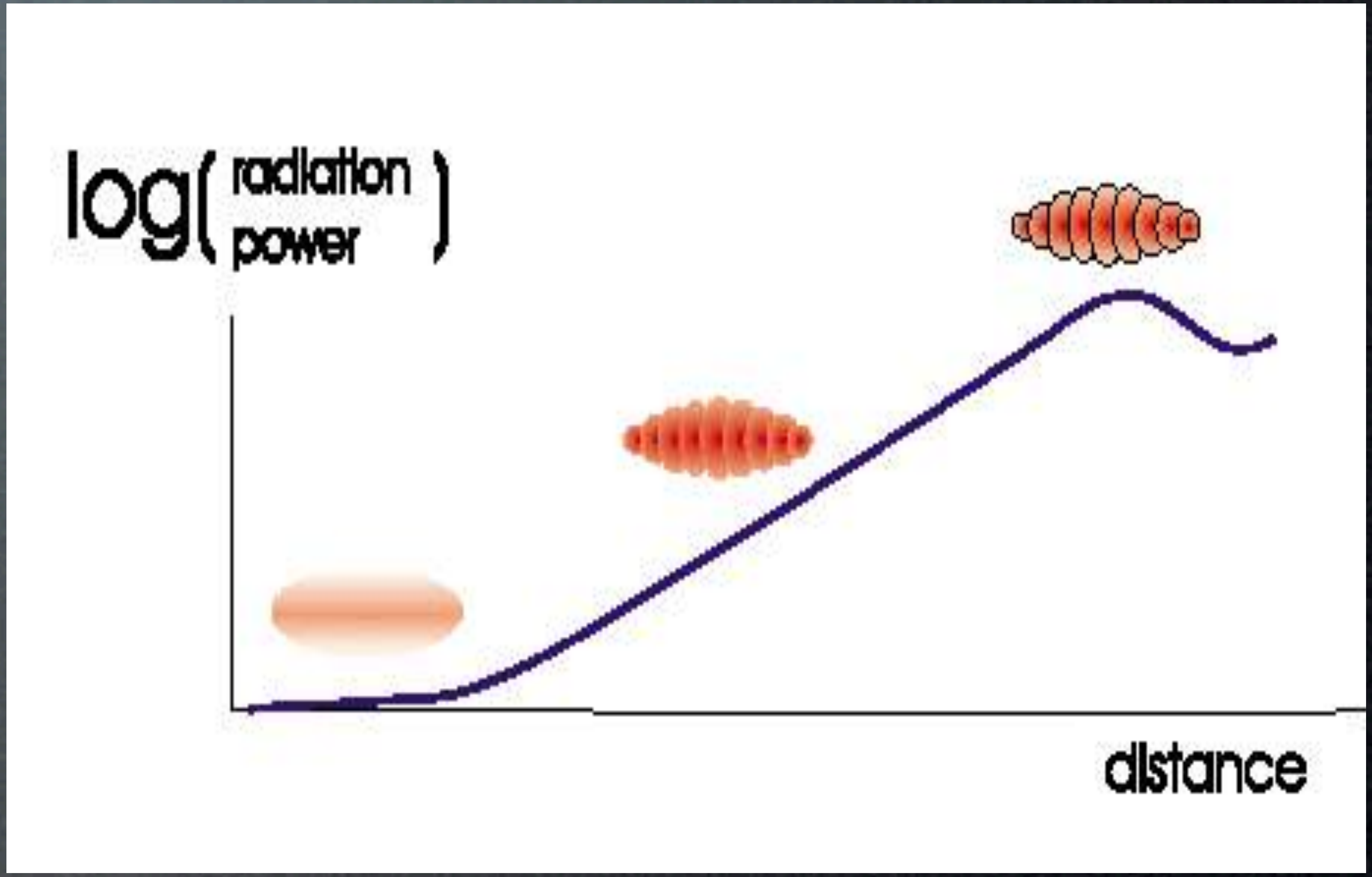
$$I(\omega) \propto \left(\frac{\sin \xi}{\xi} \right)^2$$

$$\xi = \frac{\Delta\omega T_{pulse}}{2} = \pi N_w \frac{\omega - \omega_{res}}{\omega_{res}}$$

$$\frac{\Delta\omega}{\omega} \approx \frac{1}{N_w}$$

Line width

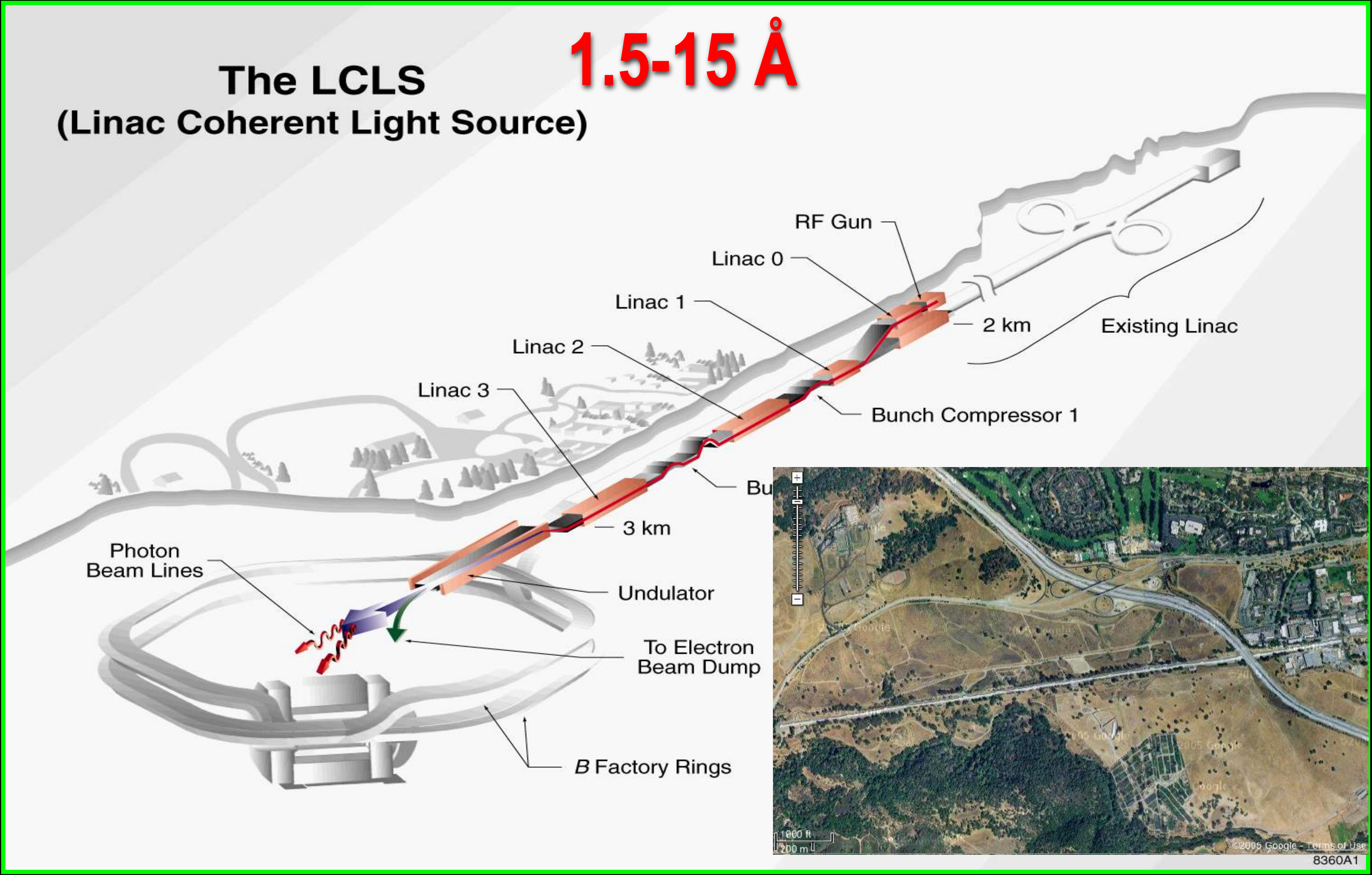
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\vartheta^2\right)$$

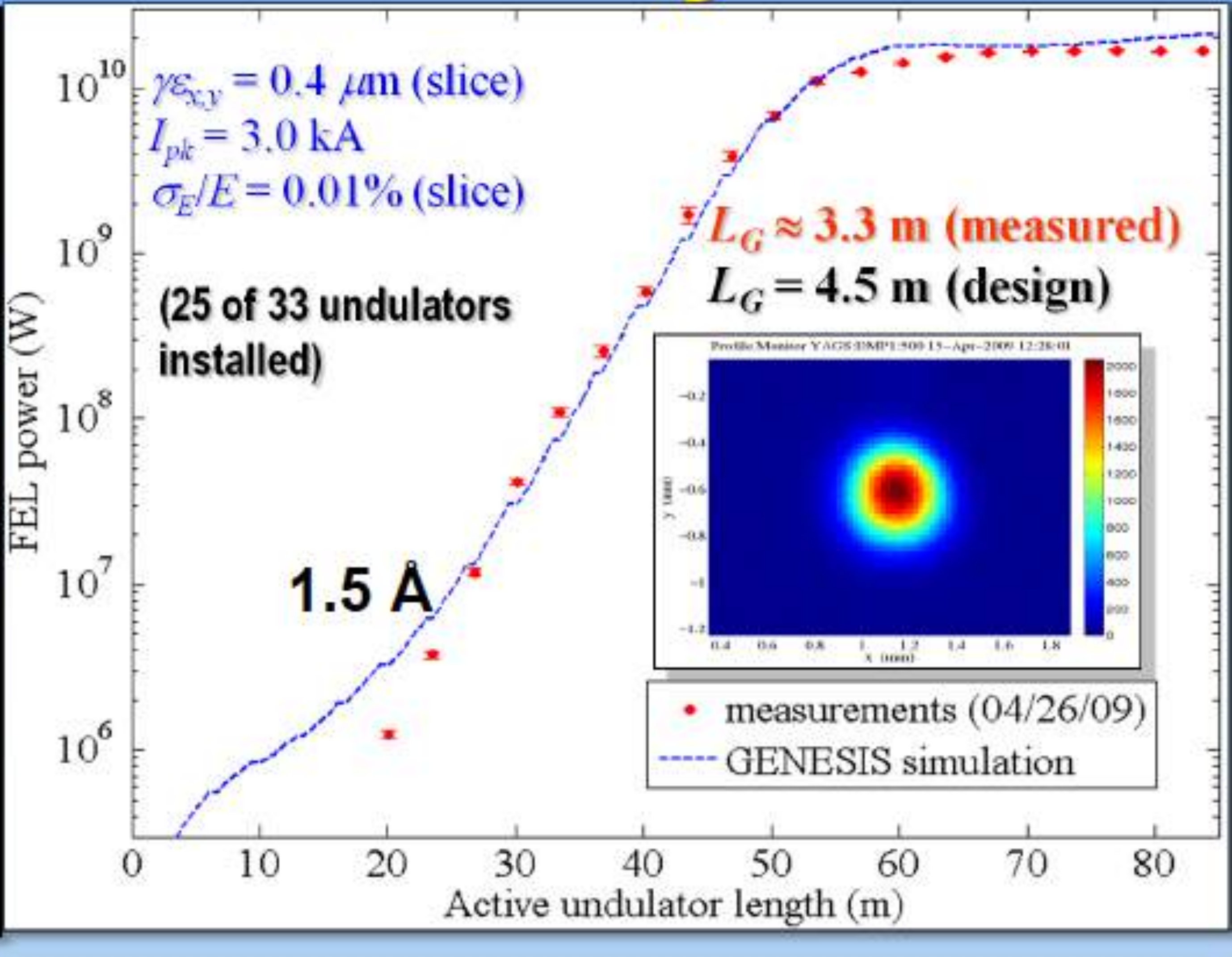
(Tunability - Harmonics)

LCLS at *SLAC*



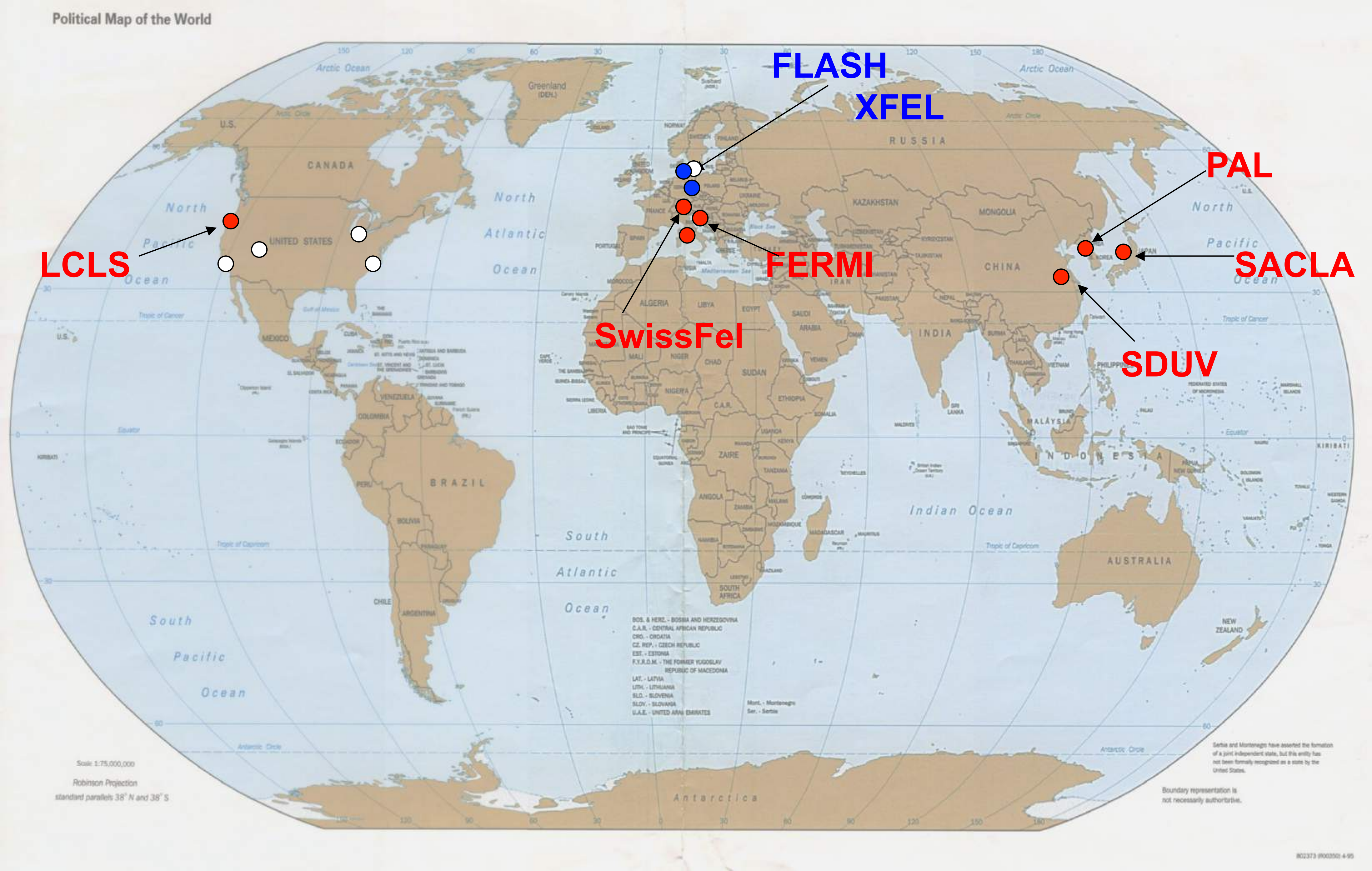
X-FEL based on last 1-km of existing *SLAC* linac

LCLS: world's first hard x-ray FEL

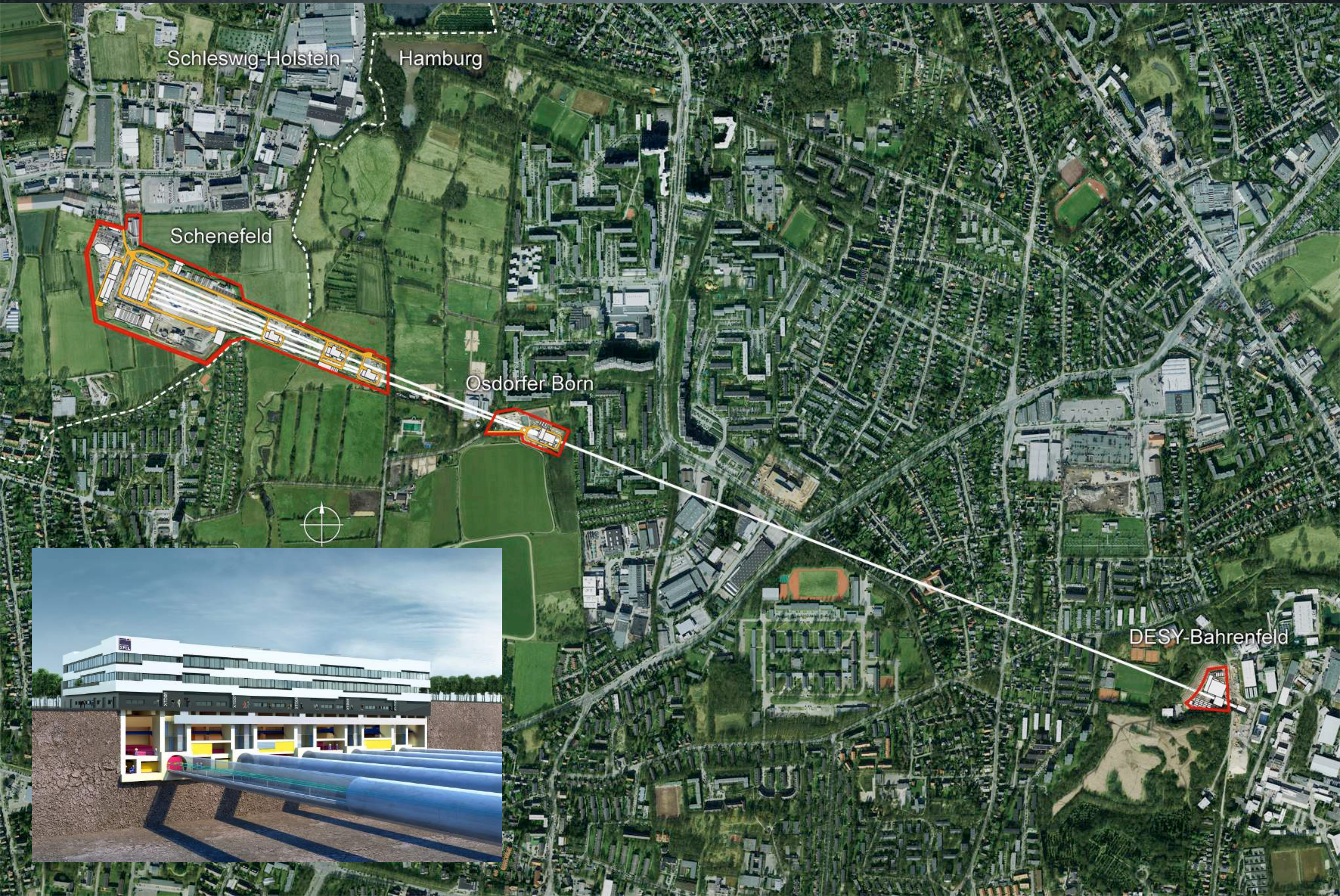


- SASE wavelength range: **25 – 1.2** Å
- Photon energy range: **0.5 - 10** keV
- Pulse length FWHM **5 - 500** fs (SXR only)
- Pulse energy up to **4** mJ

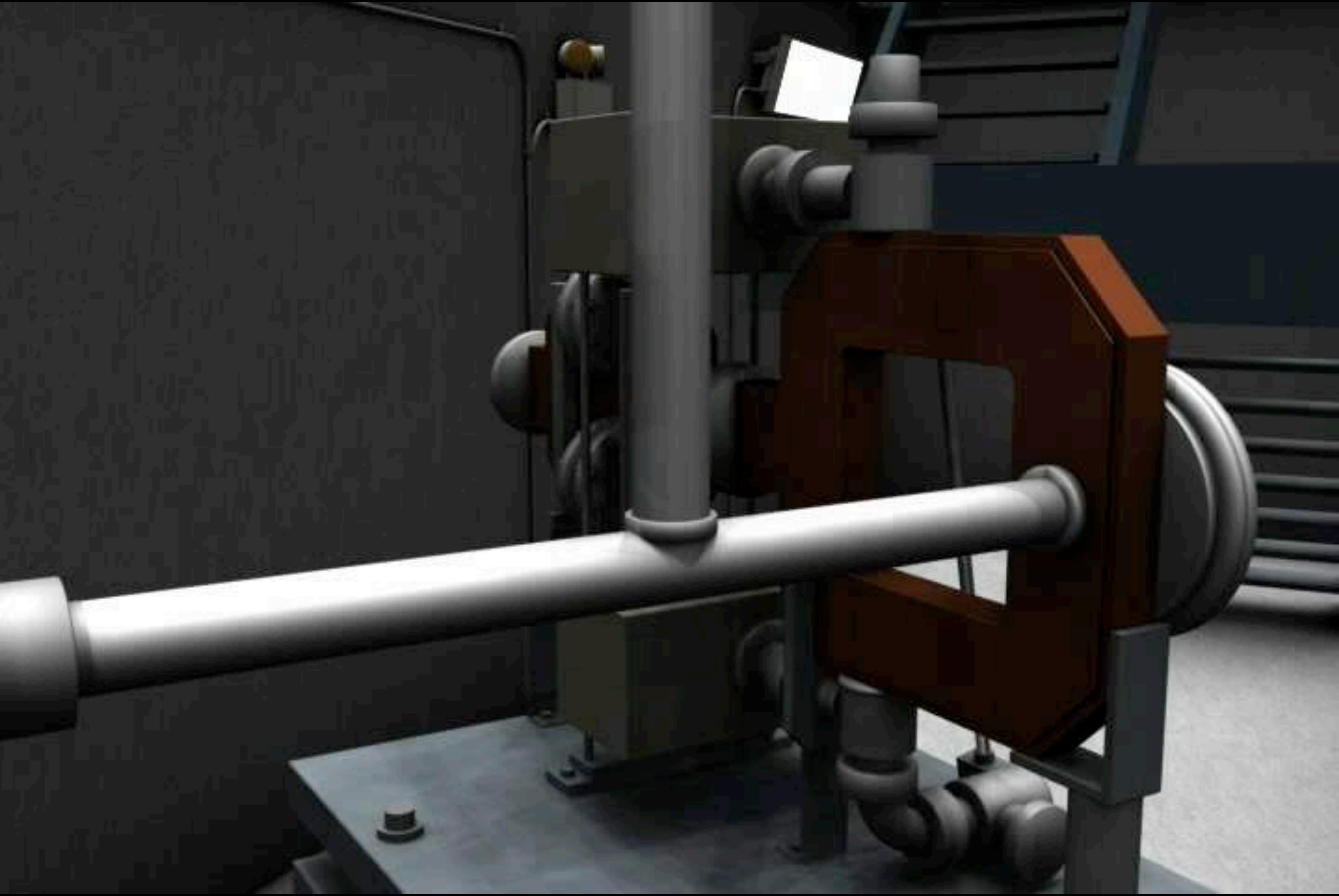
Short Wavelength SASE FEL



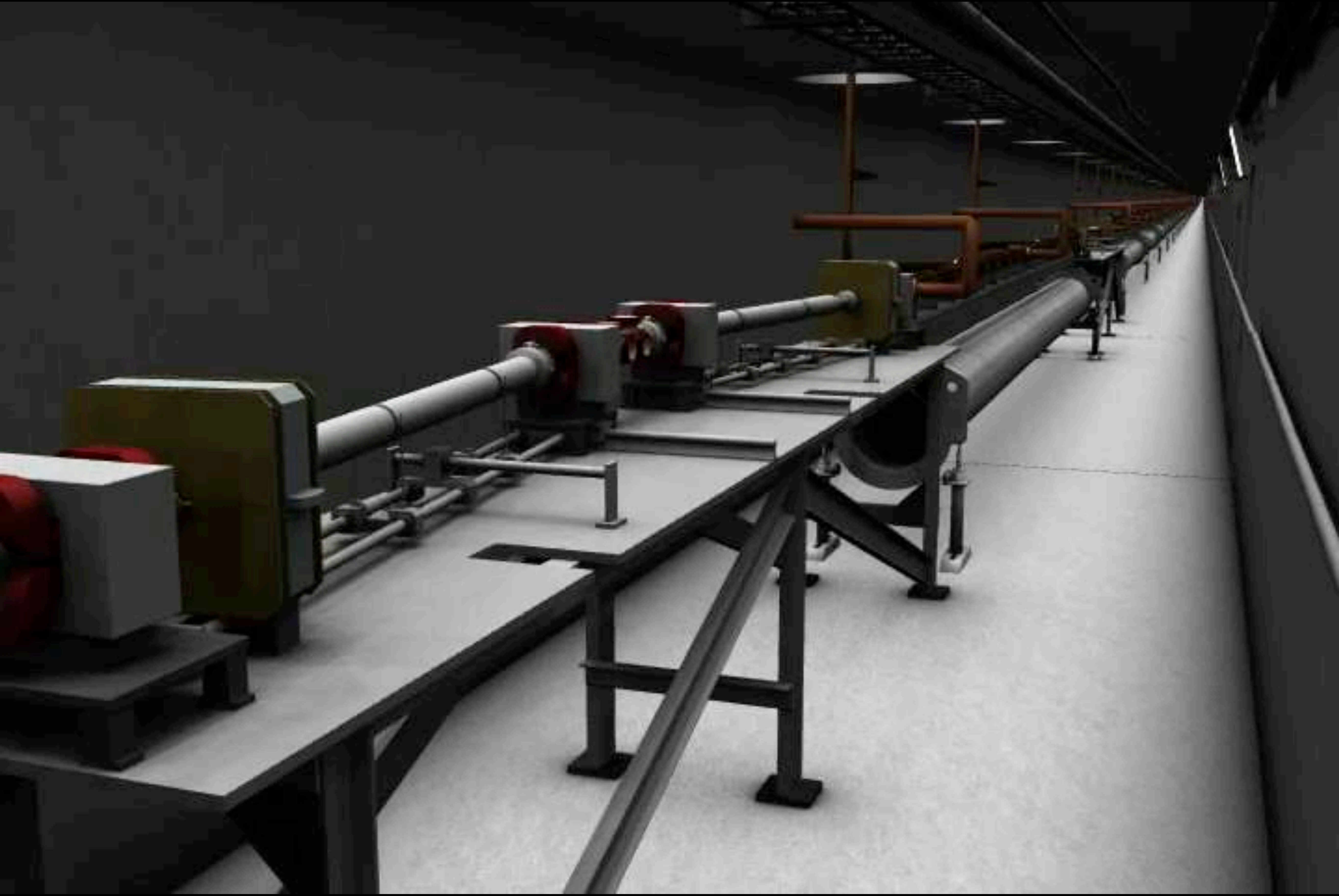
XFEL first lasing – Hamburg - May 2017



Electron source and acceleration



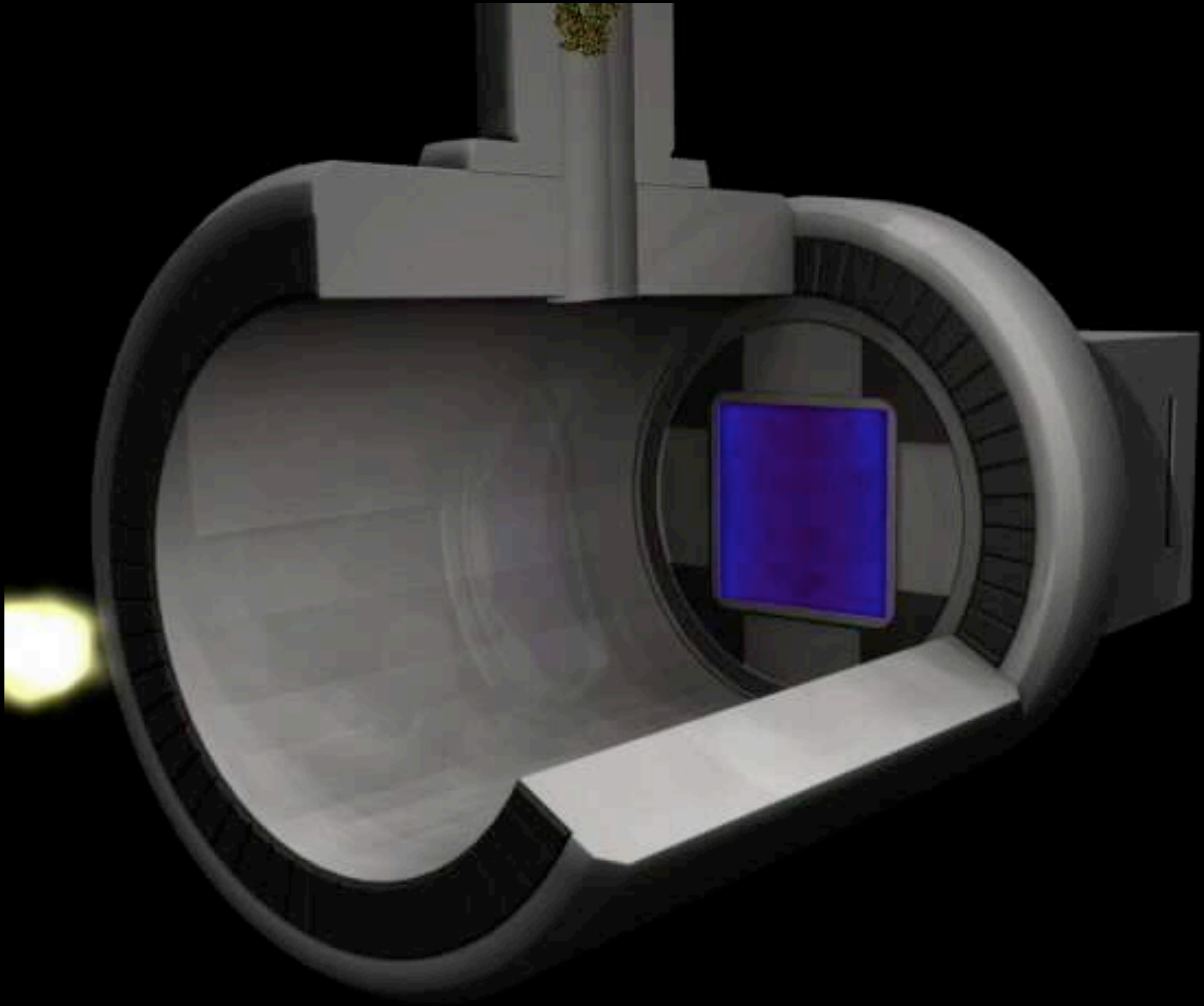
Magnetic bunch compressor (< 1 ps)



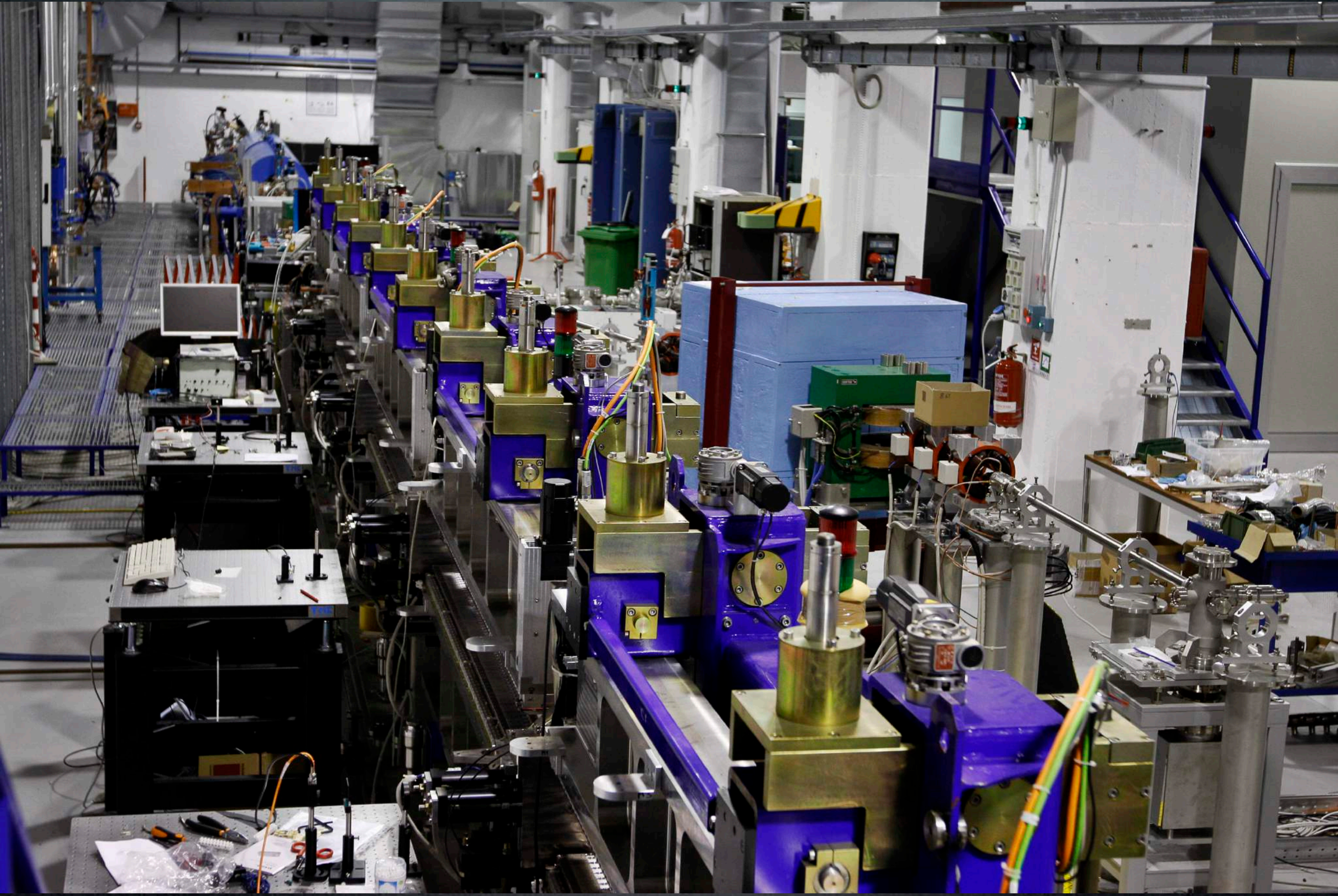
Long undulators chain

Beam separation

Experimental hall (Single Protein Imaging)



http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx



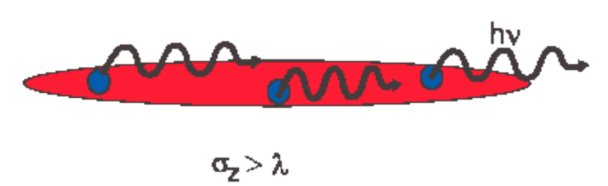
Peak power of one accelerated charge:

$$P_1 = \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$

Different electrons radiate indepedently hence the total power depends linearly on the number N_e of electrons per bunch:

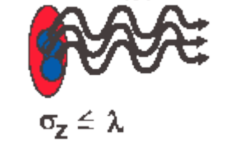
Incoherent Spontaneous Radiation Power:

$$P_T = N_e \frac{e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



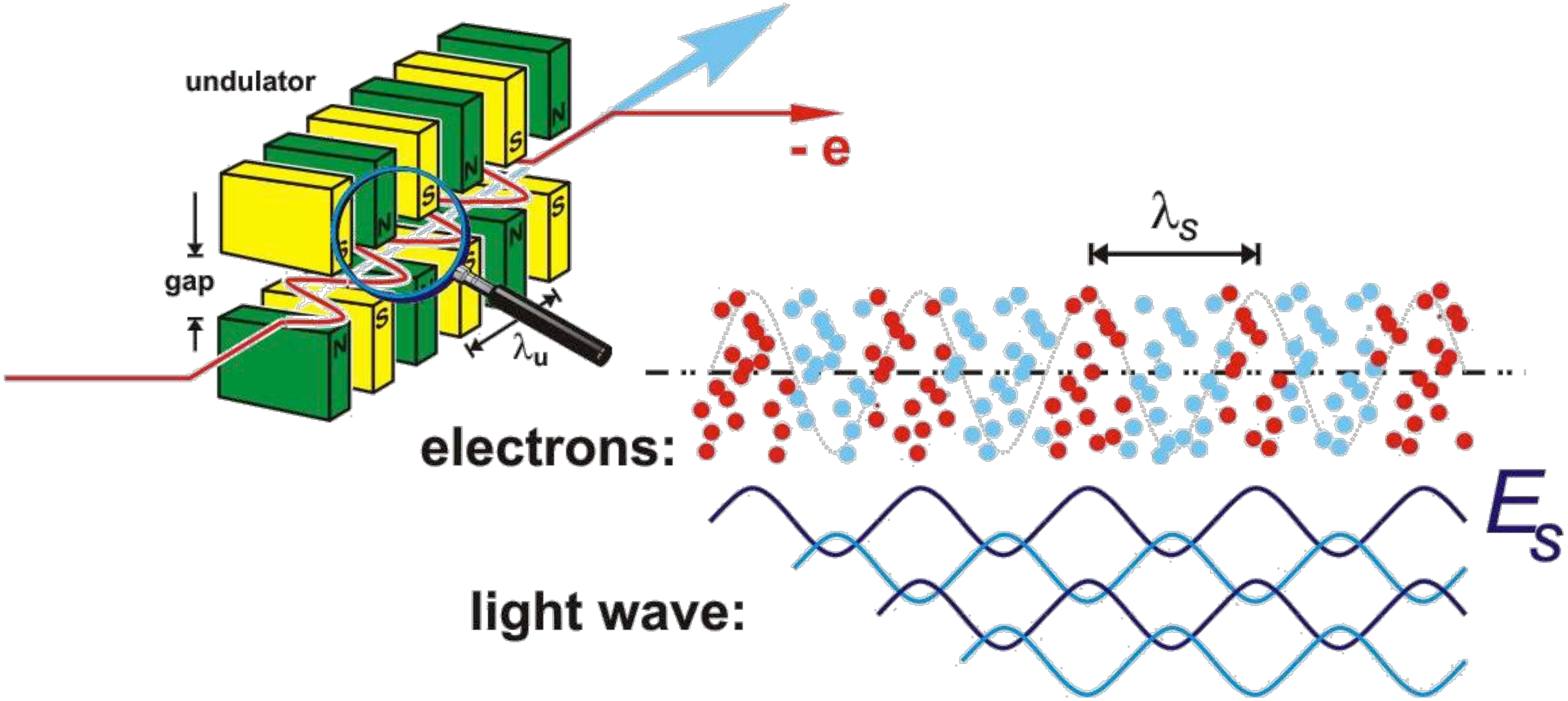
Coherent Stimulated Radiation Power:

$$P_T = \frac{N_e^2 e^2}{6\pi\varepsilon_o c^3}\gamma^4\left\langle \dot{v}_\perp^2 \right\rangle$$



Bunching on the scale of the wavelength:

Spontaneous Emission ==> Random phases



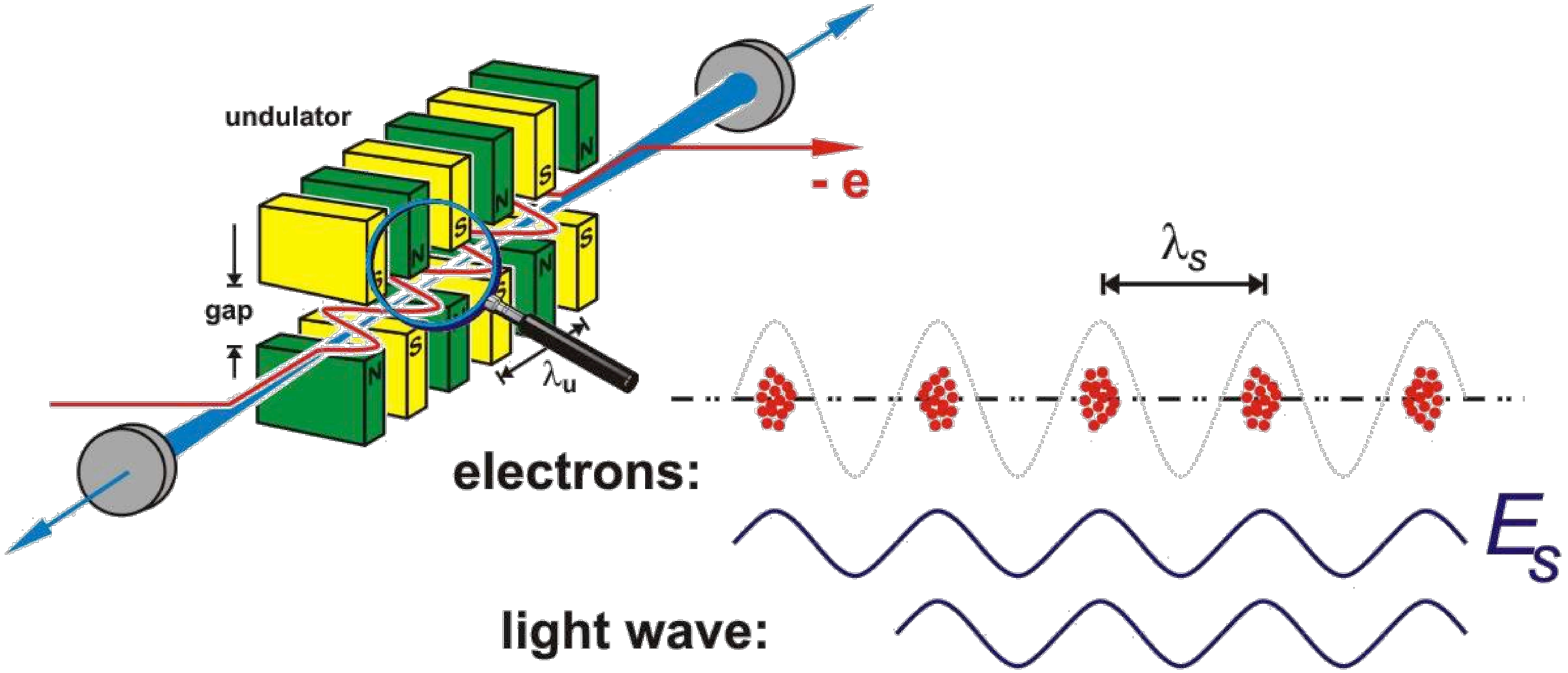
Radiated Power:

$$P \propto \mathrm{N}$$

destructive interference

⟶ **shotnoise radiation**

Coherent Light ==> Stimulated Emission

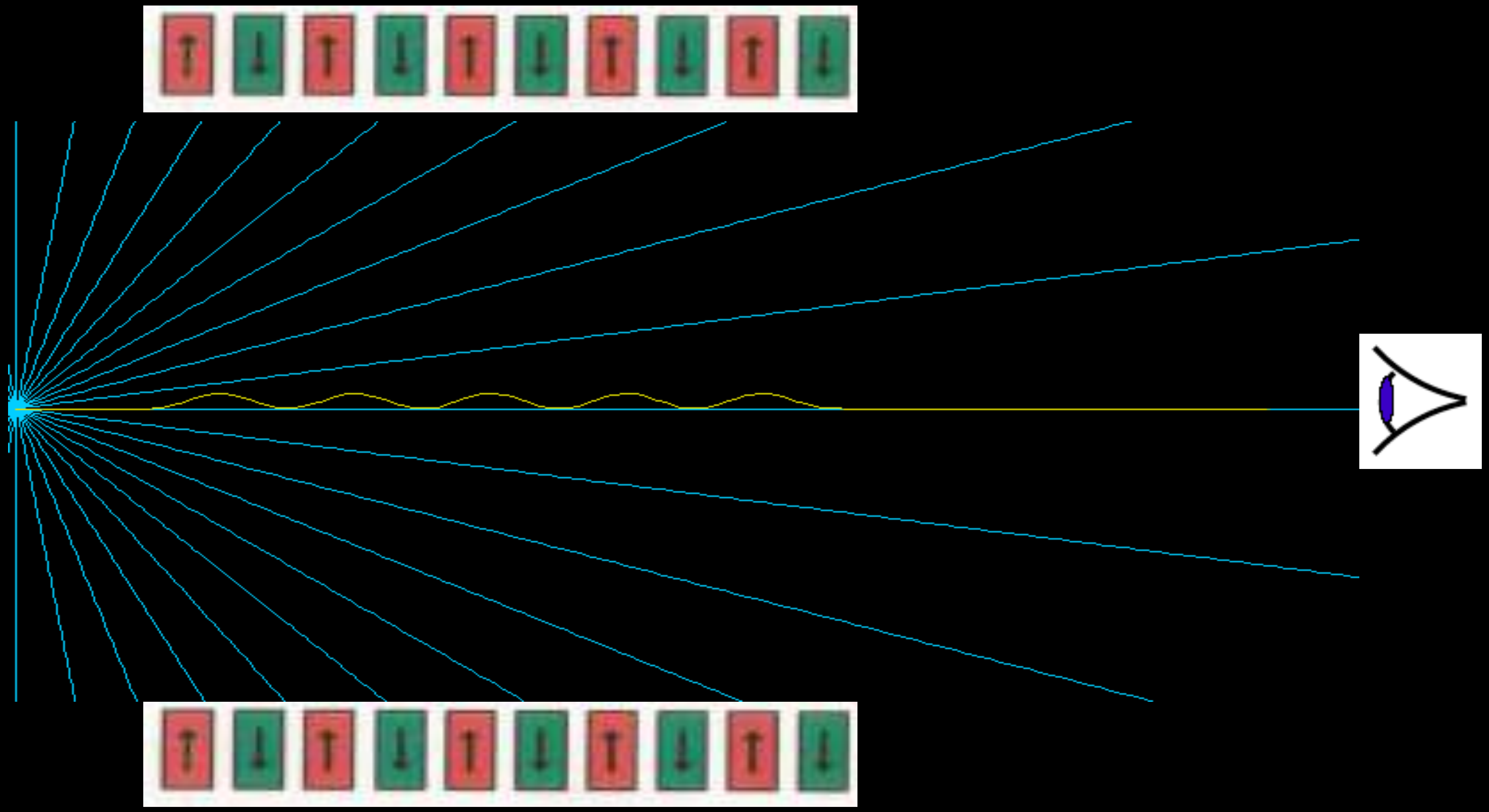


Radiated Power :

$P \propto N^2$

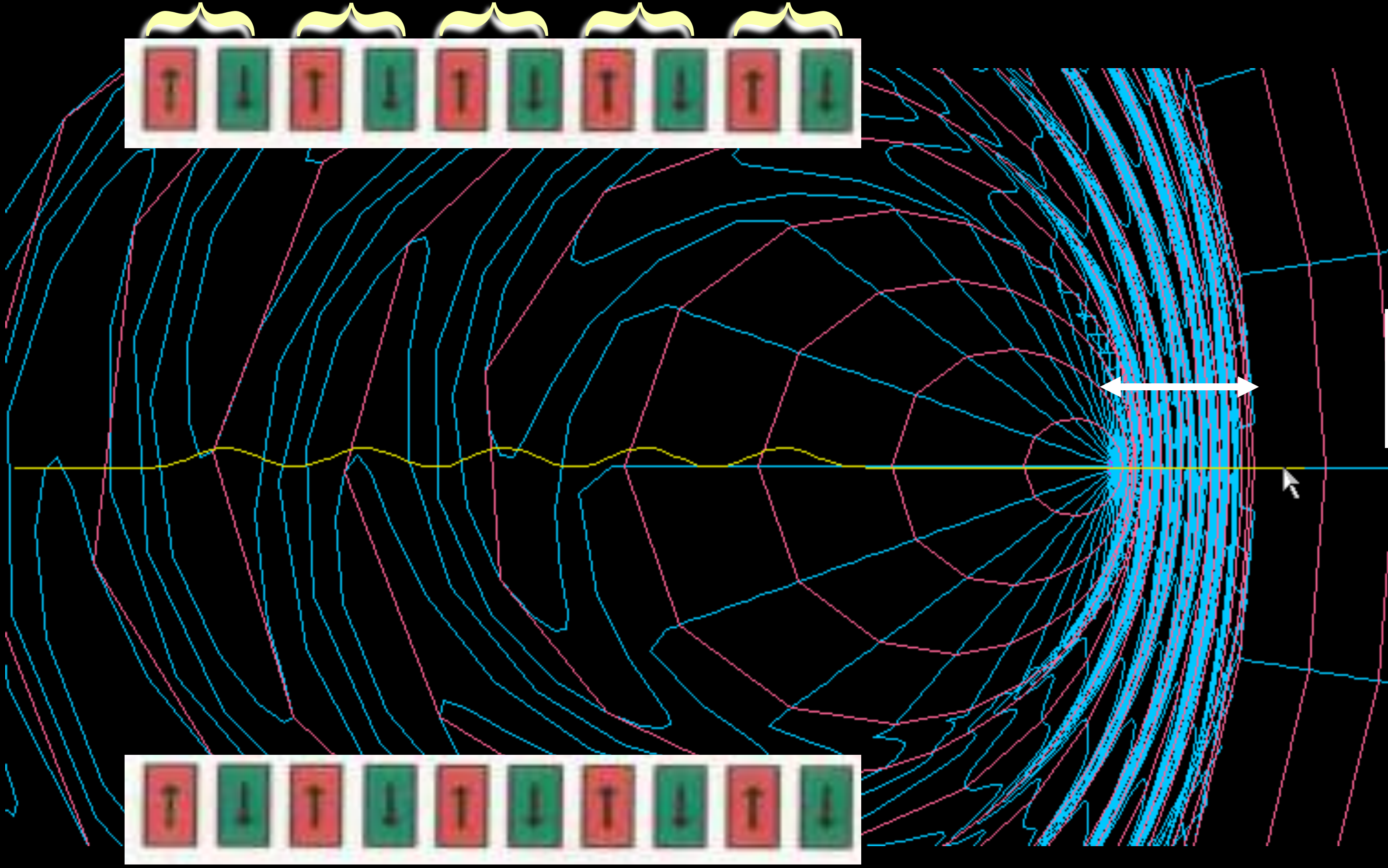
constructive interference

⟶ **enhanced emission**



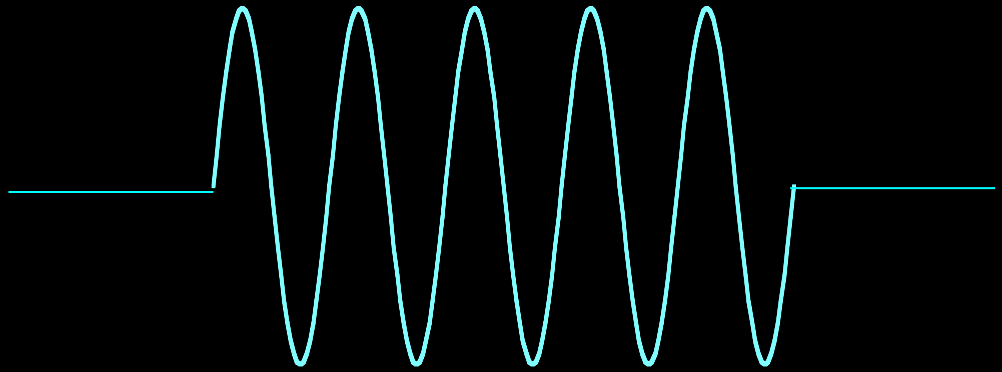
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

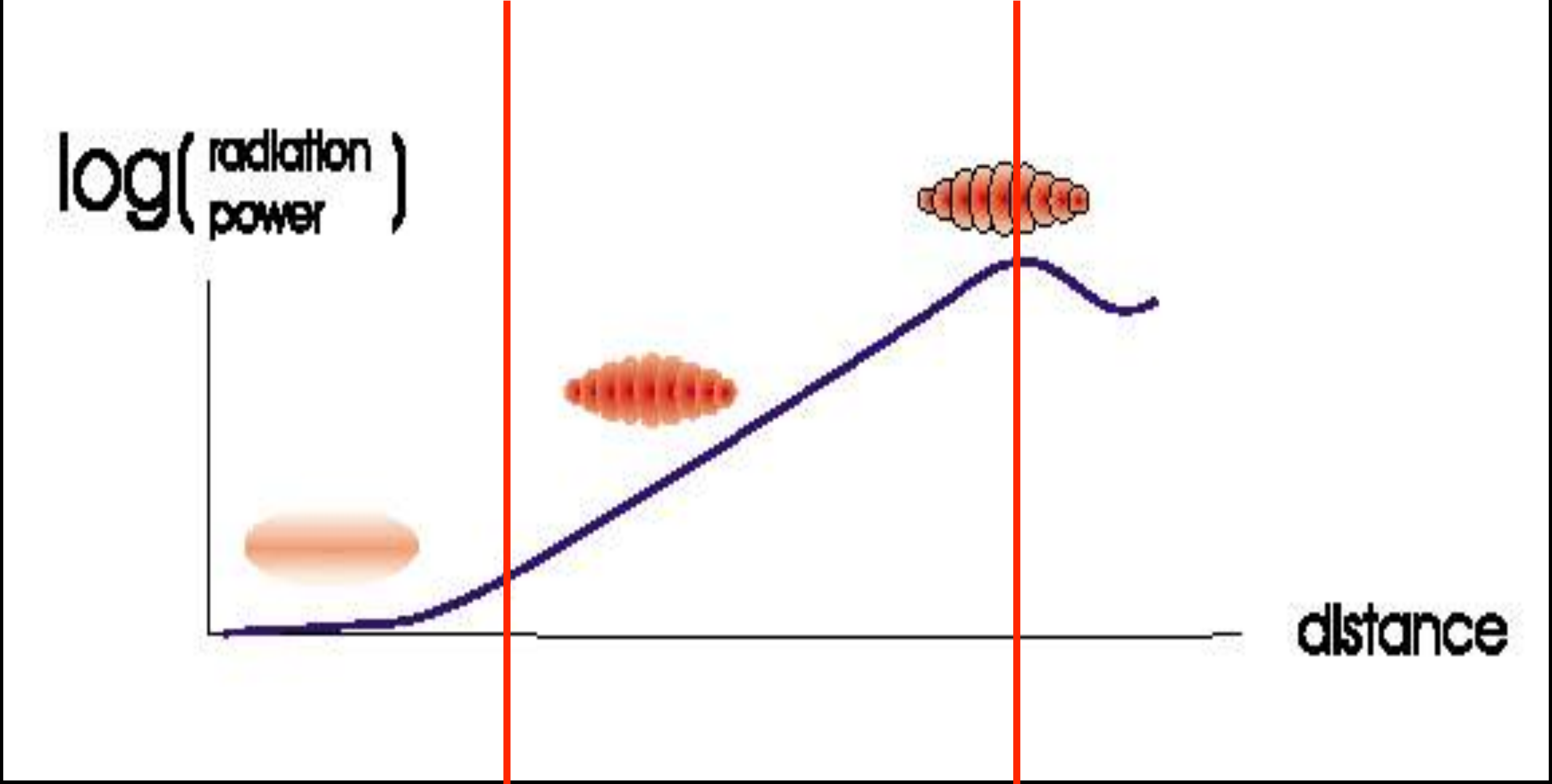
$N_u = 5$



$$L_{pulse} = N_u \lambda_{rad}$$

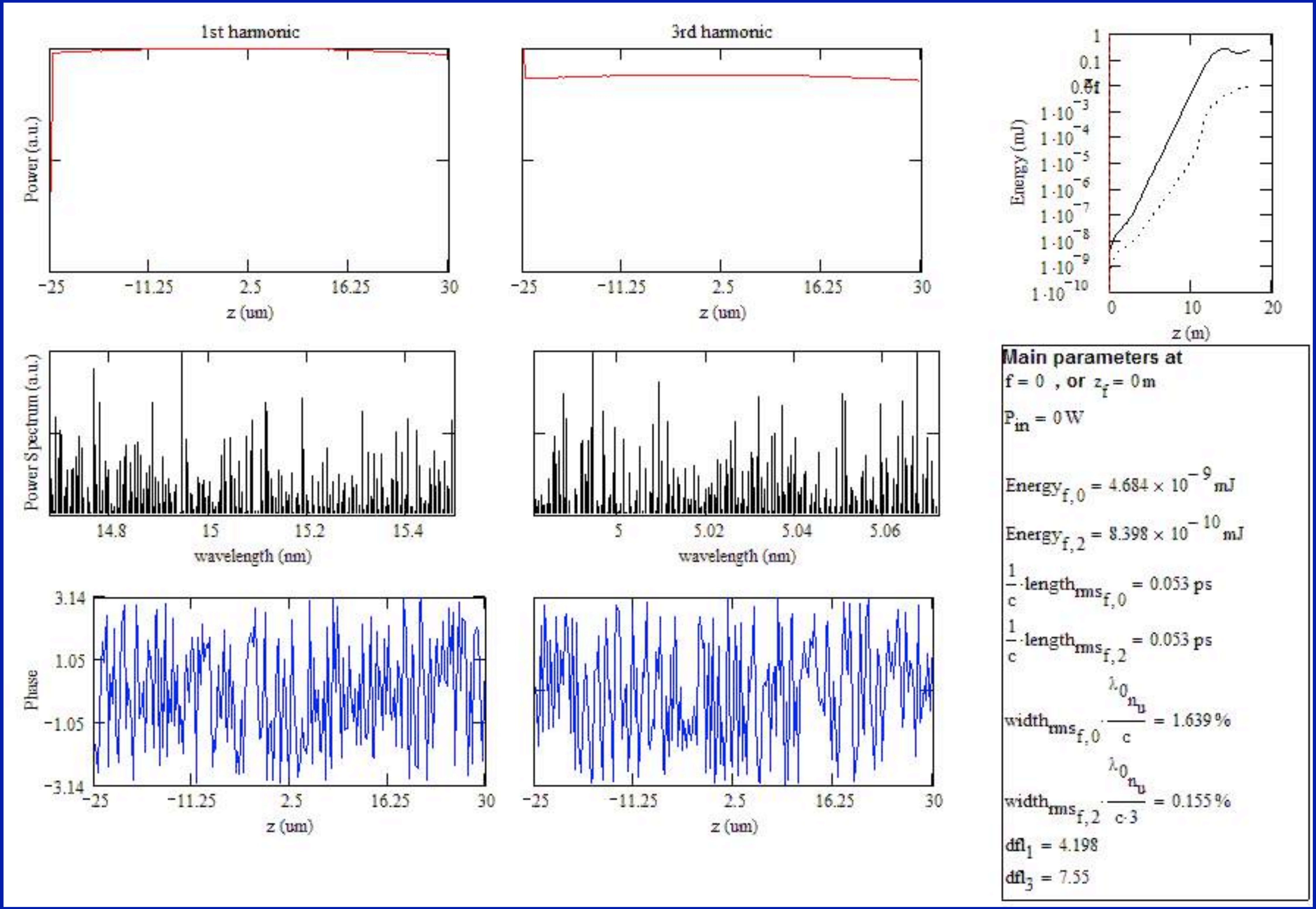
$$\lambda_{rad} \propto \frac{\lambda_u}{2\gamma^2}$$





Letargy	**Exponential Growth**	**Saturation**
Spontaneous Emission	Stimulated emission	Absorption
Low Gain	High Gain	No Gain
Slow Bunching	Enhanced Bunching	Debunching

SASE



Main parameters at

f = 0 , or $z_f = 0$ m

$P_{in} = 0$ W

$Energy_{f,0} = 4.684 \times 10^{-9}$ mJ

$Energy_{f,2} = 8.398 \times 10^{-10}$ mJ

$\frac{1}{c} \cdot length_{rms_{f,0}} = 0.053$ ps

$\frac{1}{c} \cdot length_{rms_{f,2}} = 0.053$ ps

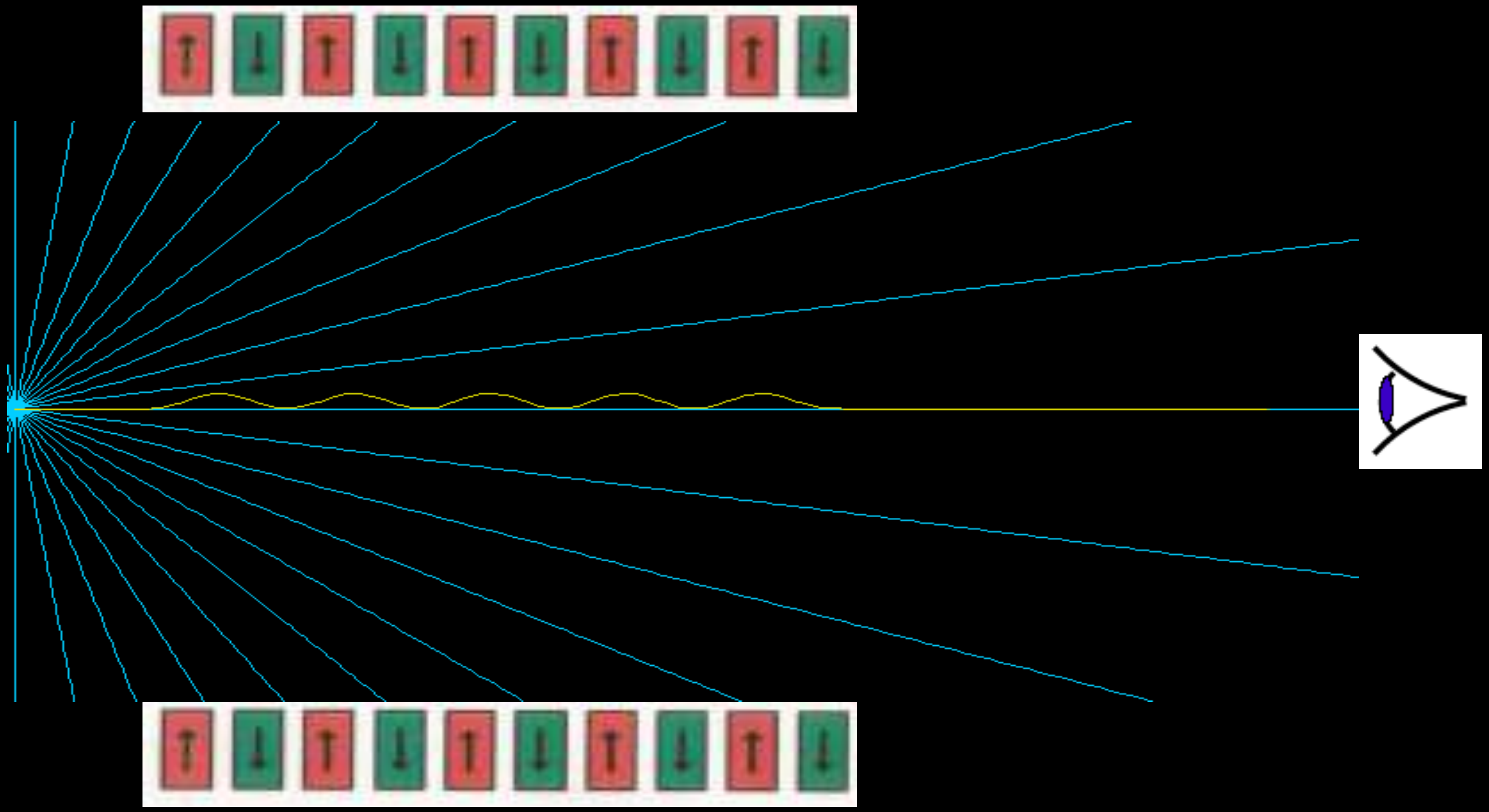
$width_{rms_{f,0}} \cdot \frac{\lambda_{0_{n_u}}}{c} = 1.639\,\%$

$width_{rms_{f,2}} \cdot \frac{\lambda_{0_{n_u}}}{c \cdot 3} = 0.155\,\%$

$dfl_1 = 4.198$

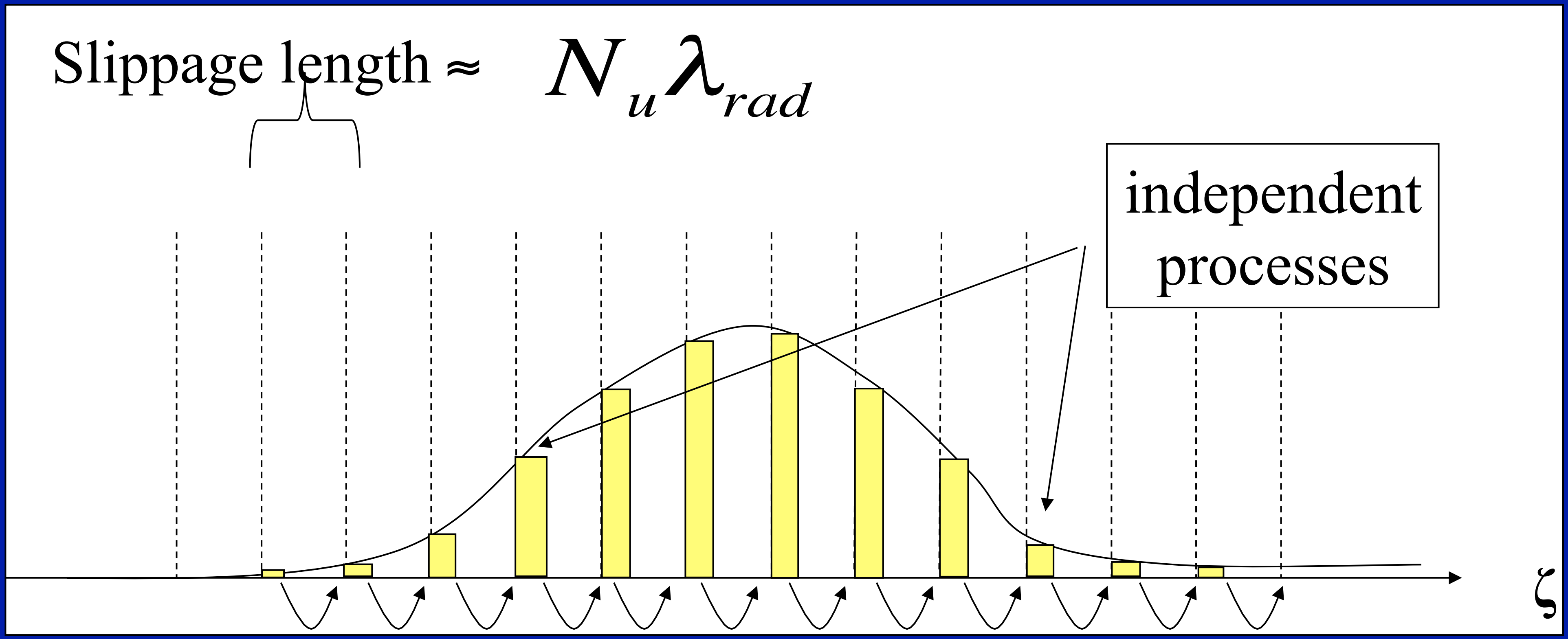
$dfl_3 = 7.55$

Courtesy L. Giannessi (Perseo in 1D mode http://www.perseo.enea.it)



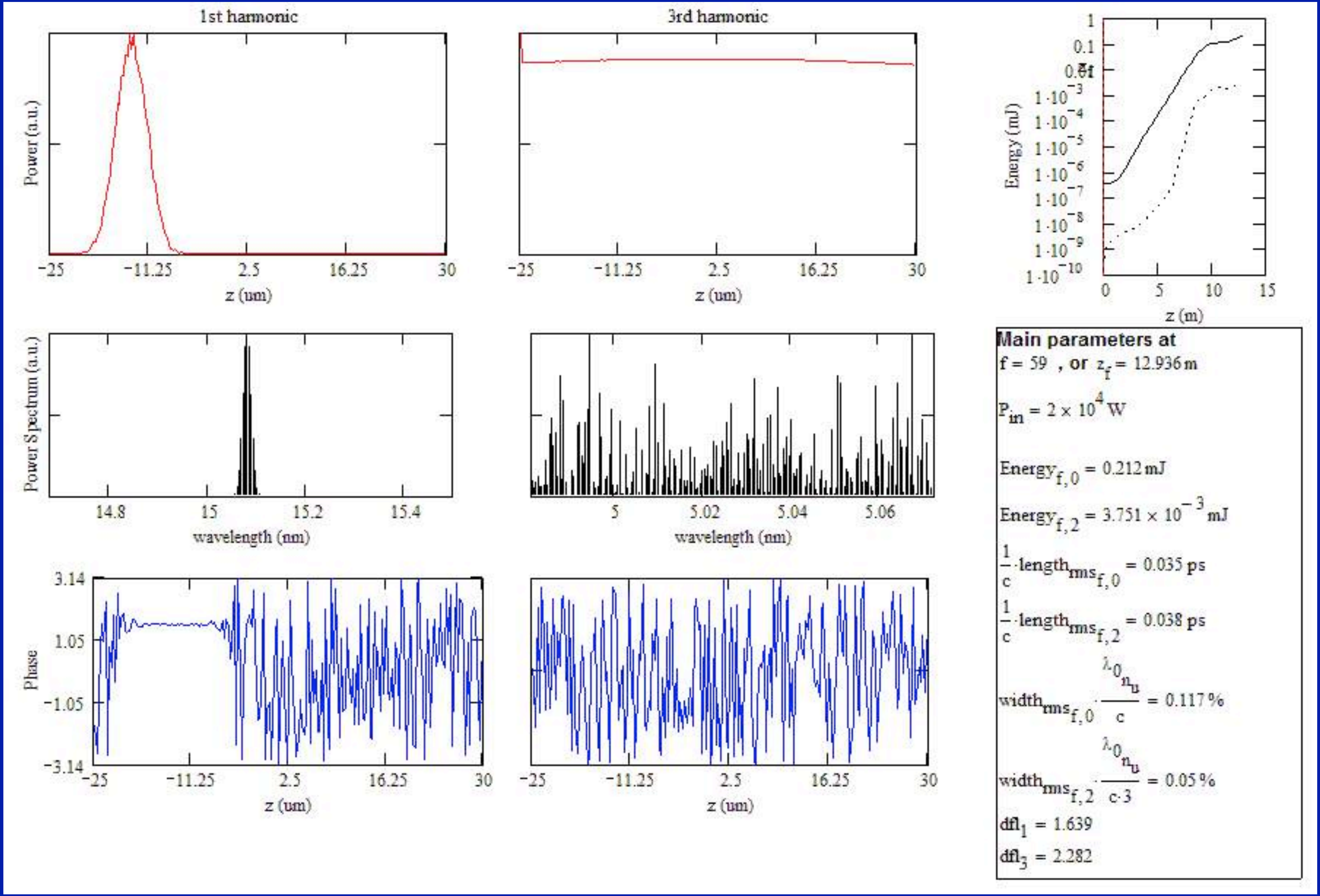
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

SASE Longitudinal coherence



The radiation "slips" over the electrons for a distance $N_u \lambda_{rad}$

SEEDING



Main parameters at

$f = 59$, **or** $z_f = 12.936\,\mathrm{m}$

$P_{in} = 2 \times 10^{4}\,\mathrm{W}$

$\mathrm{Energy}_{f,0} = 0.212\,\mathrm{mJ}$

$\mathrm{Energy}_{f,2} = 3.751 \times 10^{-3}\,\mathrm{mJ}$

$\frac{1}{c}\cdot \mathrm{length}_{\mathrm{rms}_{f,0}} = 0.035\,\mathrm{ps}$

$\frac{1}{c}\cdot \mathrm{length}_{\mathrm{rms}_{f,2}} = 0.038\,\mathrm{ps}$

$\mathrm{width}_{\mathrm{rms}_{f,0}} \cdot \frac{\lambda_{0_{n_u}}}{c} = 0.117\,\%$

$\mathrm{width}_{\mathrm{rms}_{f,2}} \cdot \frac{\lambda_{0_{n_u}}}{c\cdot 3} = 0.05\,\%$

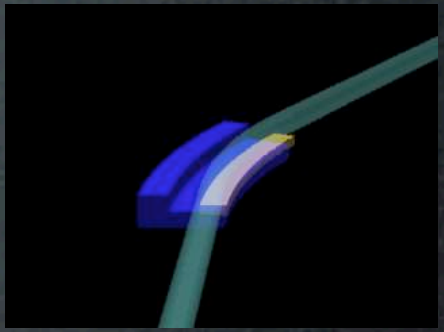
$\mathrm{dfl}_1 = 1.639$

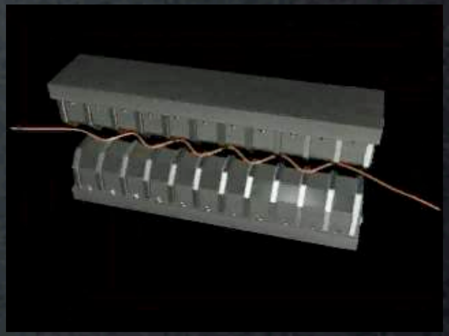
$\mathrm{dfl}_3 = 2.282$

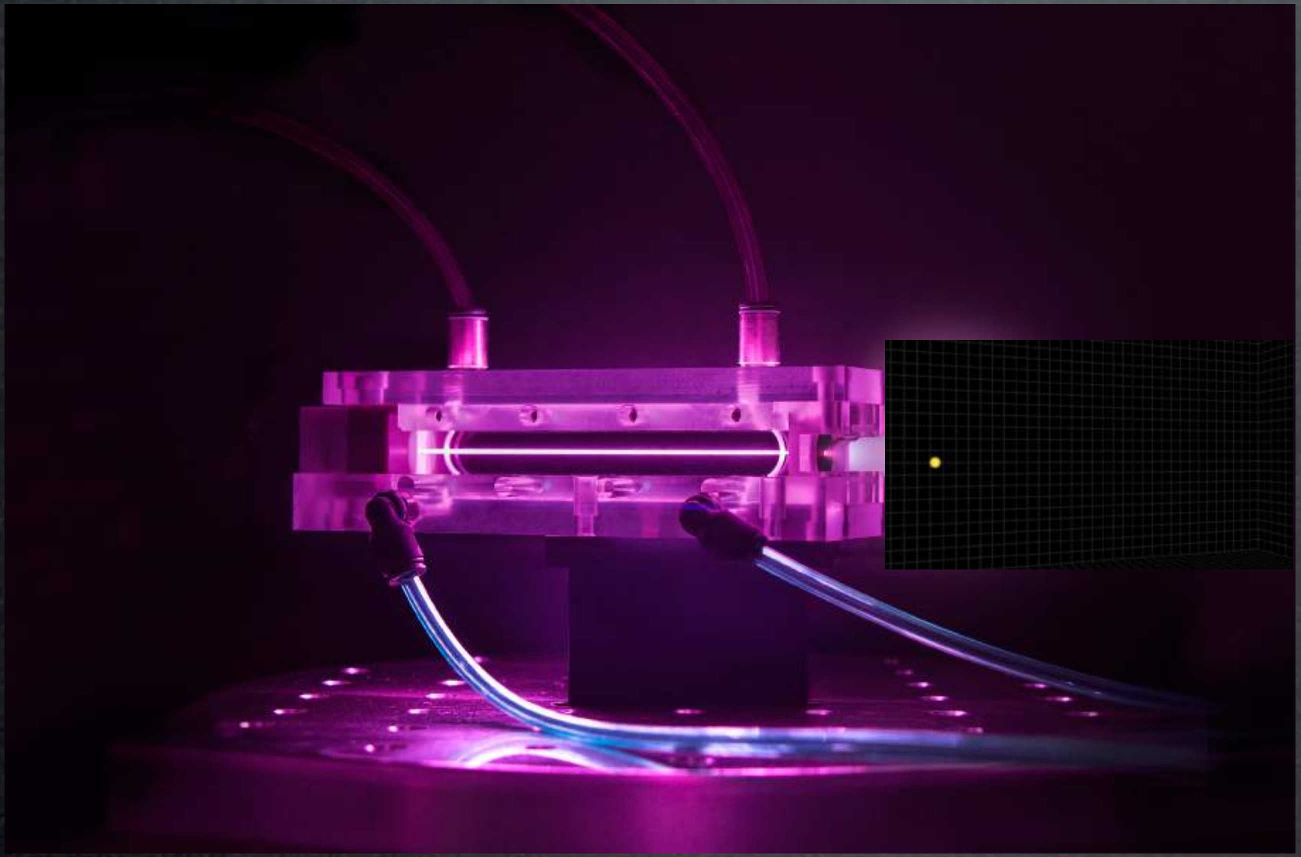
Courtesy L. Giannessi (Perseo in 1D mode http://www.perseo.enea.it)

Generations of Synchrotron Light Sources

I. Bending magnets in HEP rings



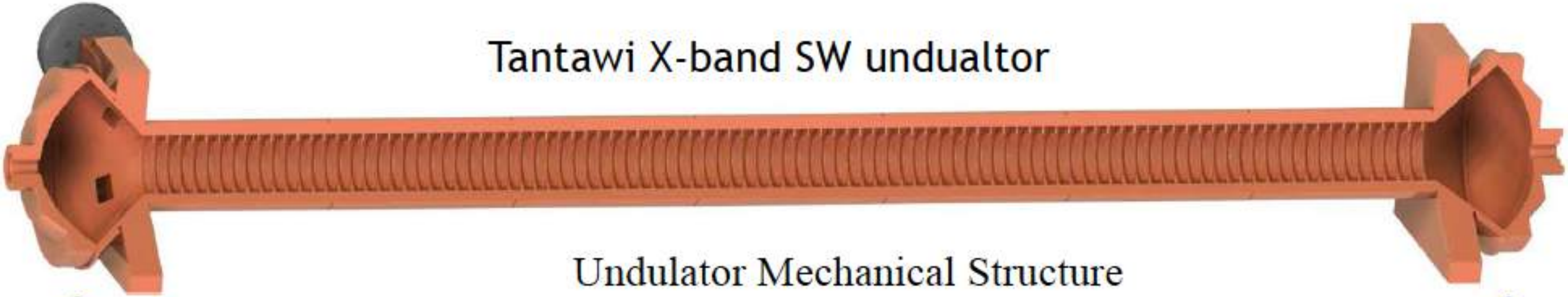




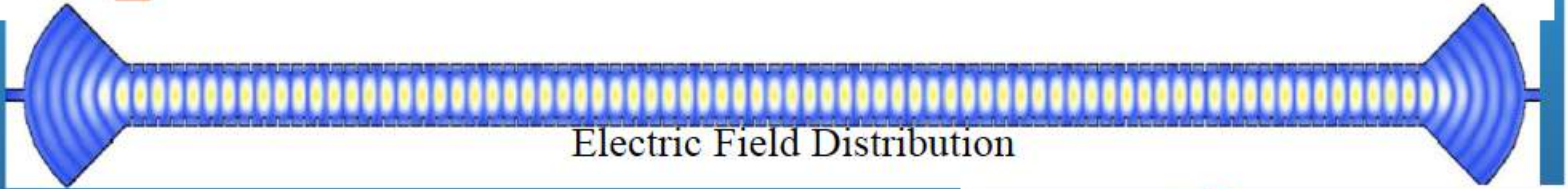
V. Compact Sources

The next generation undulator: The electromagnetic era

Tantawi X-band SW undualtor

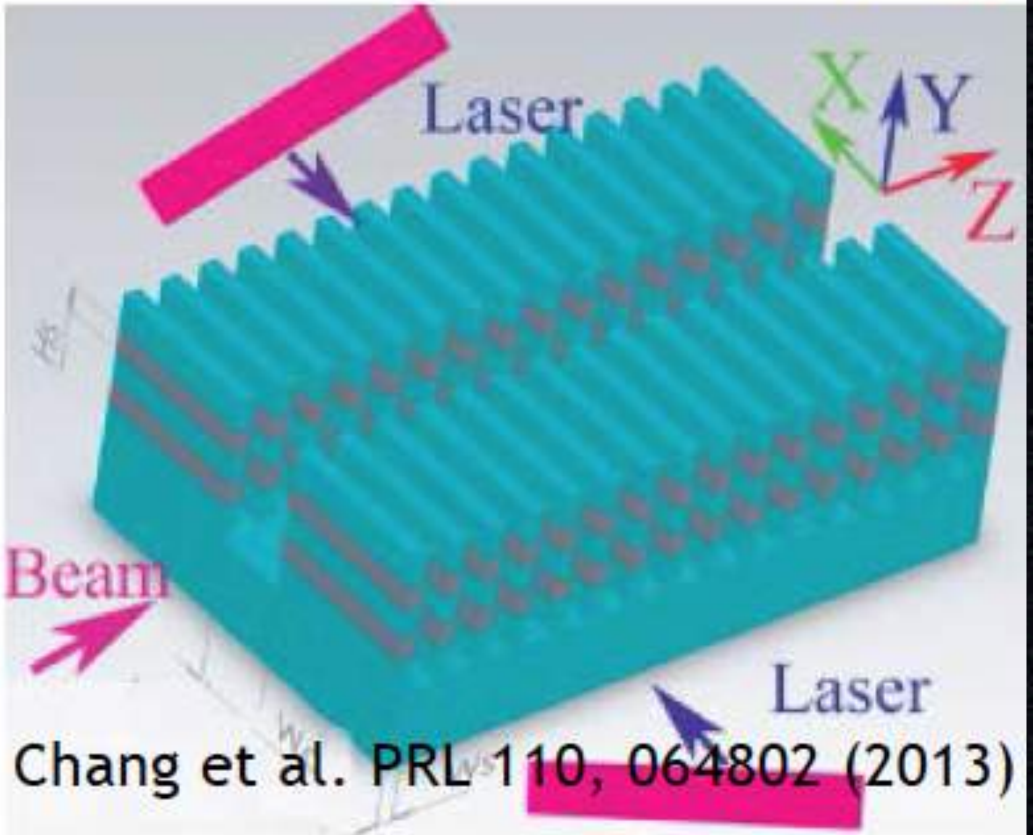


Undulator Mechanical Structure



Electric Field Distribution

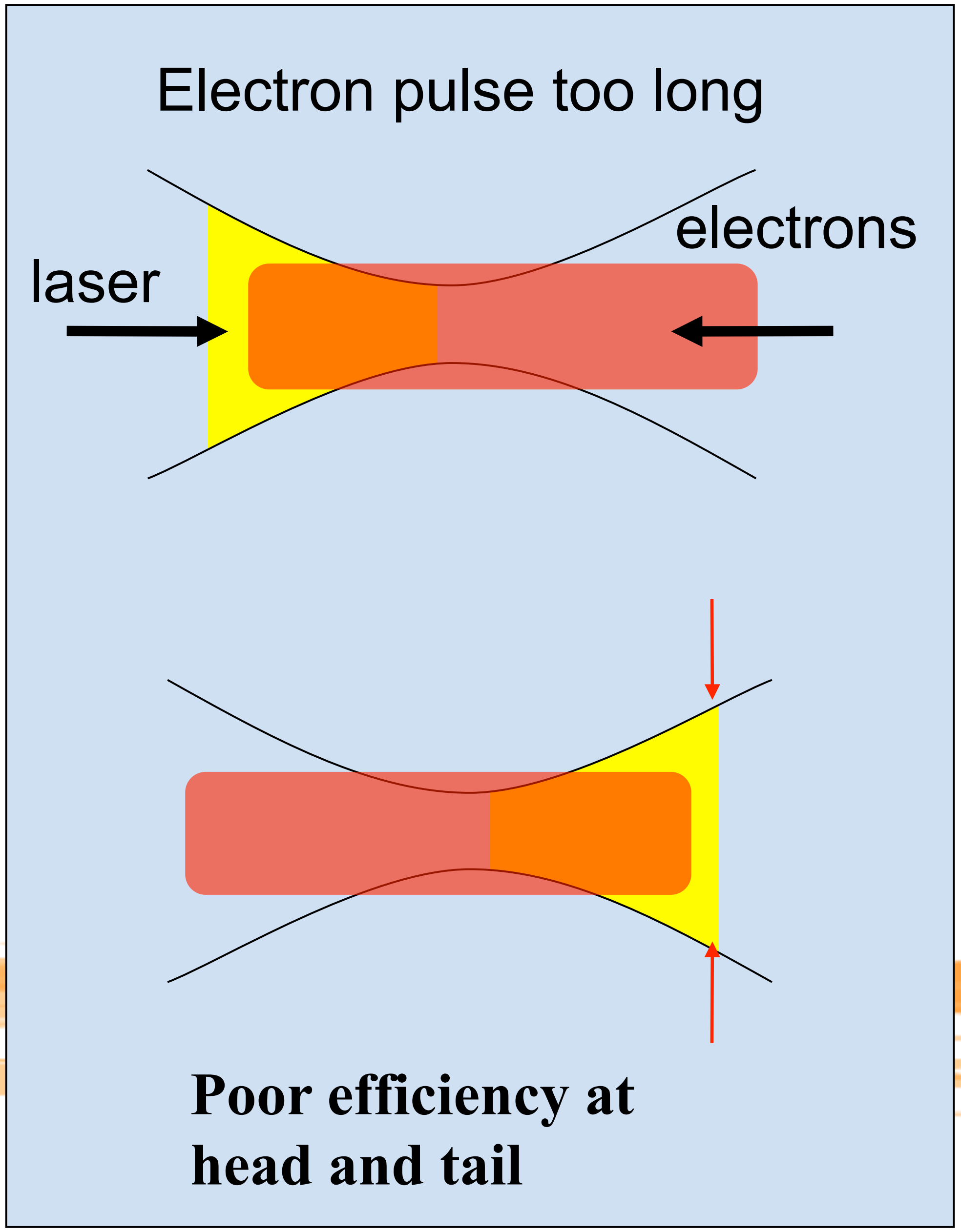
- To use <1 GeV in XFEL, need λ=100 um undulator
- *K*~0.1 or above means *T*-level B_0 inadequate
- On to *EM undulators*: THz SW structures, IR TW guides, free-space Thompson



Chang et al. PRL 110, 064802 (2013)

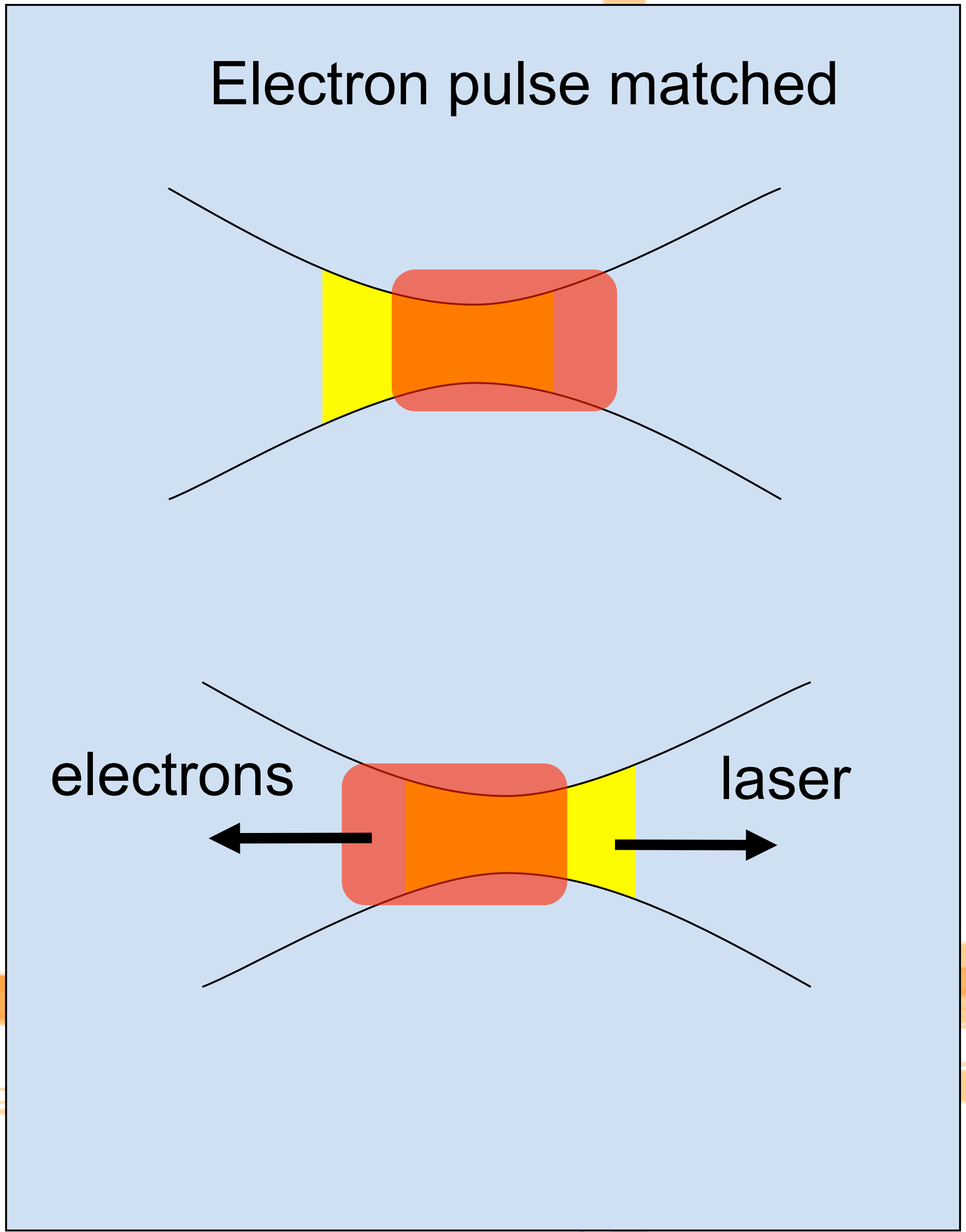
Optical Undulator

➔ Matching electron beam length to Rayleigh Length



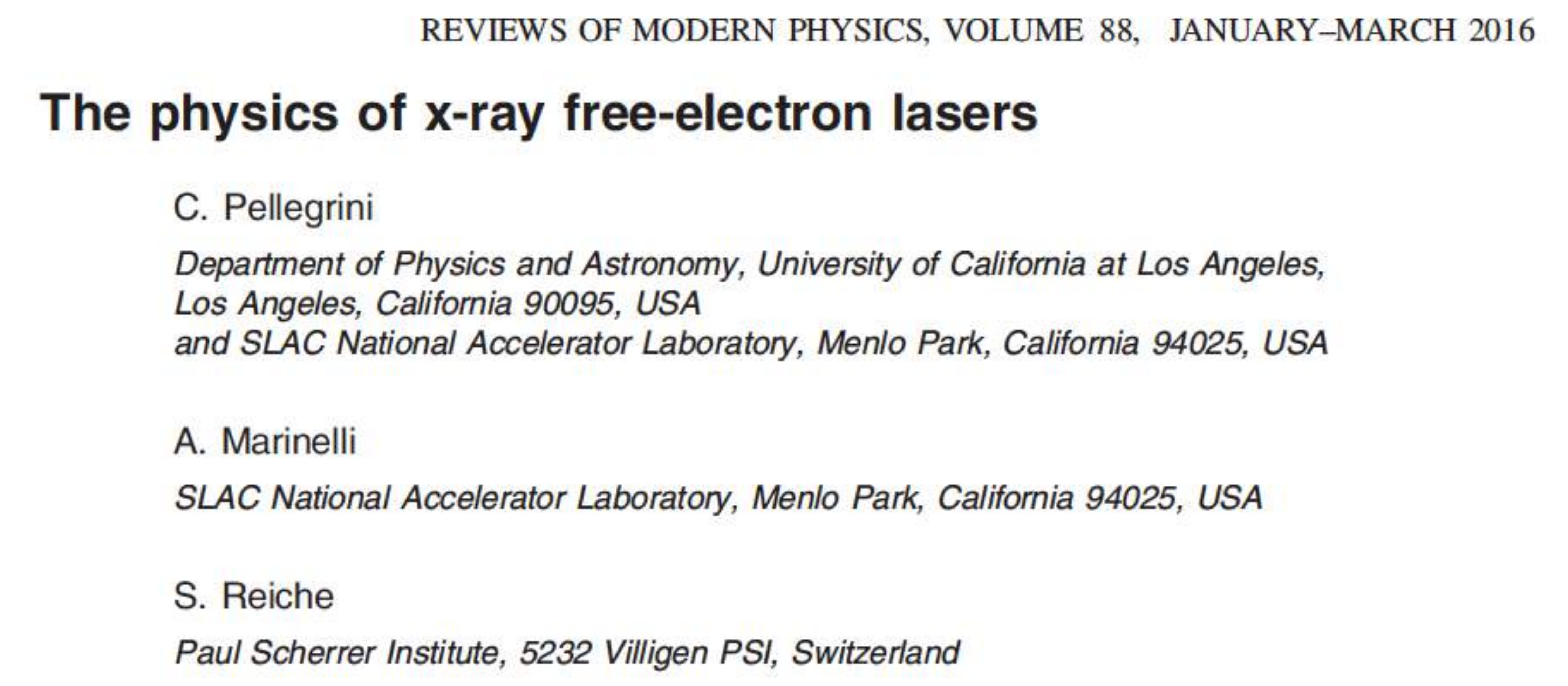
Electron pulse too long

Poor efficiency at head and tail



Electron pulse matched

courtesy of D. Moncton



REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

The physics of x-ray free-electron lasers

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Department of Physics and Astronomy, University of California at Los Angeles,
Los Angeles, California 90095, USA
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A. Marinelli

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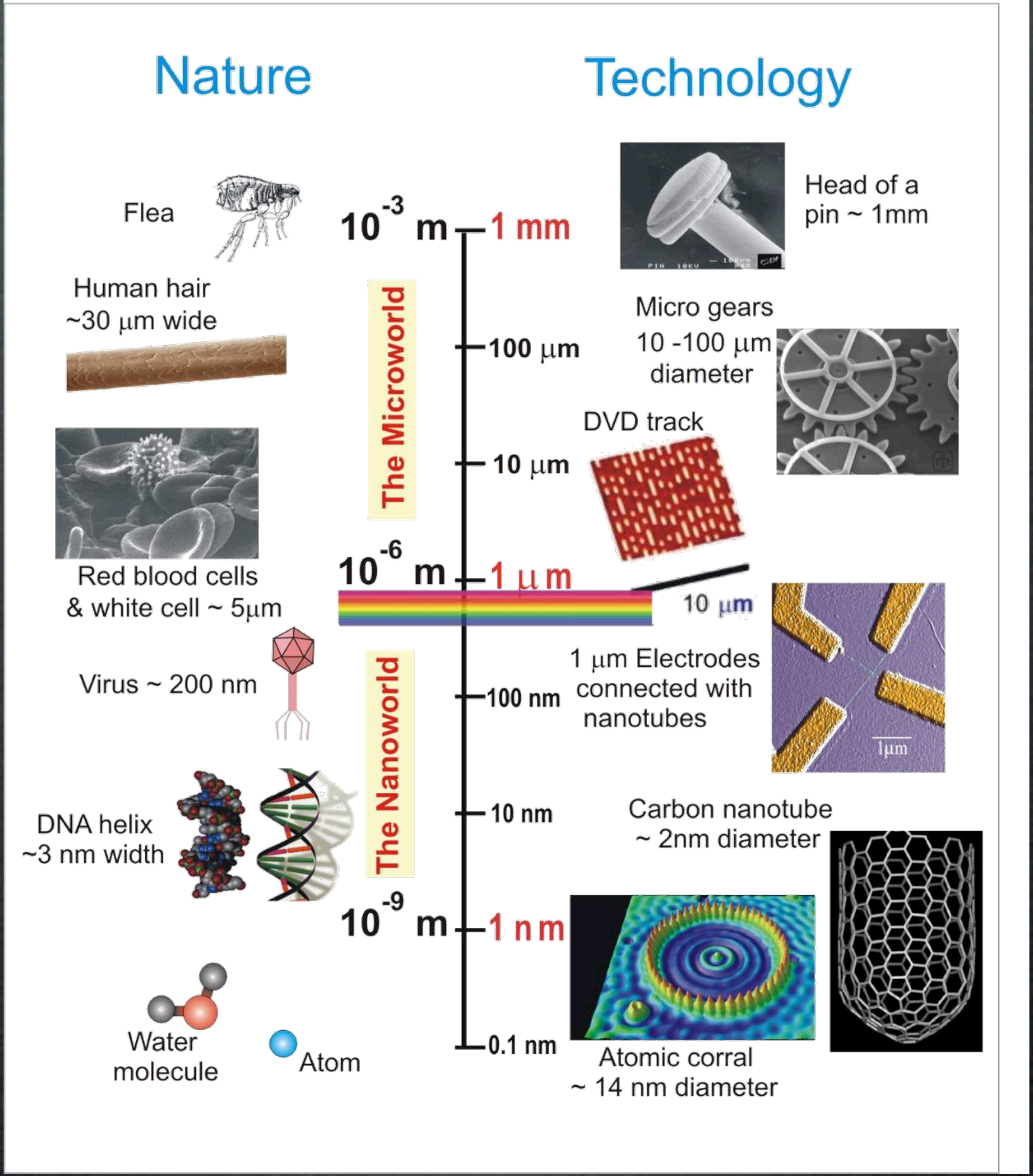
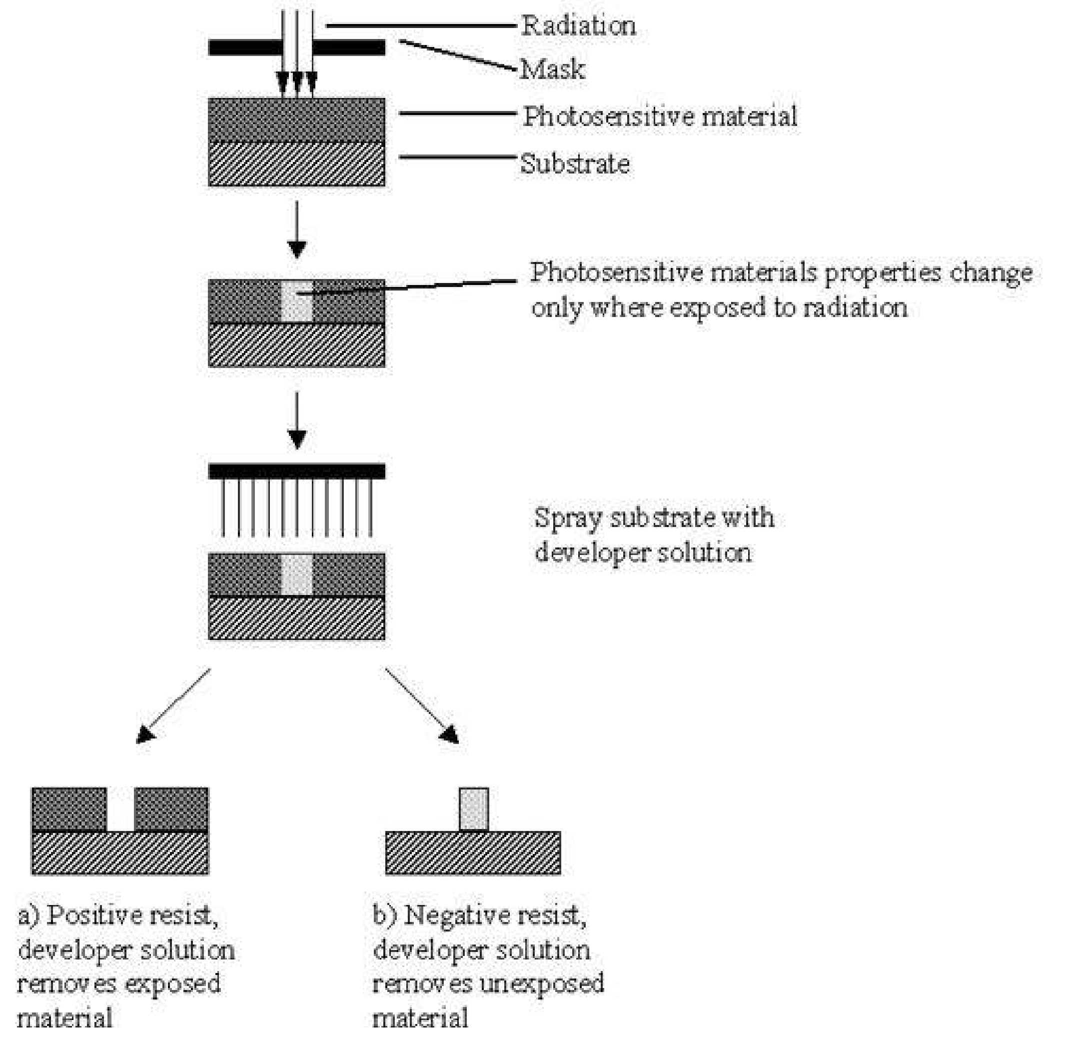
Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

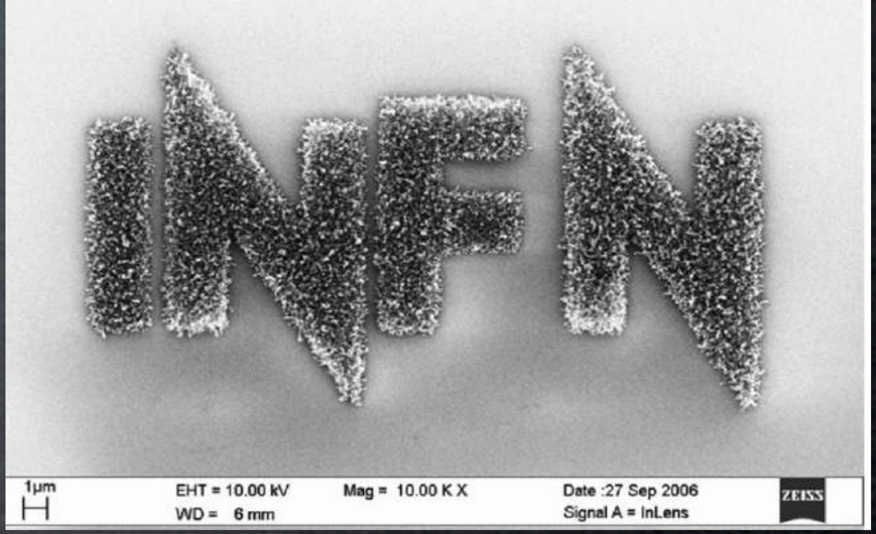
Ultra-Small


Nature
Technology
Flea
Human hair
~30 µm wide
Red blood cells
& white cell ~ 5µm
Virus ~ 200 nm
DNA helix
~3 nm width
Water
molecule
Atom
10^-3 m
1 mm
100 µm
10 µm
10^-6 m
1 µm
100 nm
10 nm
10^-9 m
1 nm
0.1 nm
The Microworld
The Nanoworld
Head of a
pin ~ 1mm
Micro gears
10 -100 µm
diameter
DVD track
10 µm
1 µm Electrodes
connected with
nanotubes
1µm
Carbon nanotube
~ 2nm diameter
Atomic corral
~ 14 nm diameter

nano lithography



Michelangelo Ambrosio INFN-GINT



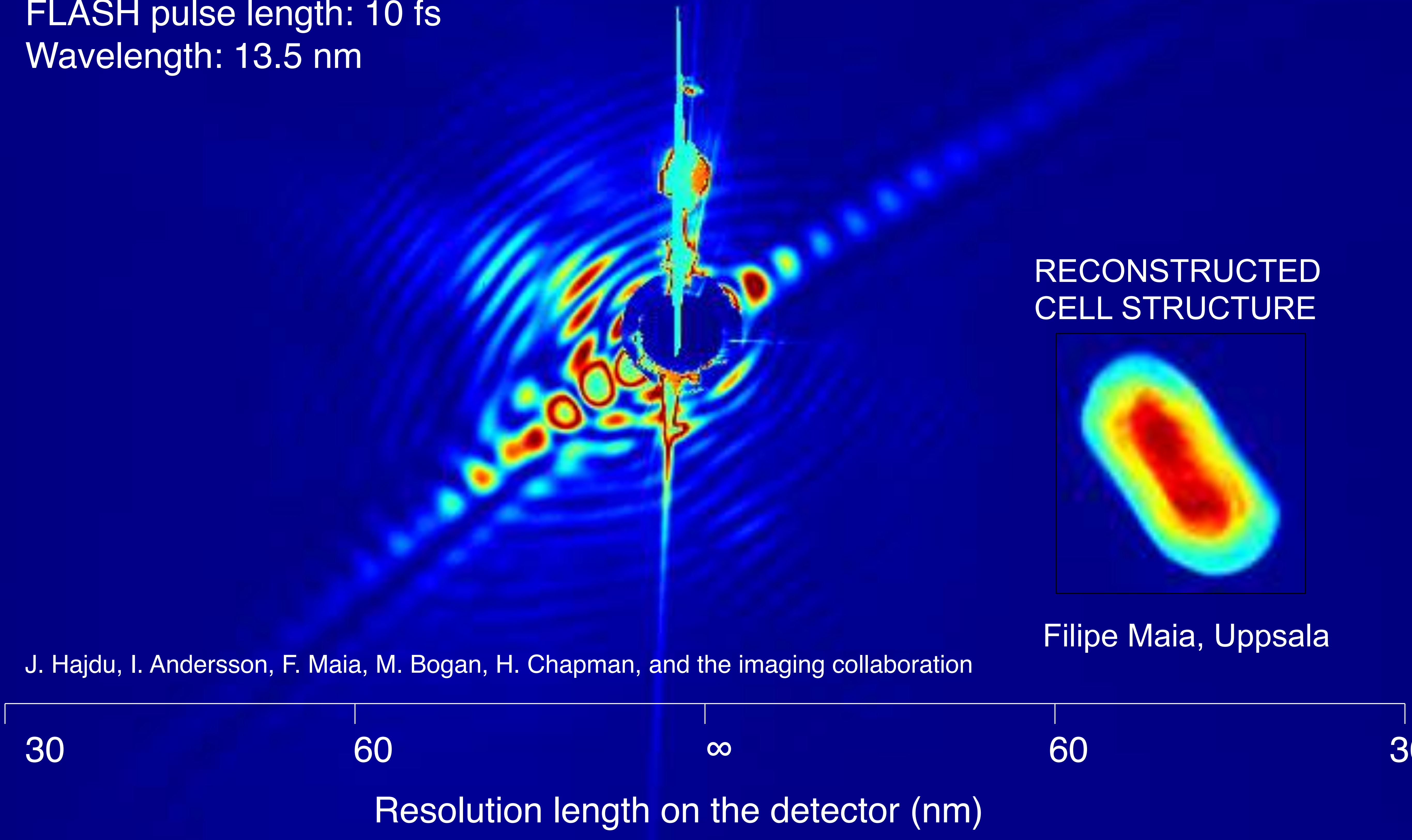
- Extreme UV Lithographt is the candidate technology with <50-35 nm

- Cost effective solutions based on FEL sources can be foreseen

FIRST FLASH DIFFRACTION IMAGE OF A LIVING CELL

FLASH soft X-ray laser, Hamburg, Germany

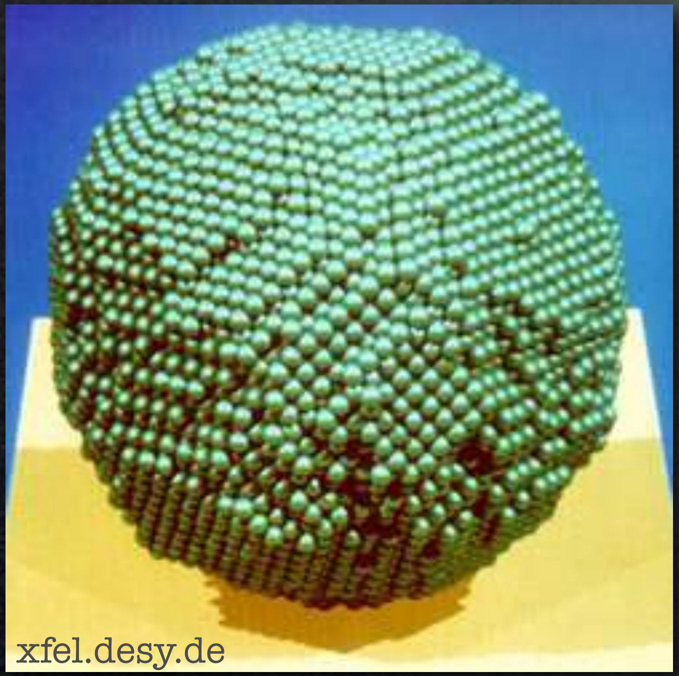
FLASH pulse length: 10 fs
Wavelength: 13.5 nm



Filipe Maia, Uppsala

J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration

cluster and nanoparticle



xfel.desy.de

Clusters are small bits of matter composed of anywhere from a few to tens of thousands of atoms.

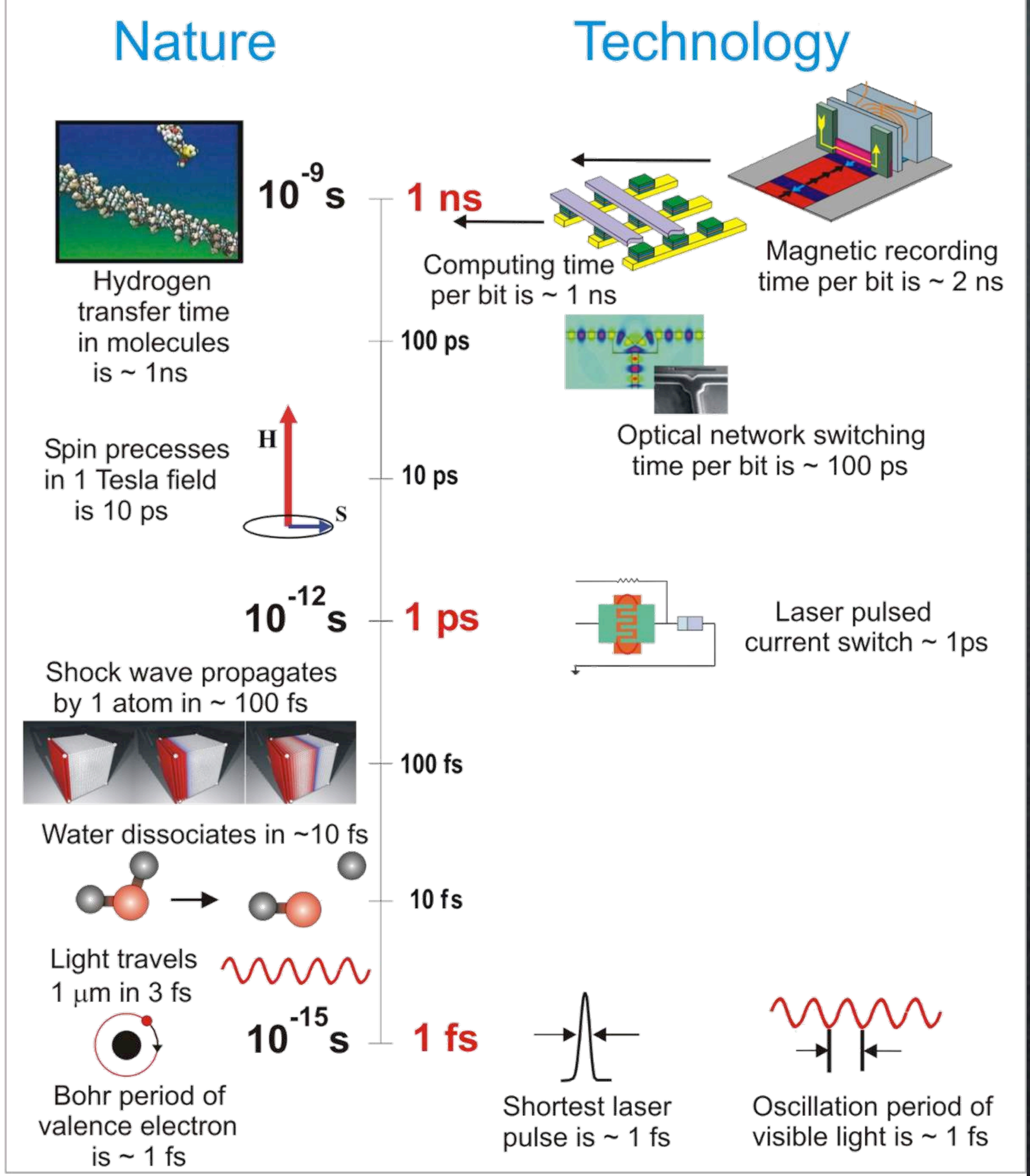
Small particles are different from bulk matter; finite size effects influence all properties of matter.

Examples are tiny carbon spheres and carbon tubes that are considered promising candidates for use as nanotechnological components.
(17 000 copper atoms in the picture on the right).

Limited photon energy of standard laser systems prevents measuring the full valence electron structure as well or performing photon energy dependent spectroscopy across shallow core edges

The beam intensities available at 3rd generation synchrotron radiation facilities are still far below what is required for meaningful gas phase experiments.

Ultra-Fast



Nature

Technology

Hydrogen transfer time in molecules is ~ 1ns

10^{-9} s — **1 ns**

Computing time per bit is ~ 1 ns

Magnetic recording time per bit is ~ 2 ns

100 ps

Optical network switching time per bit is ~ 100 ps

Spin precesses in 1 Tesla field is 10 ps

10 ps

10^{-12} s — **1 ps**

Laser pulsed current switch ~ 1ps

Shock wave propagates by 1 atom in ~ 100 fs

100 fs

Water dissociates in ~10 fs

10 fs

Light travels 1 μm in 3 fs

10^{-15} s — **1 fs**

Bohr period of valence electron is ~ 1 fs

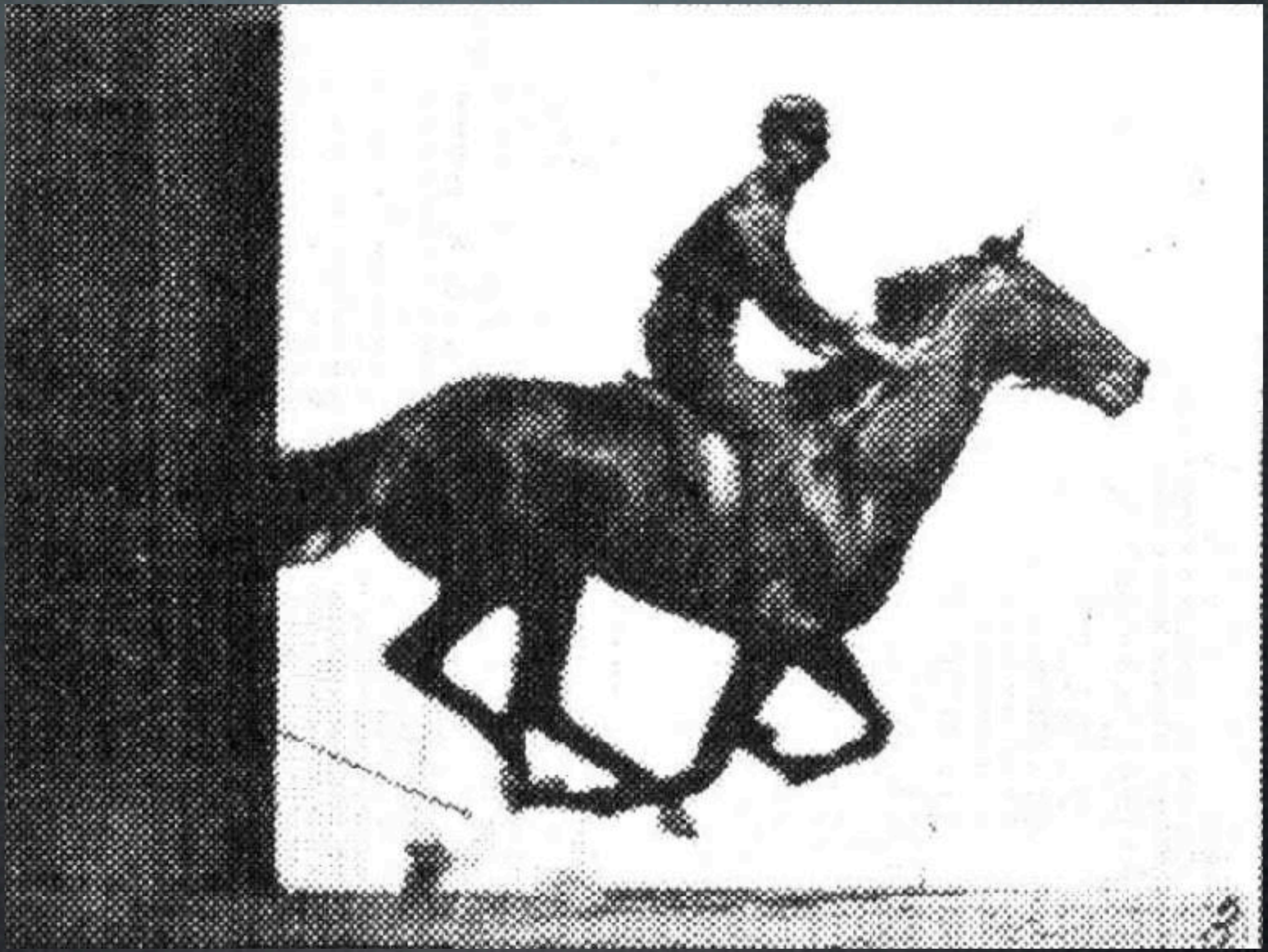
Shortest laser pulse is ~ 1 fs

Oscillation period of visible light is ~ 1 fs

E. Muybridge at L. Stanford in **1878**

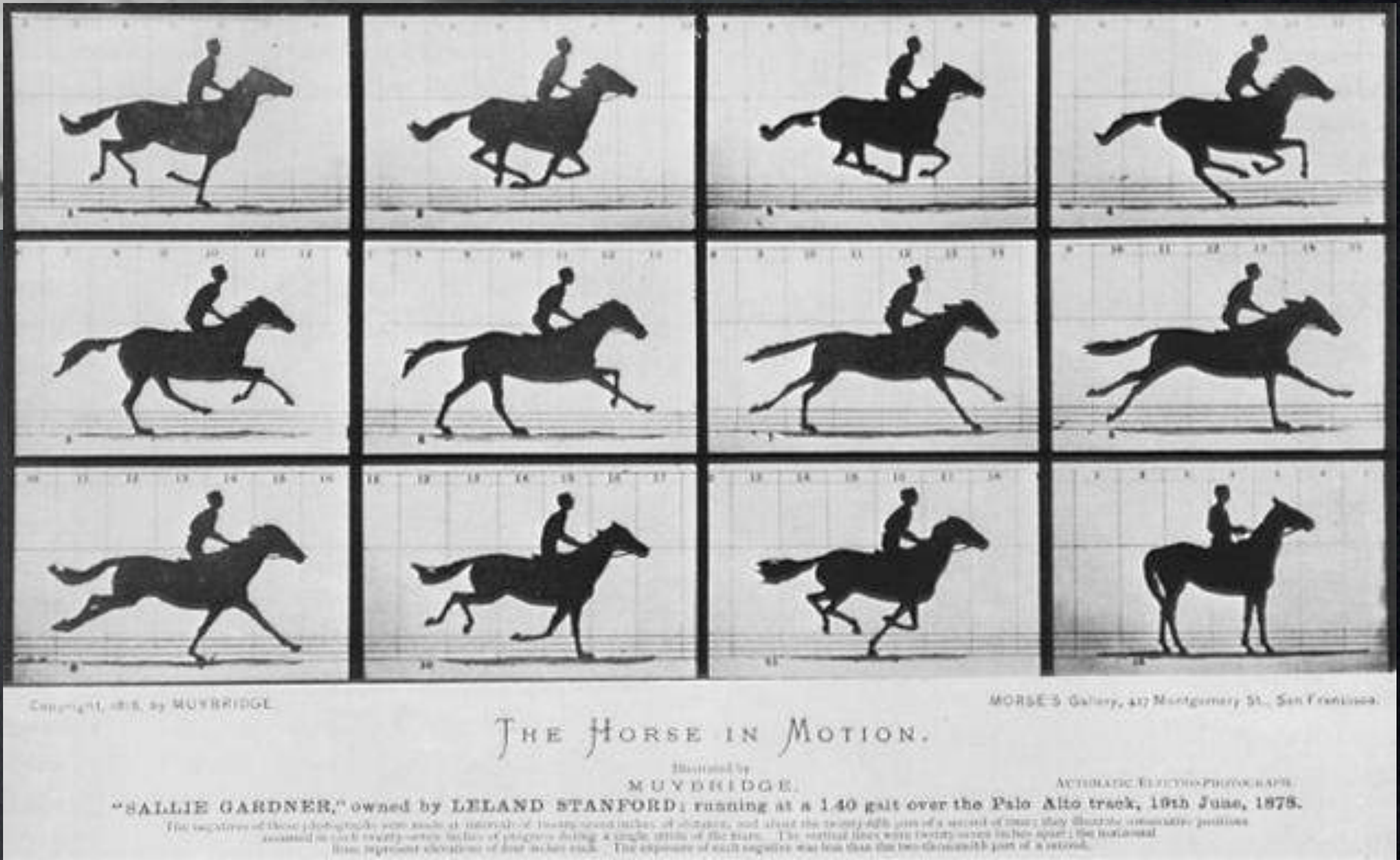

E. Muybridge

disagree whether all feet leave the ground during gallop...



used spark photography to freeze this 'ultra-fast' process

E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957)
Courtesy Paul Emma (SLAC).



Copyright, 1878, by MUYBRIDGE.

MORSE'S Gallery, 417 Montgomery St., San Francisco.

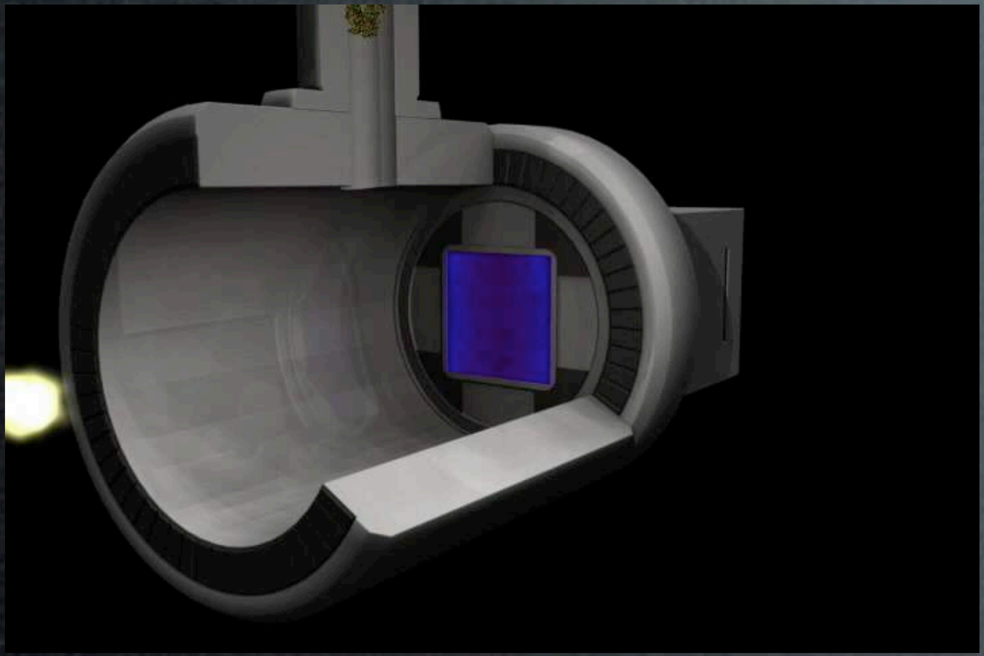
THE HORSE IN MOTION.

Illustrated by
MUYBRIDGE.

AUTOMATIC ELECTRO-PHOTOGRAPH.

"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1:40 gait over the Palo Alto track, 19th June, 1878.

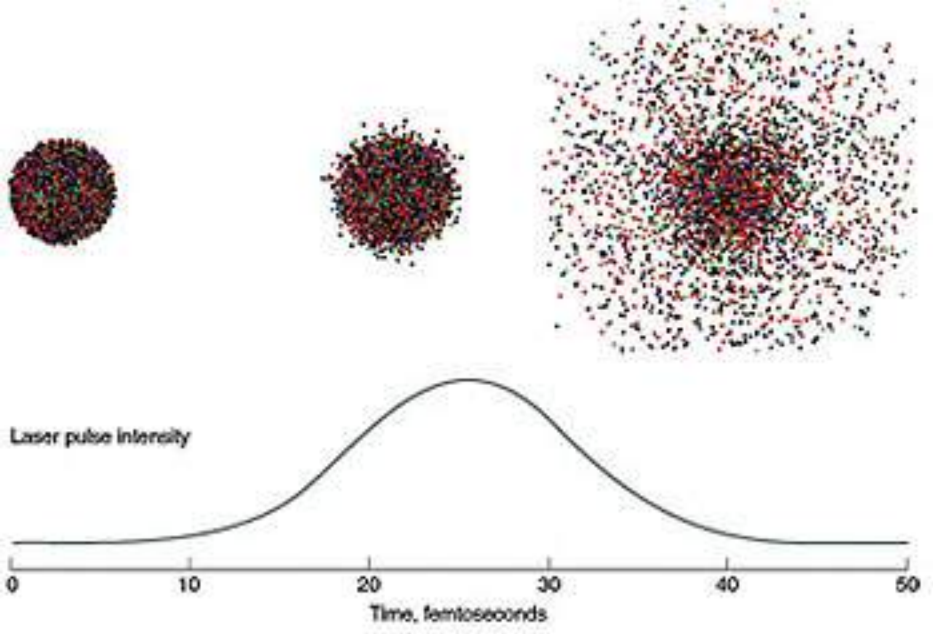
Protein imaging



Using extremely short and intense X-ray pulses to capture images of objects such as proteins before the X-rays destroy the sample.

Single-molecule diffractive imaging with an X-ray free-electron laser.

Individual biological molecules will be made to fall through the X-ray beam, one at a time, and their structural information recorded in the form of a diffraction pattern.



Lawrence Livermore National Laboratory (LLNL)

The pulse will ultimately destroy each molecule, but not before the pulse has diffracted from the undamaged structure.

The patterns are combined to form an atomic-resolution image of the molecule.

The speed record of 25 femtoseconds for flash imaging was achieved.

Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

make a movie of chemical reactions

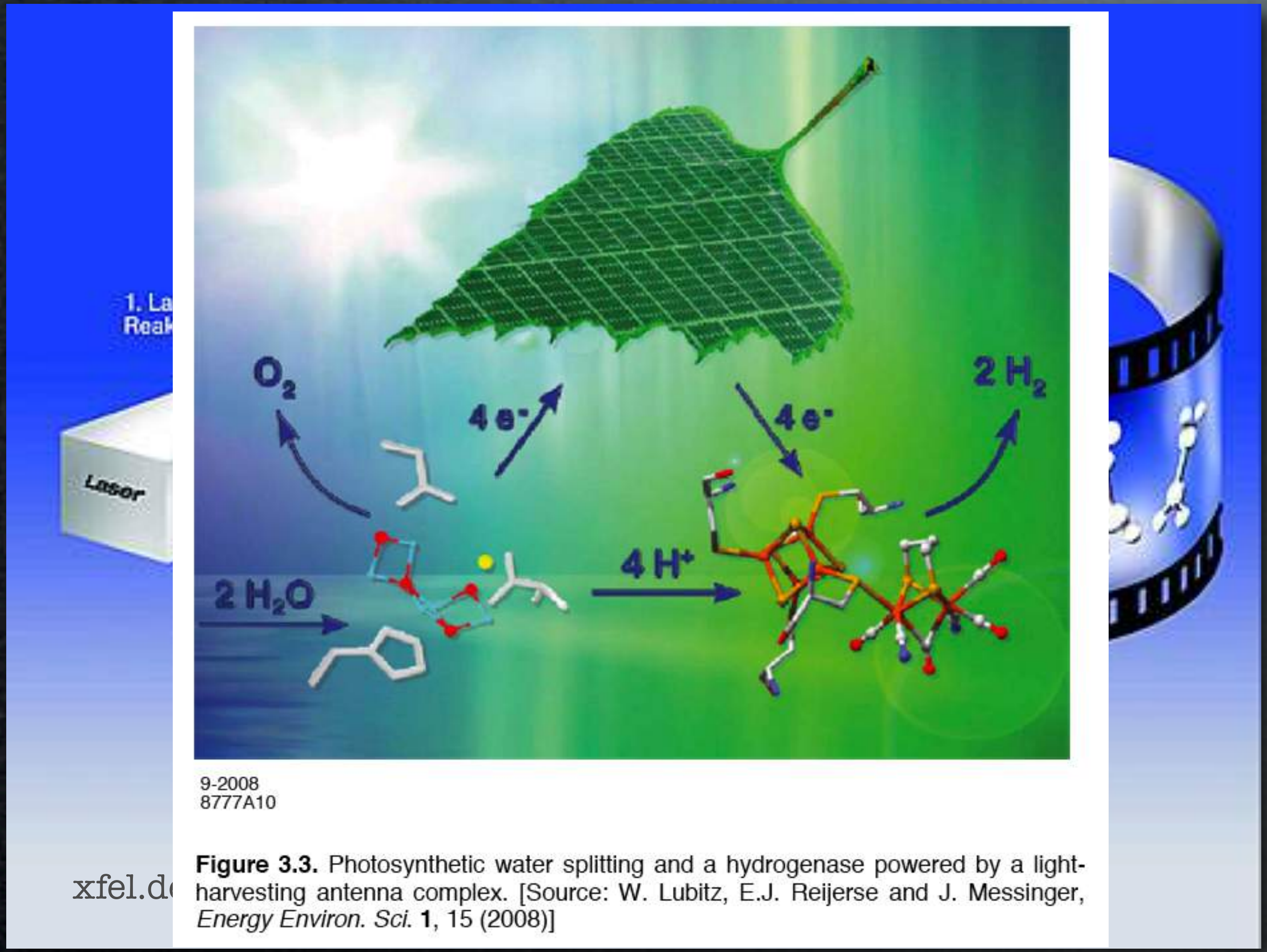


Figure 3.3. Photosynthetic water splitting and a hydrogenase powered by a light-harvesting antenna complex. [Source: W. Lubitz, E.J. Reijerse and J. Messinger, *Energy Environ. Sci.* **1**, 15 (2008)]

Chemical reactions often take place incredibly quickly: orders of magnitude of femtosecond are not rare. The atomic changes that occur when molecules react with one another take place in moments that brief.

The XFEL X-ray laser flashes make it possible to film these rapid processes with an unprecedented level of quality.

Since the flash duration is less than 100 femtoseconds, images can be made in which the movements of detail are not blurred.

And thanks to the short wavelength, atomic details become visible in the films.

To film a chemical reaction, one needs a series of pairs of X-ray laser flashes.

The first flash in each pair triggers the chemical reaction. With the second flash, a snapshot is then made.

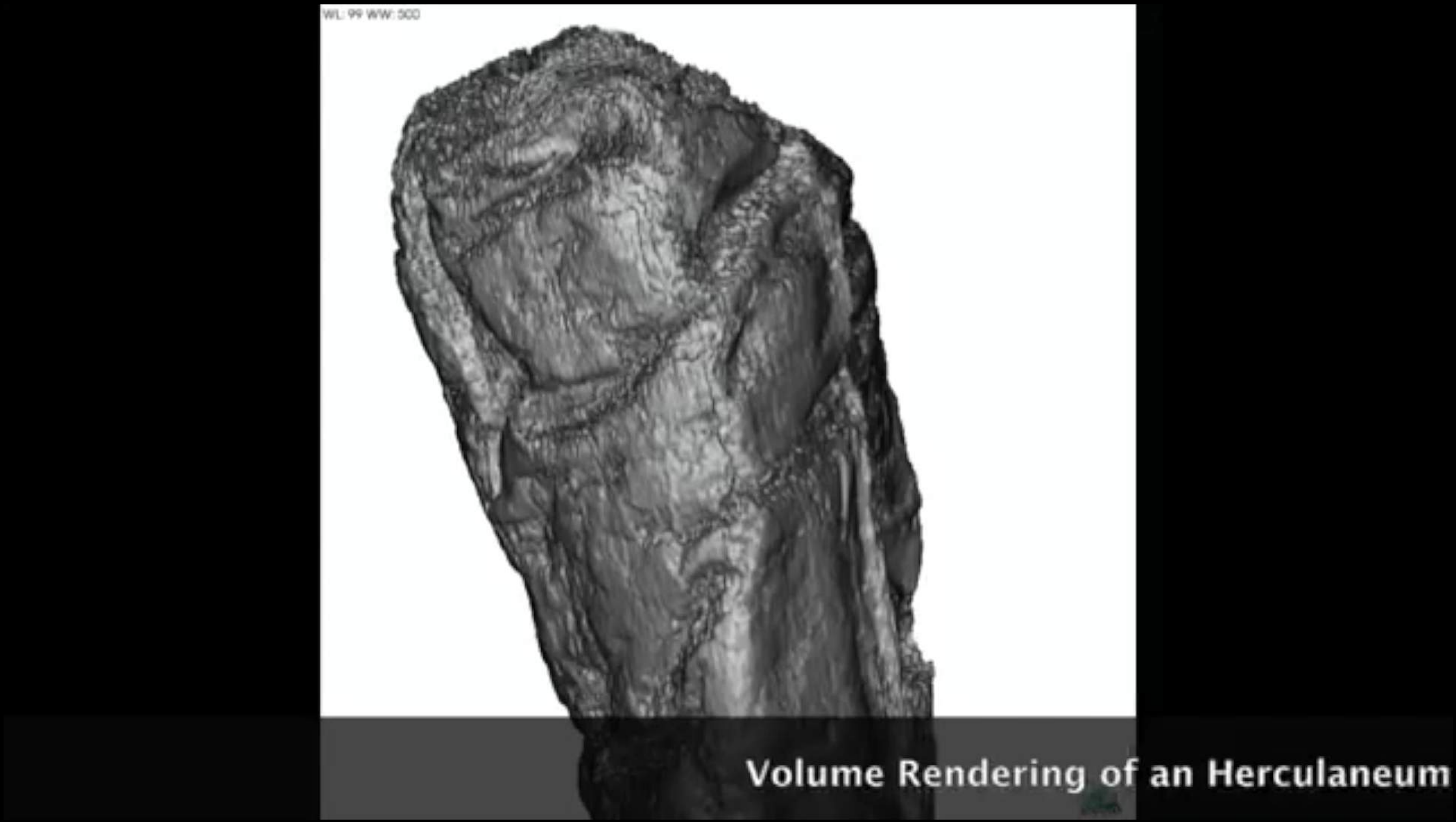
The delay between the two flashes can be precisely modified to within femtosecond and a series of snapshots can be made at various times following the start of the reaction.

In each case, the images are of different molecules, but these images can be combined into a film.

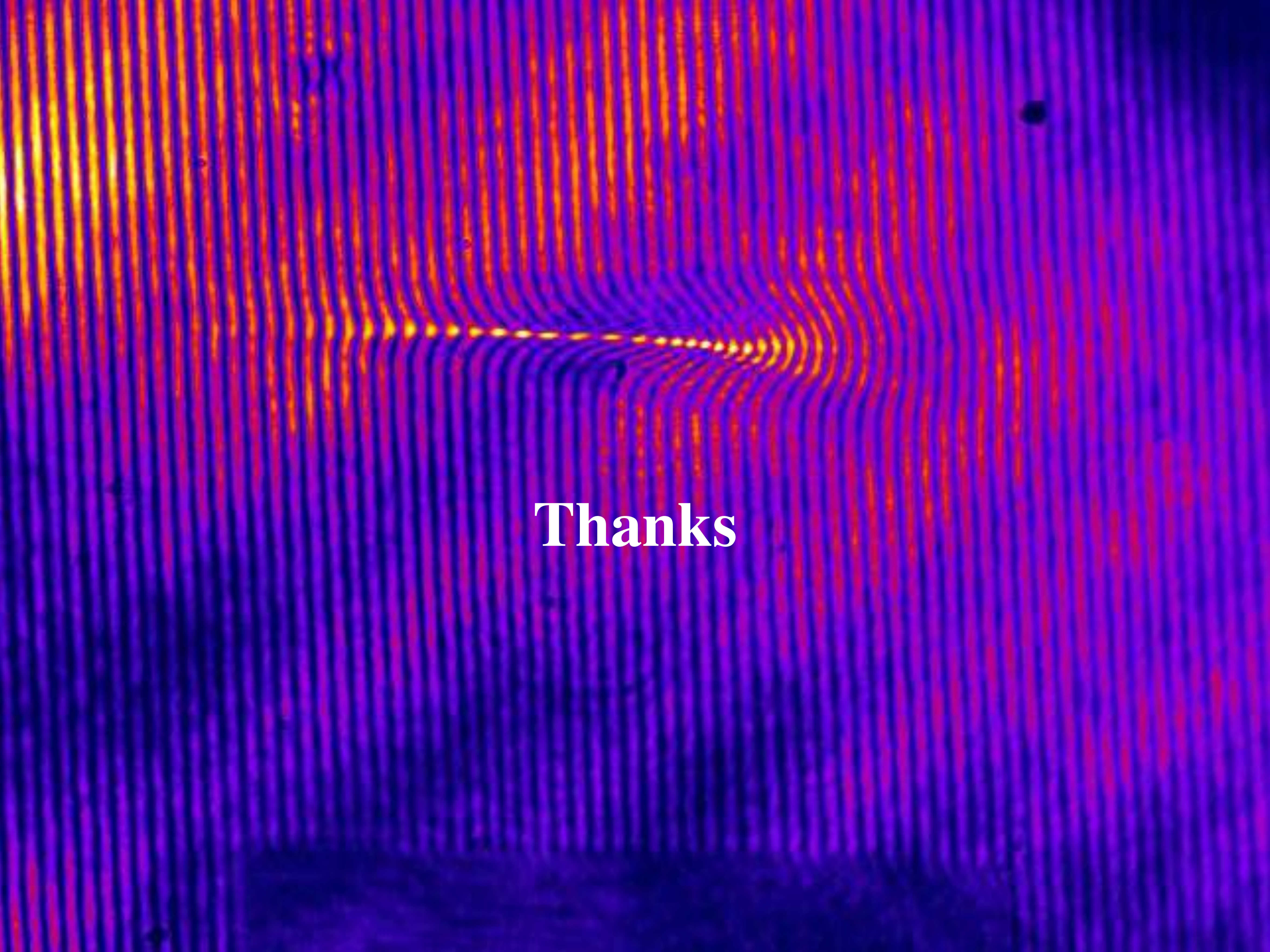
Villa dei papiri – Ercolano – 79 d. C.

Tomografia a raggi X in contrasto di fase

Vito Mocella del CNR-IMM di Napoli in collaborazione con E.Brun e C. Ferrero dell'ESRF




a
Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν
b
Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω



Thanks

Resonant Wavelength Sensitivity to beam parameters

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\vartheta^2\right)$$

Undulator tolerances

$$\frac{\Delta\lambda_{rad}}{\lambda_{rad}} = -2\frac{\Delta\gamma}{\gamma}+\frac{2K^2}{1+K^2}\frac{\Delta K}{K}+\frac{\gamma^2\vartheta^2}{1+K^2}$$

Energy spread

Beam Emittance

$$\gamma^2\vartheta^2 = \gamma^2\sigma_{x'}^2 = \frac{\gamma^2\varepsilon^2}{\sigma_x^2} = \frac{\varepsilon_n^2}{\sigma_x^2}$$