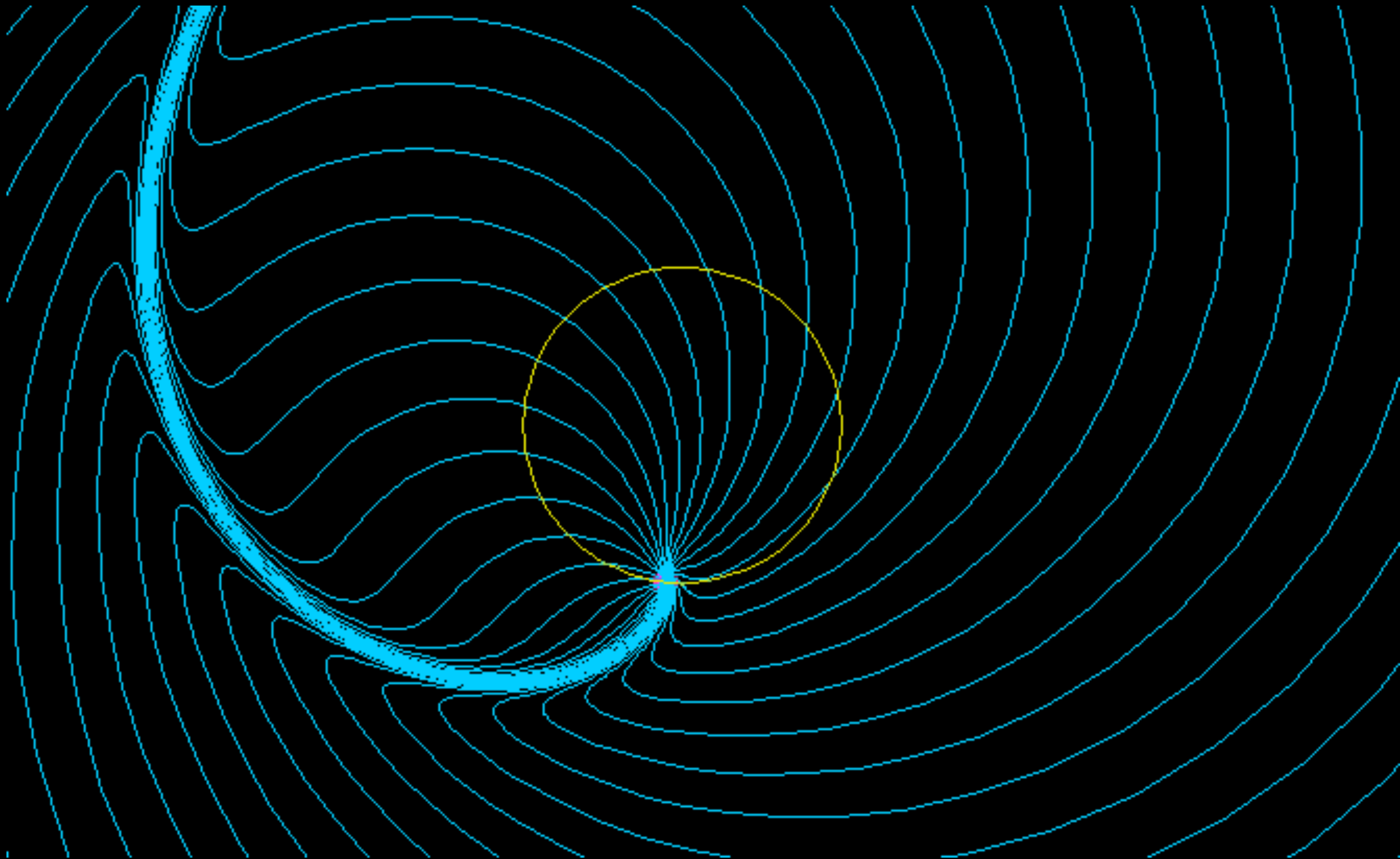
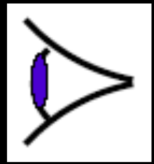
Synchrotron Radiation Sources

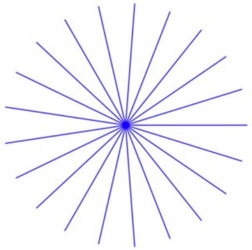




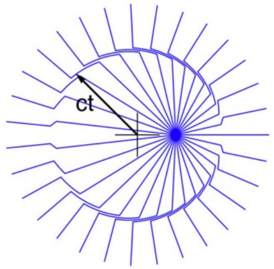
Radiation Simulator – T. Shintake

When a point charge is accelerated, it radiates electromagnetic waves. Why?

To understand the process of radiation we c llowing scenario: a point charge was at rest until t = 0,



then it is abruptly accelerated to velocity v this velocity at t > 0.

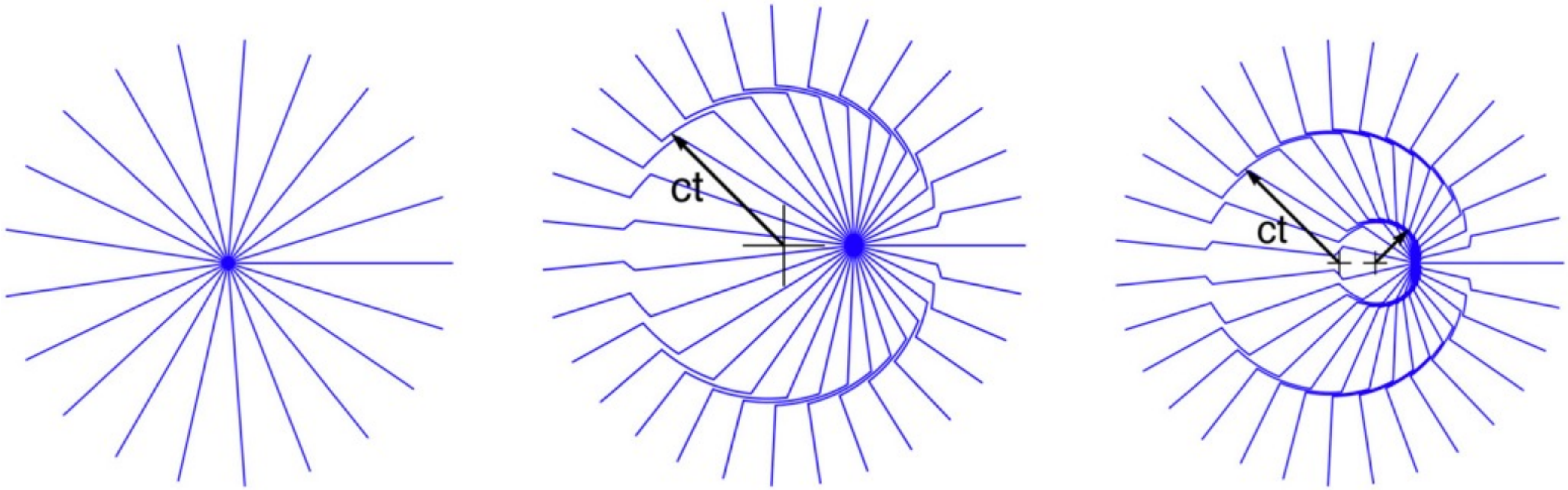


The field outside of the sphere of radius ct does not change because the information about the charge acceleration propagating with the speed of light has not yet reached this region at time t.

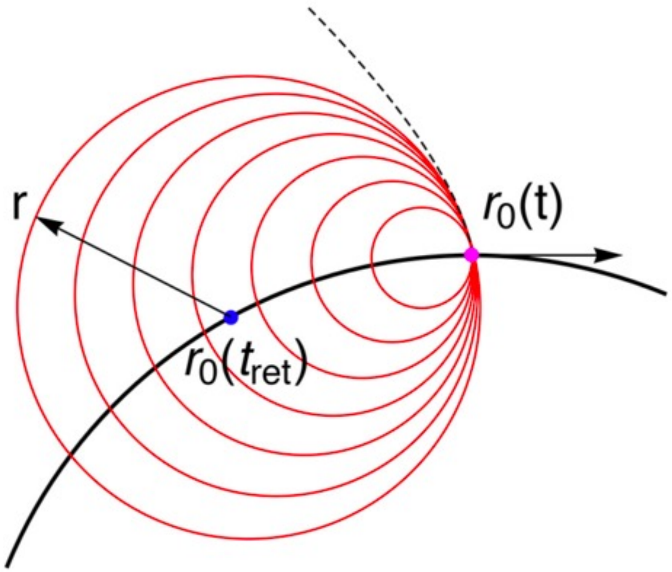
The field inside the sphere corresponds to the Coulomb field of a point charge moving with the constant velocity v.

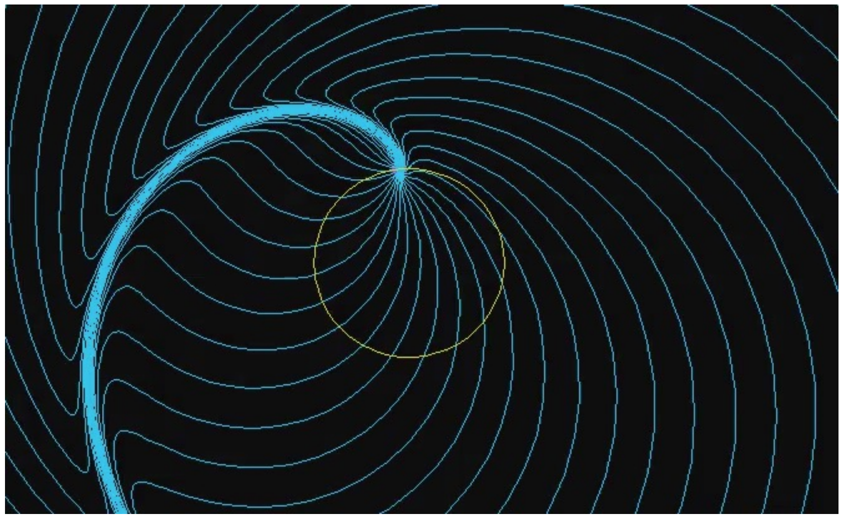
In a thin spherical layer between the two regions, there is a transition from one field to the other. => It appears a transverse component of the field as a consequence of finiteness of the speed of light.

If the charge is accelerated two times — at t = 0, and then at $t = t_1$ — then at time $t > t_1$ there will be two spheres, with the radiation layers between them

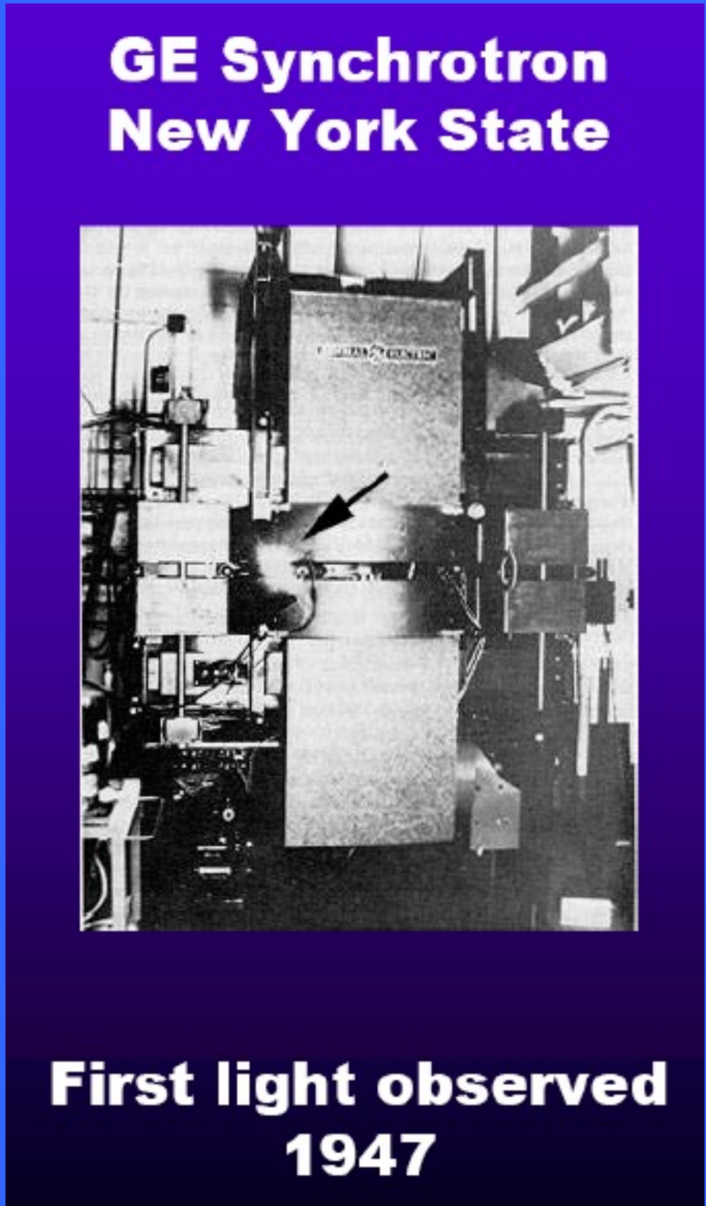


A constantly accelerating charge is continuously emitting radiation spheres that expand with the speed of light

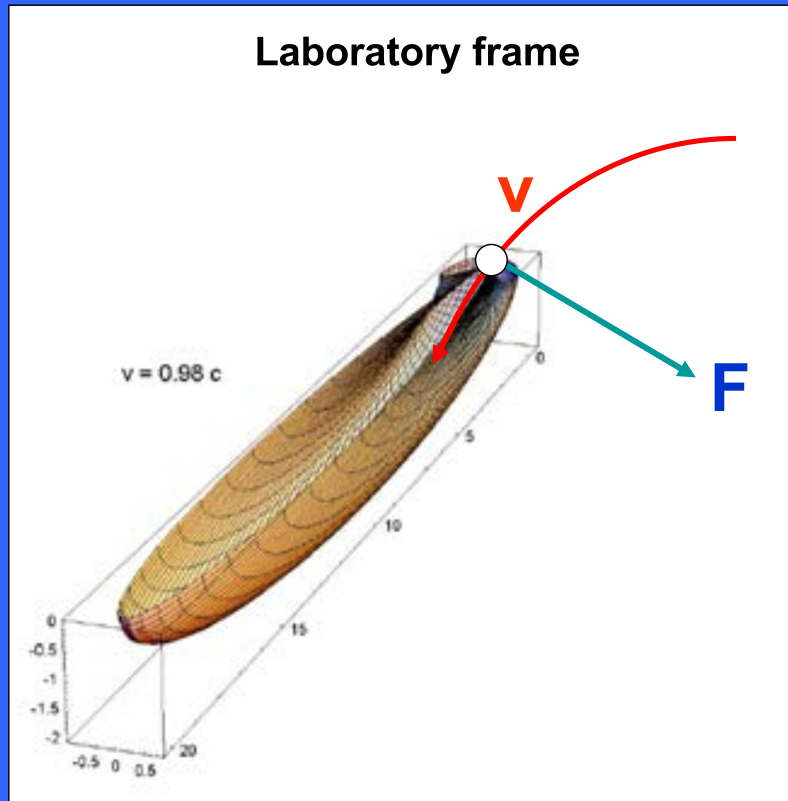




Synchrotron Radiation



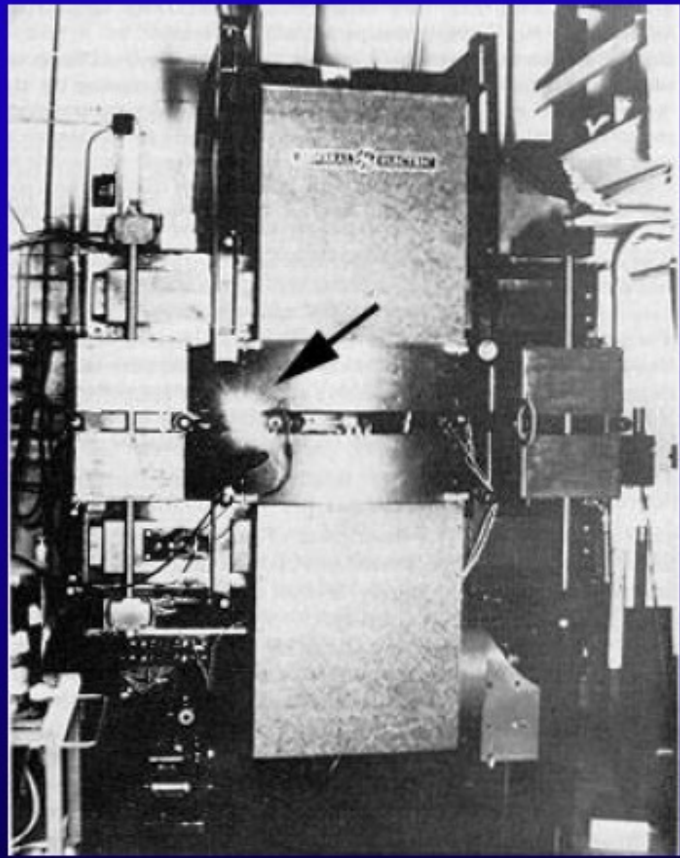
$$P_\gamma = \frac{cC_\gamma}{2\pi} \cdot \frac{E^4}{\rho^2}$$



Crab Nebula
6000 light years away

First light observed 1054 AD

GE Synchrotron
New York State

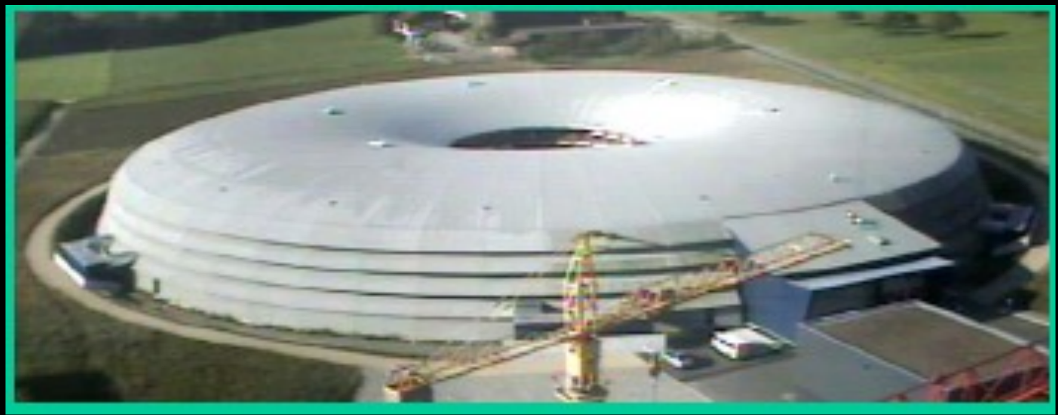


First light observed 1947

Elettra (Trieste)

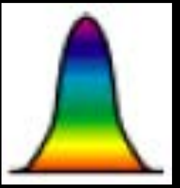
ESRF (Francia)

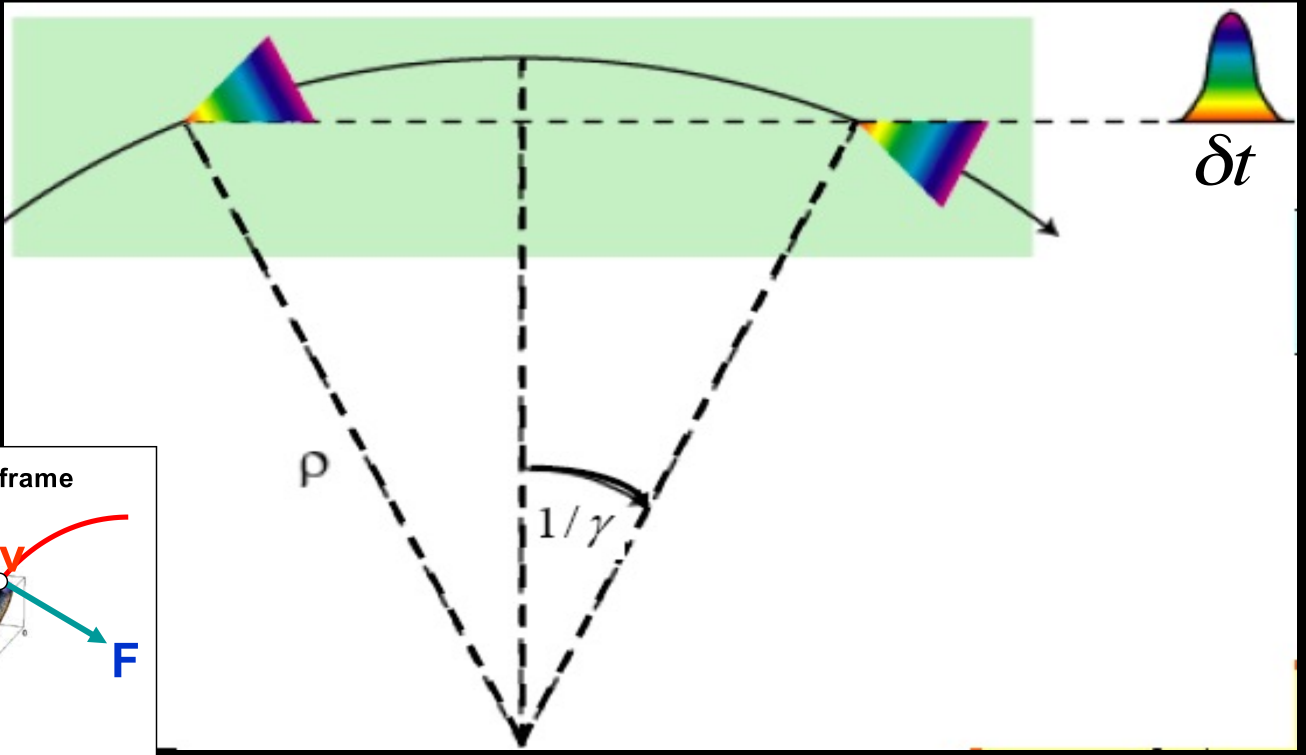
SLS (Svizzera)

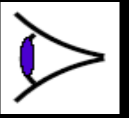


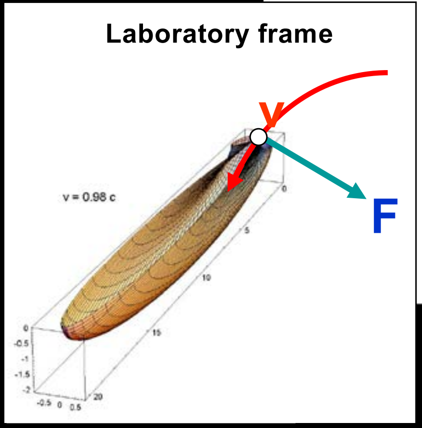
Pulse length

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



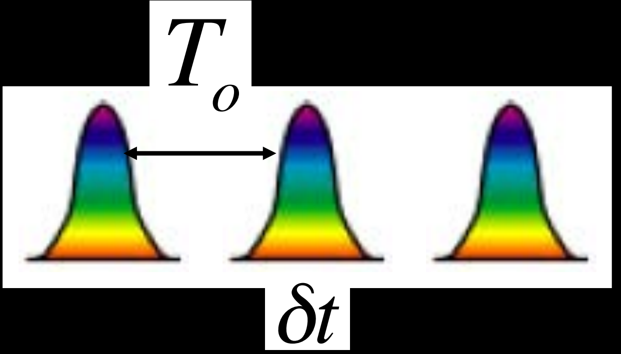




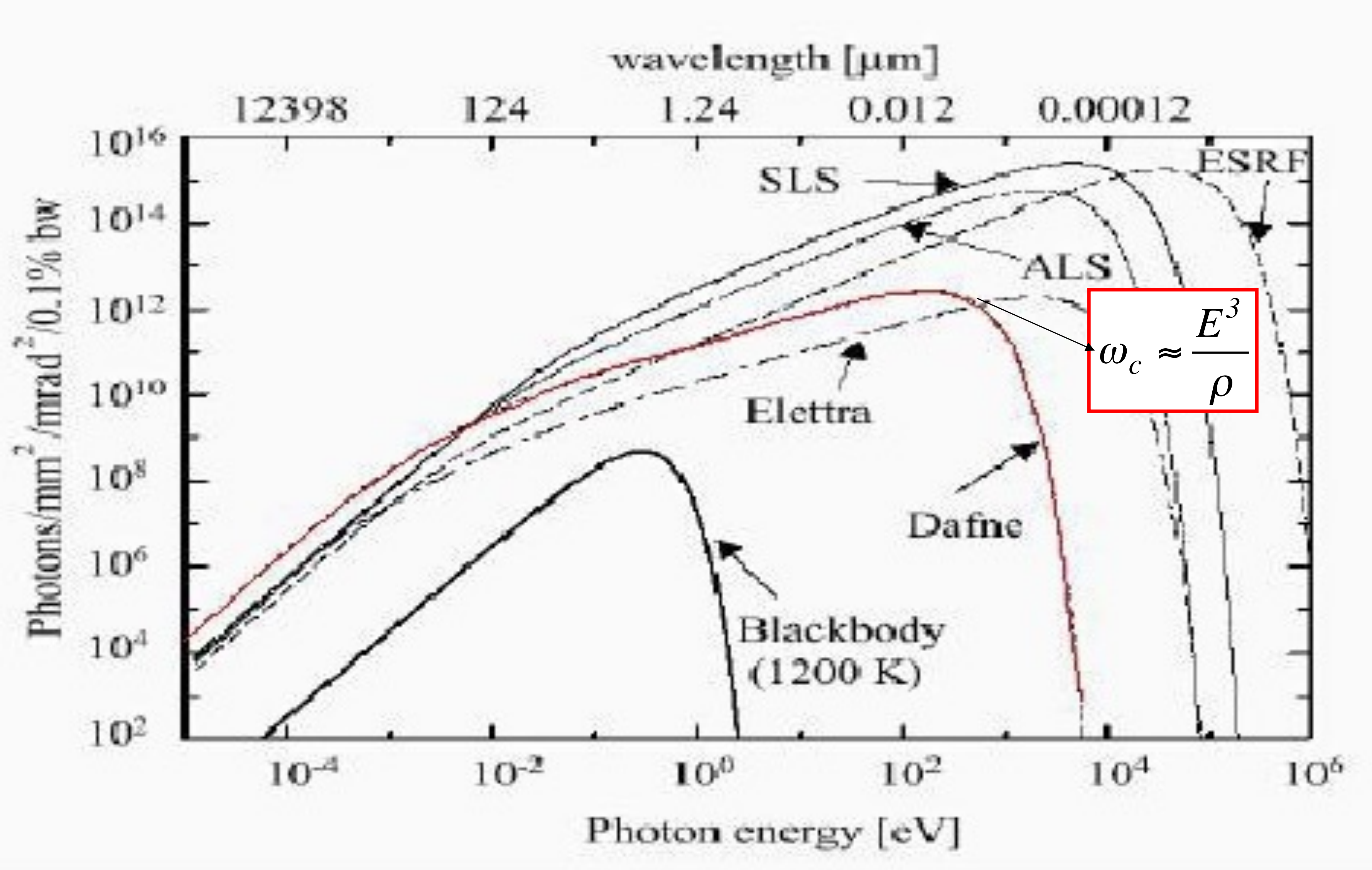


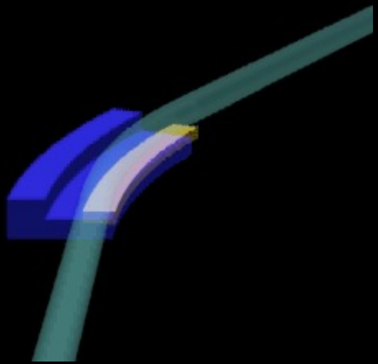
Pulse repetition rate

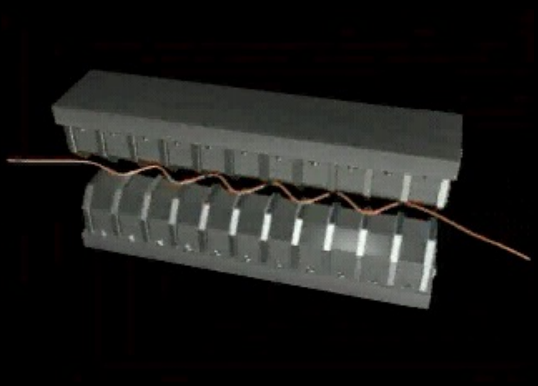
$$\omega_o = \frac{2\pi}{T_o}$$

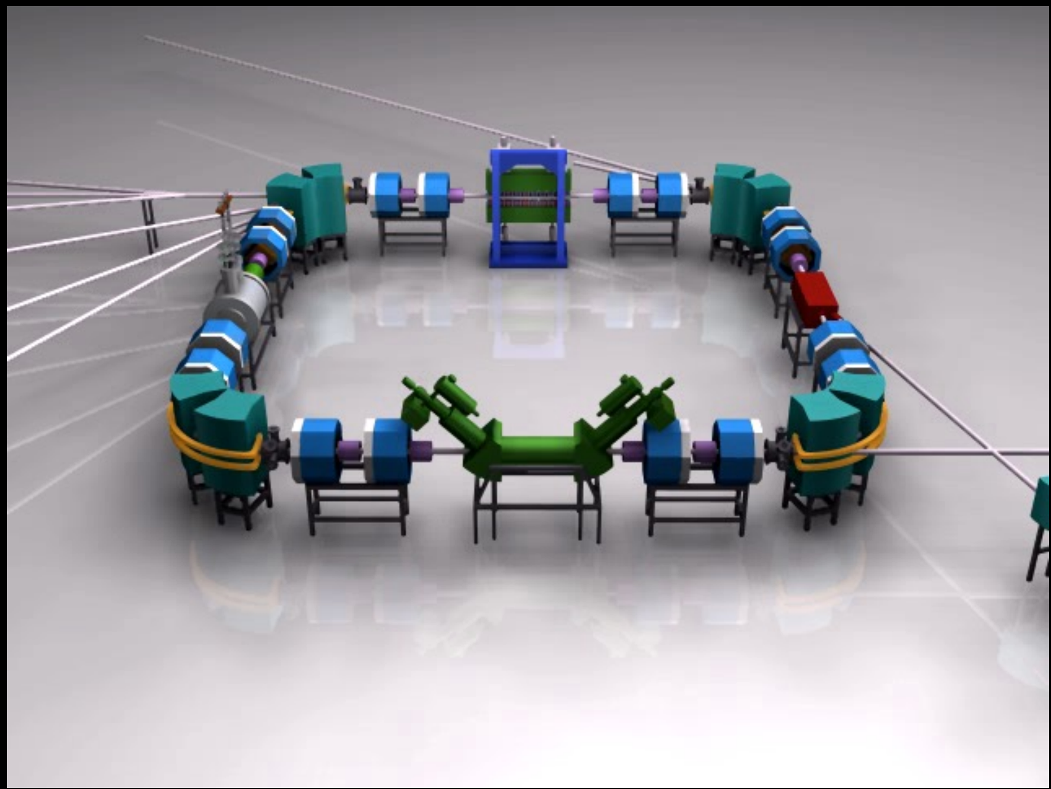


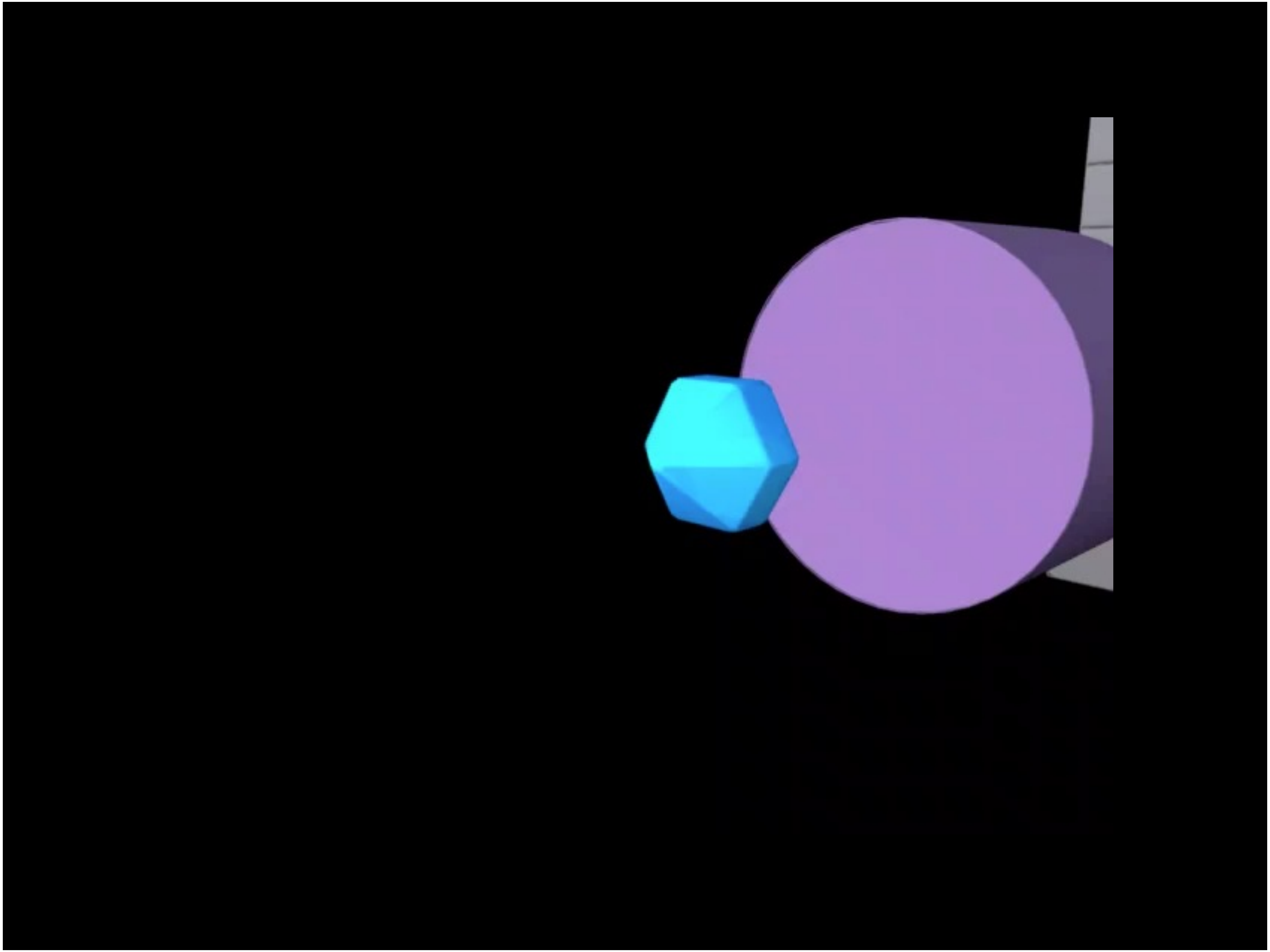
$$\langle P_s\,(\mathrm{MW})\rangle_{\mathrm{iso}} = 0.088463\,\frac{E^4\,(\mathrm{GeV})}{\rho\,(\mathrm{m})}\,I\,(\mathrm{A})\ .$$

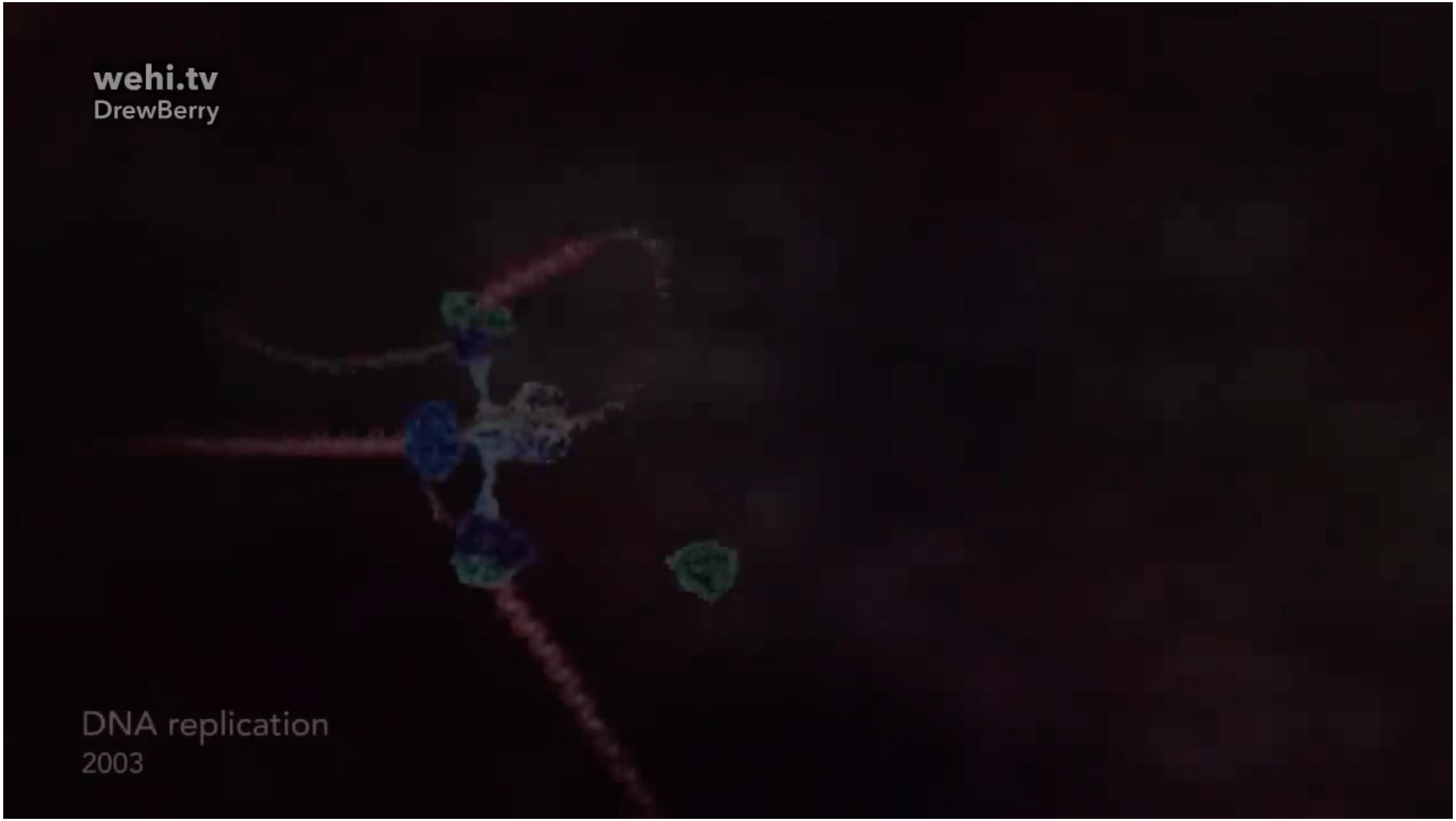











wehi.tv
DrewBerry
DNA replication
2003

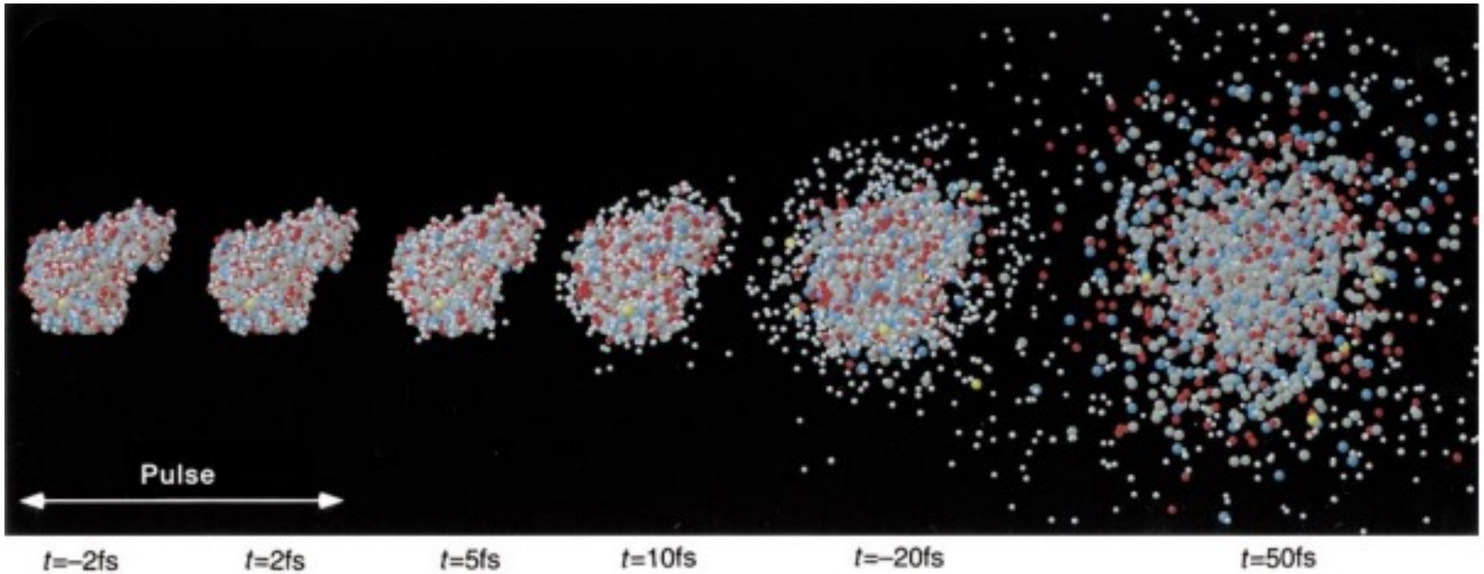
Static properties of matter

Static picture of a macro-molecule

Need light !

<u>Required properties</u>

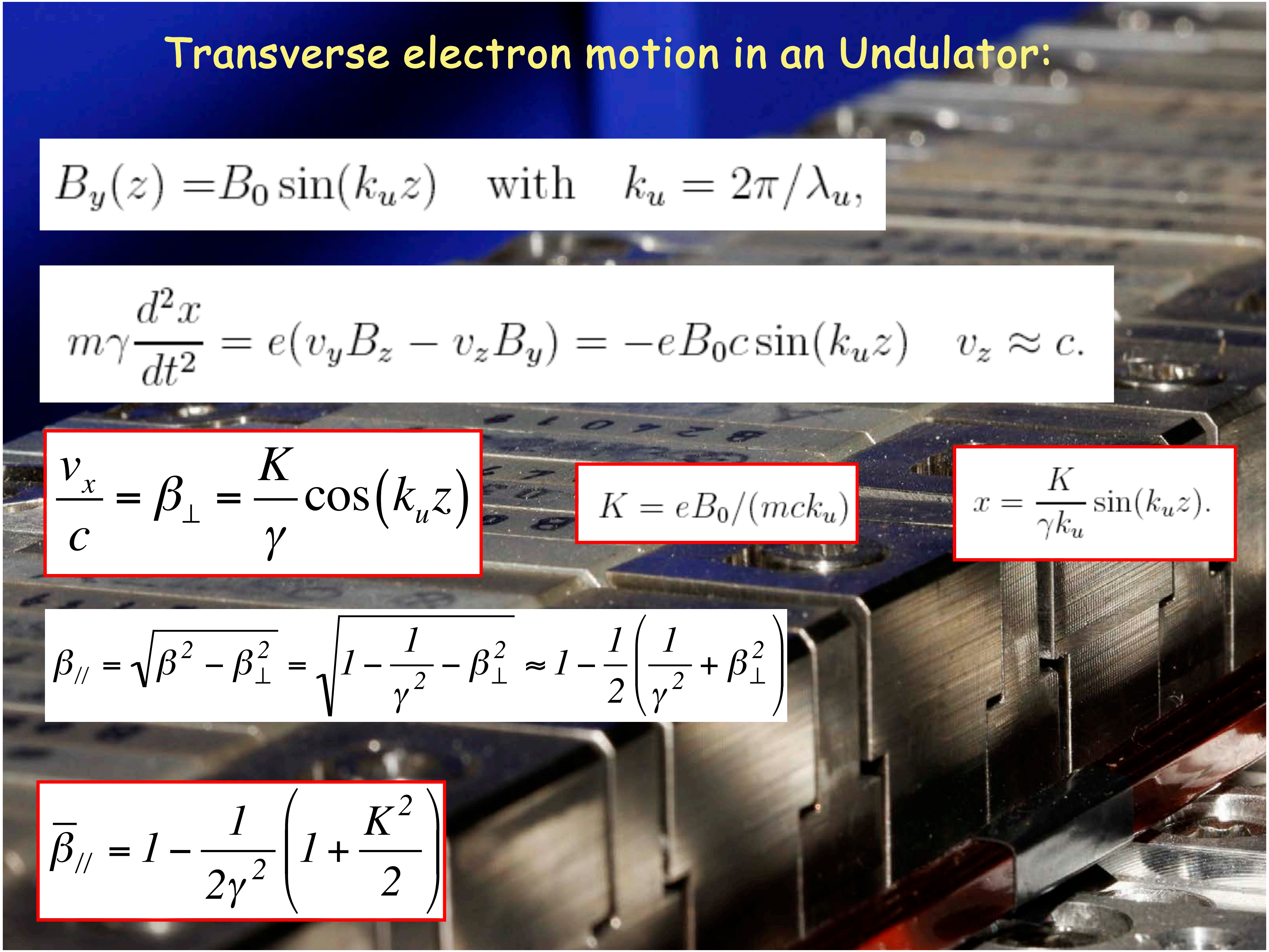
- Short wavelength (X-ray)
- High energy per pulse
- Ultra-short pulse (few femtoseconds)
- Coherence



Free Electron Laser


M5
M6
s.p.a.

Transverse electron motion in an Undulator:



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

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

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

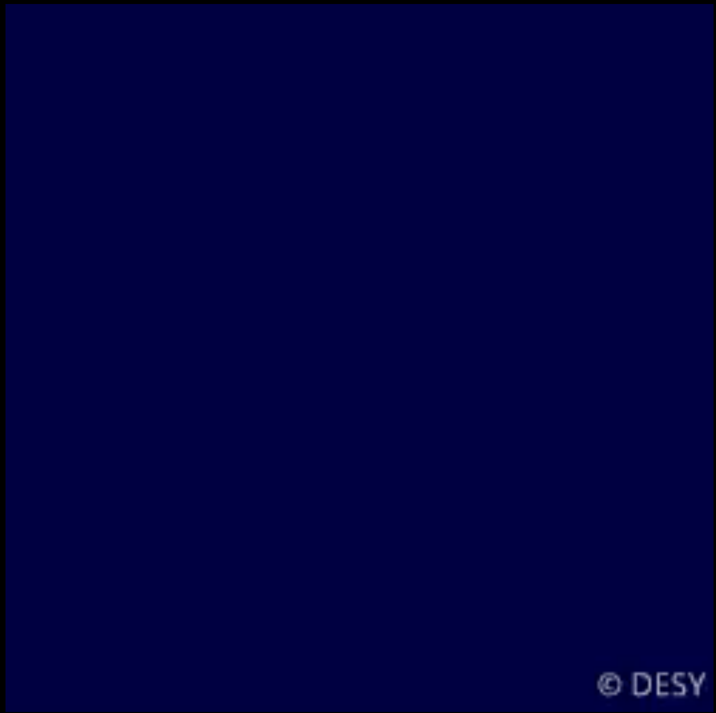
$$K = eB_0/(mck_u)$$

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

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

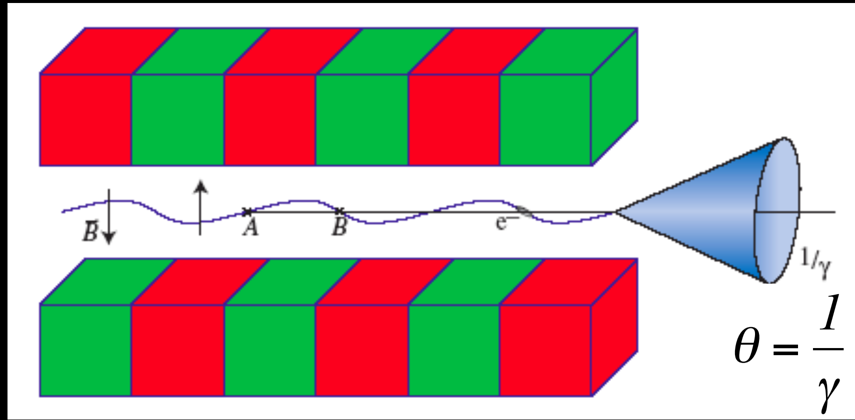
$$\overline{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Undulator Radiation



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

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



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

$$K = eB_0/(mck_u)$$

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

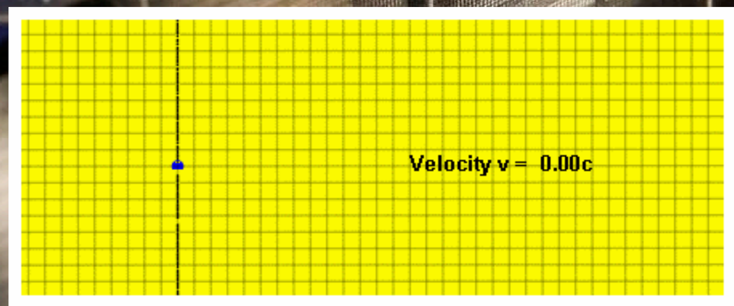
The picture can't be displayed

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

Doppler effect in the laboratory frame

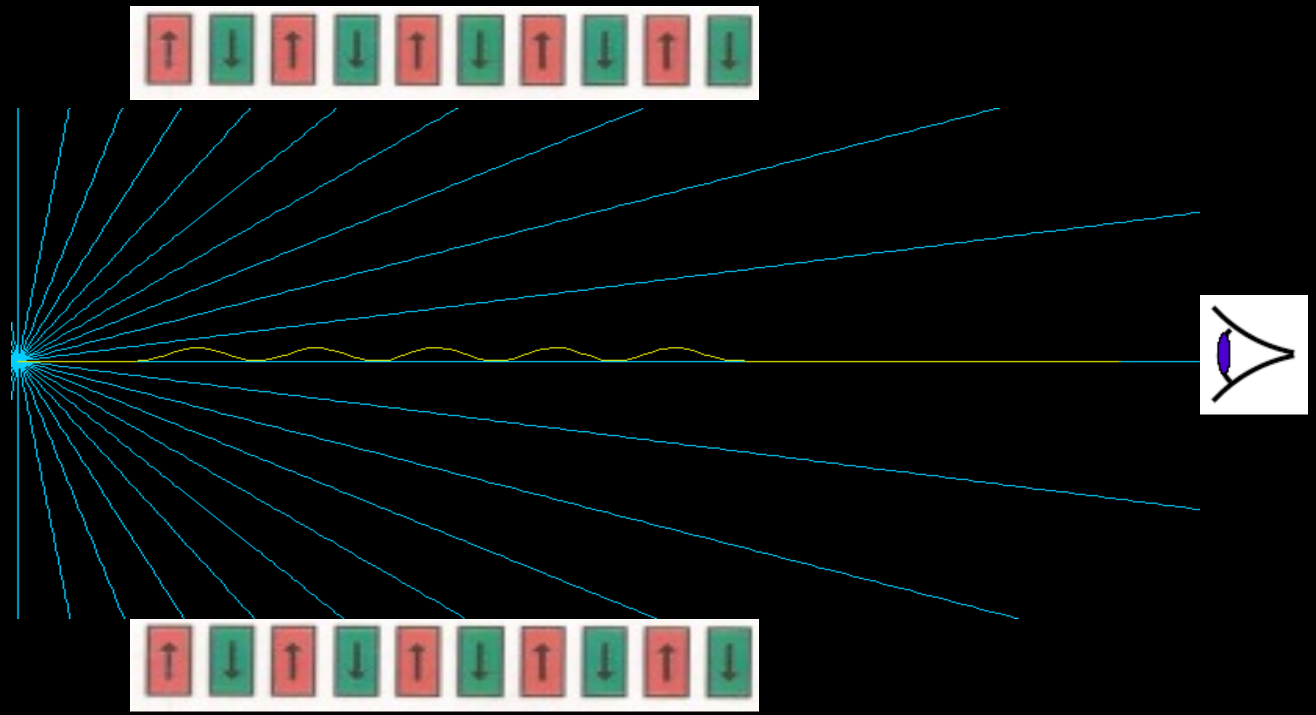
$$\bar{\beta}_{//} = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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



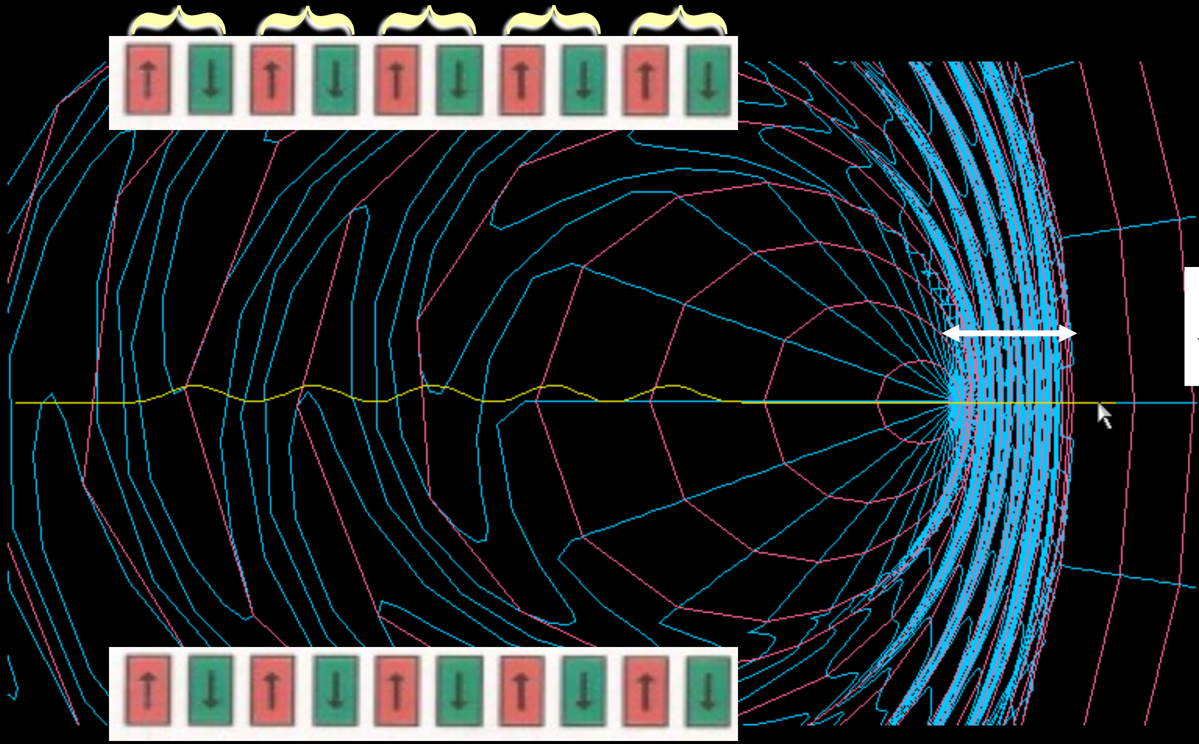
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2 \vartheta^2\right)$$

Tunability & Red Shift



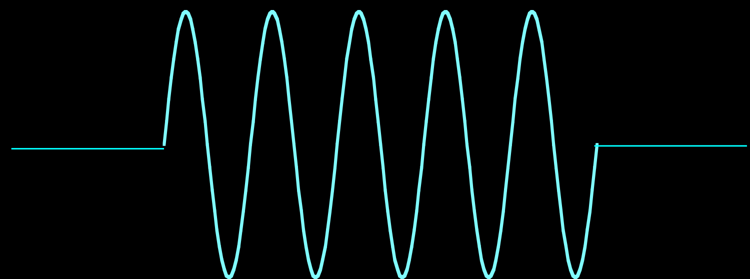
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

$$N_u = 5$$

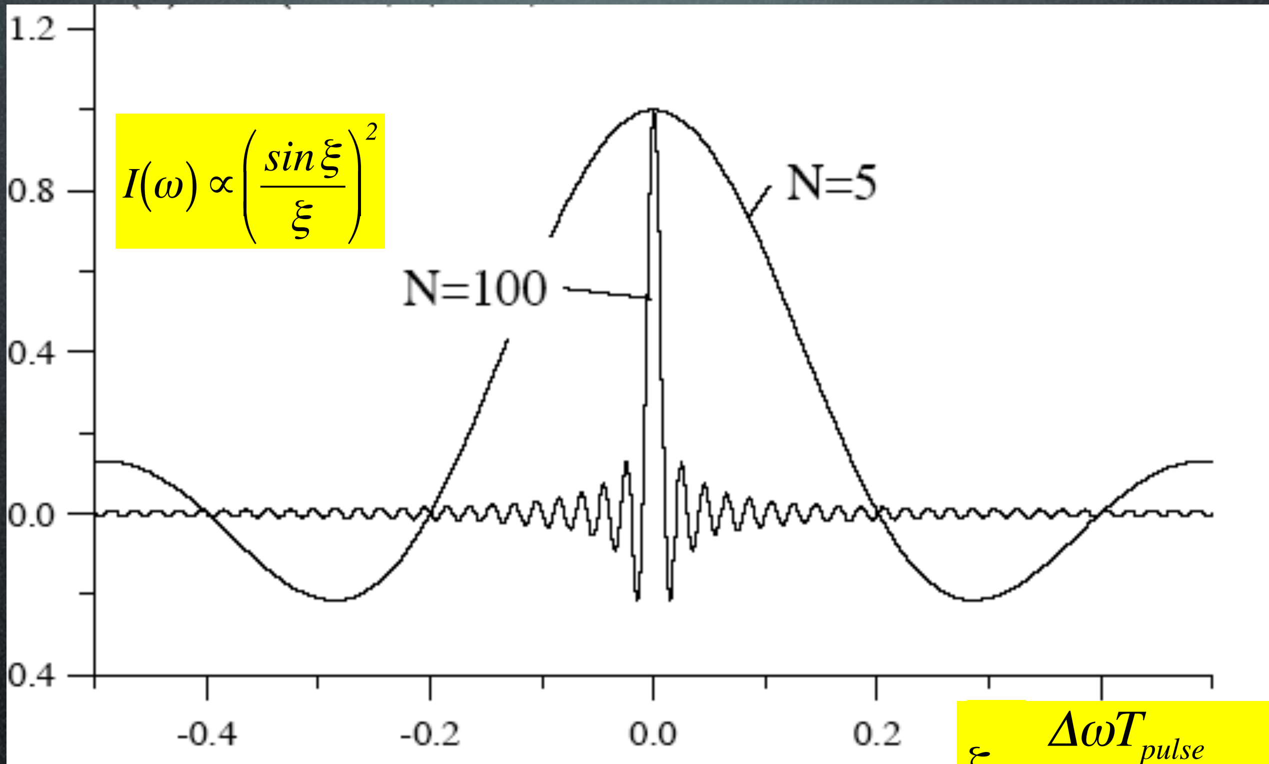


$$L_{pulse} = N_u \lambda_{rad}$$

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



Spectral Intensity



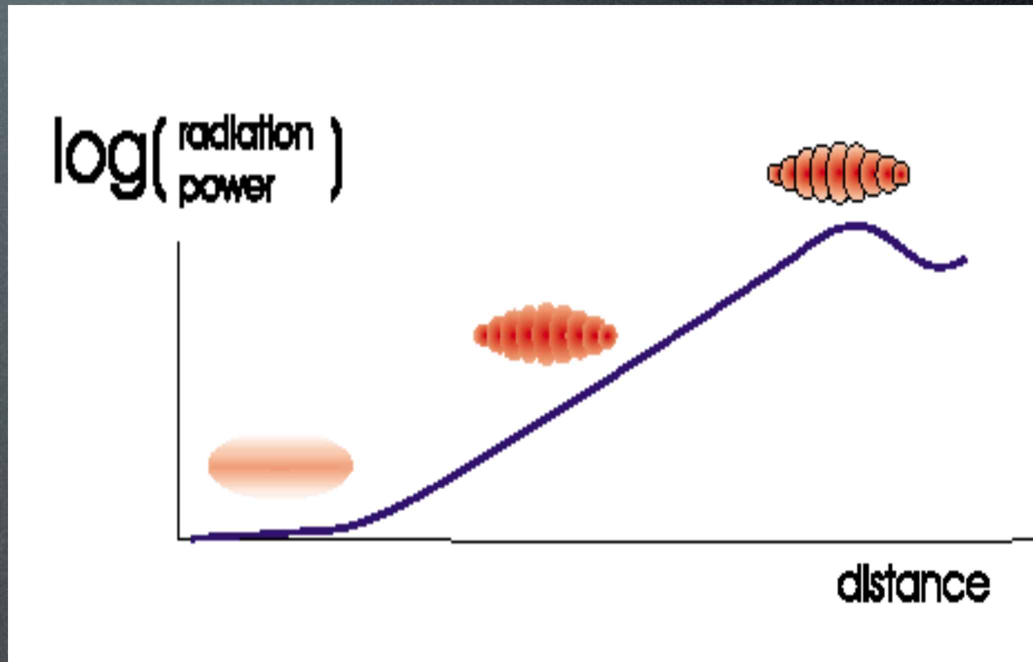
$$I(\omega) \propto \left(\frac{\sin\xi}{\xi}\right)^2$$

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

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

Line width

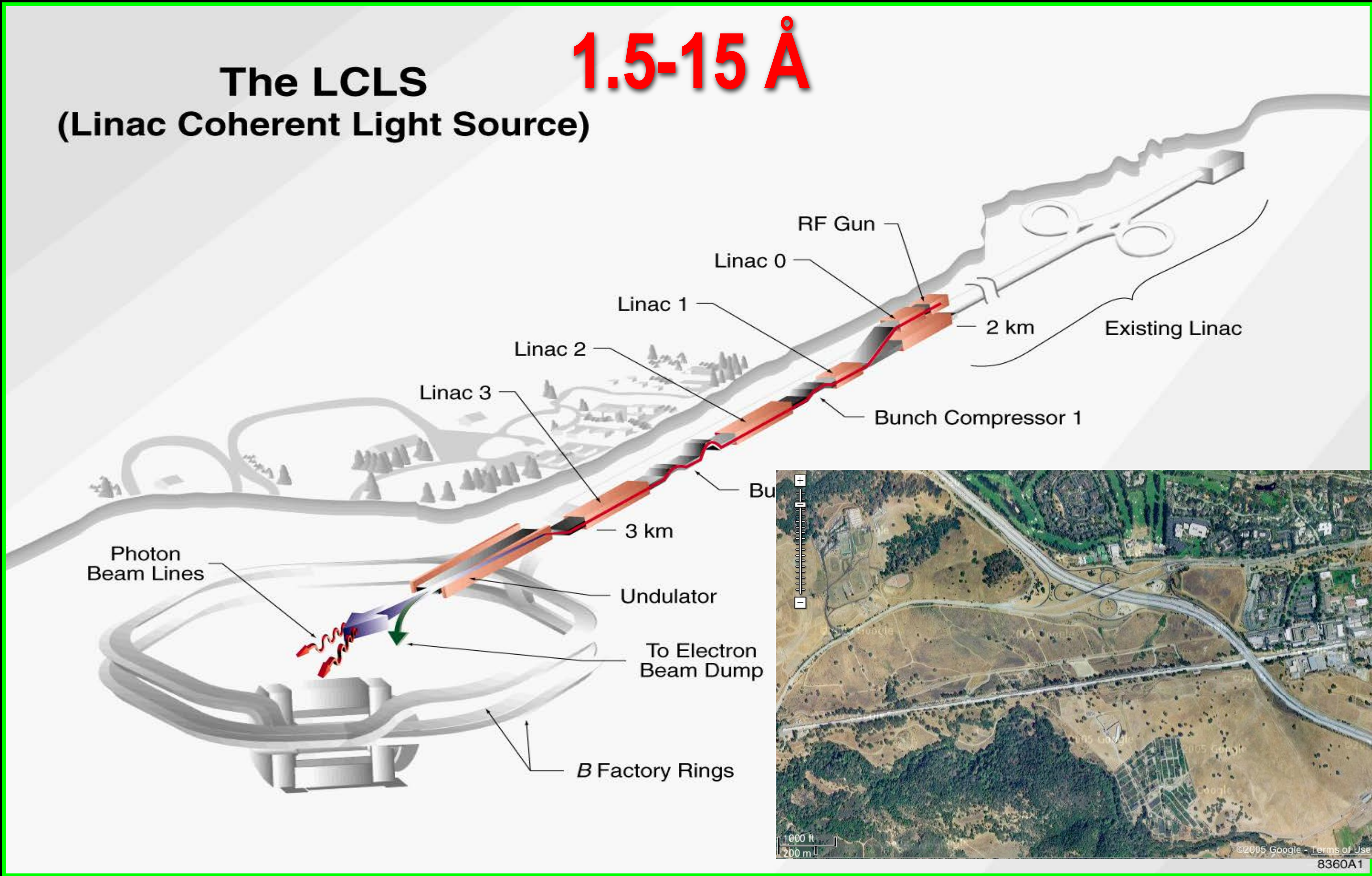
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



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

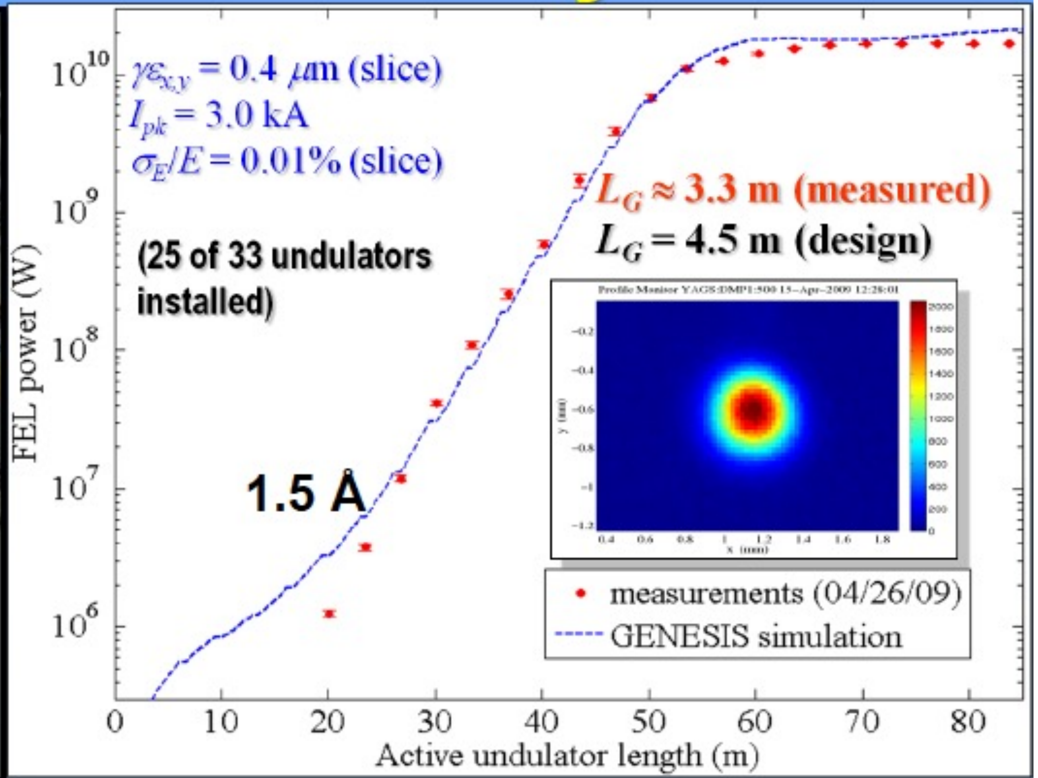
(Tunability - Harmonics)

LCLS at *SLAC*



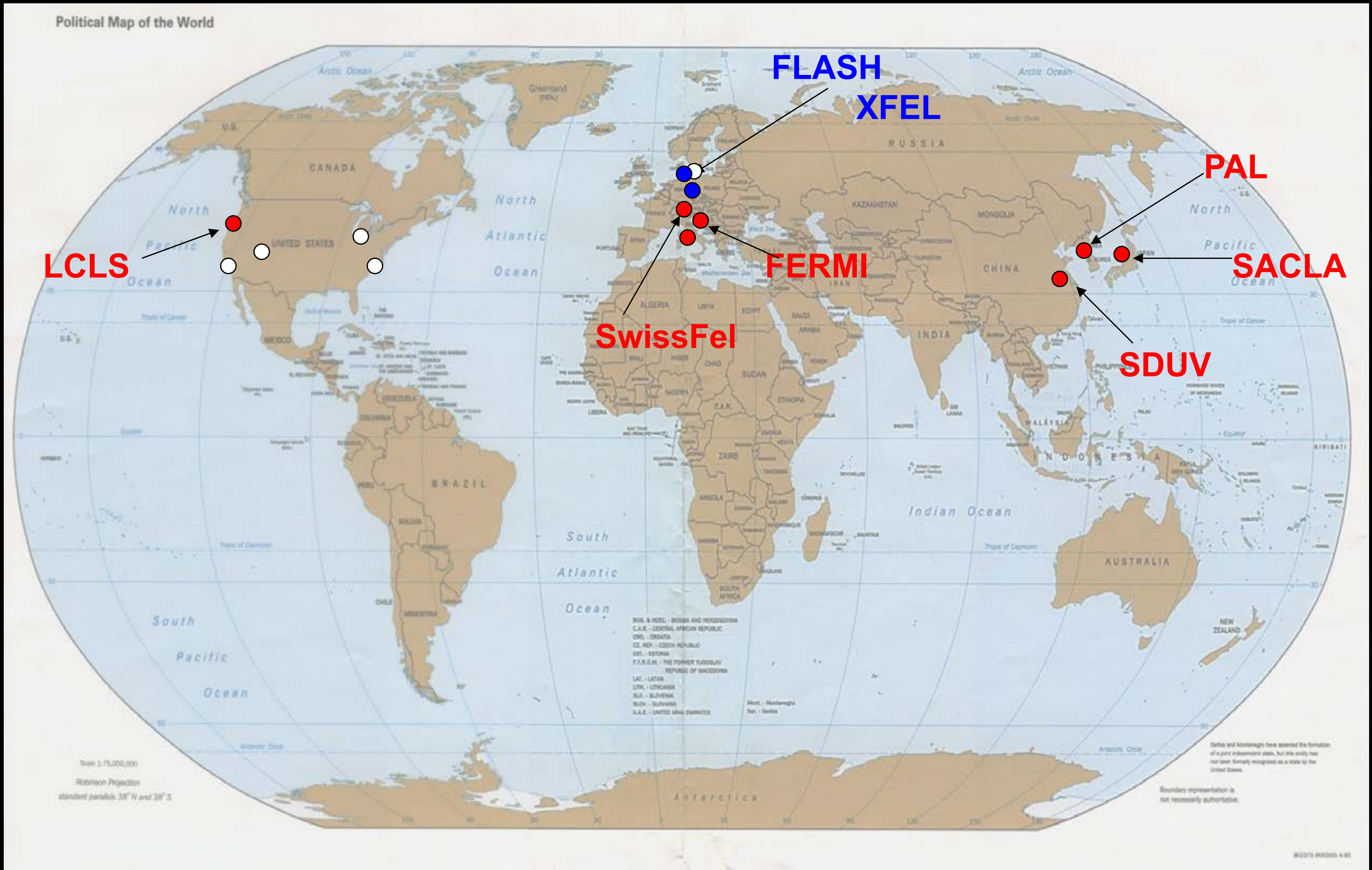
X-FEL based on last 1-km of existing *SLAC* linac

LCLS: world's first hard x-ray FEL



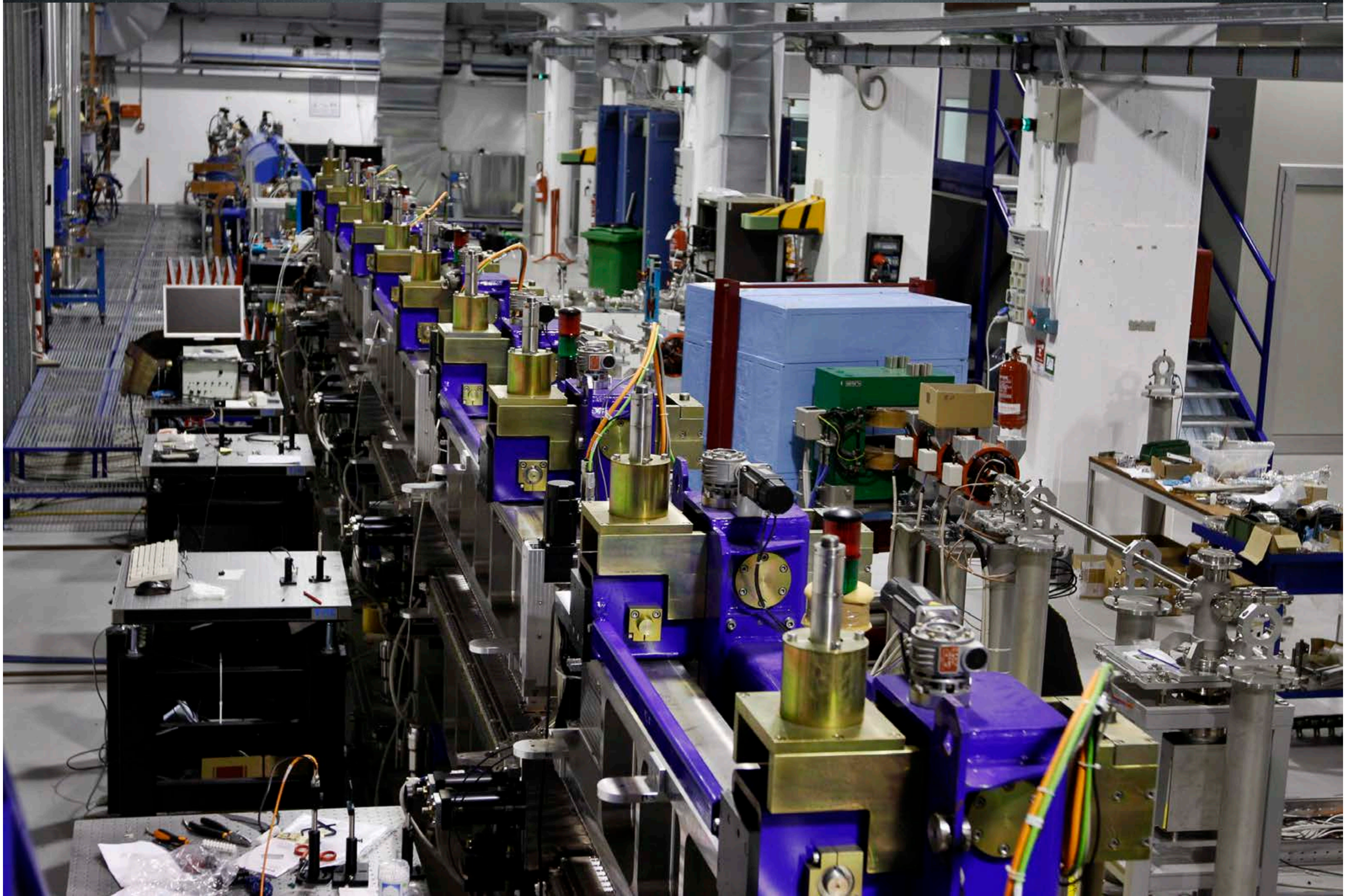
- SASE wavelength range: **25 – 1.2** Å
- Photon energy range: **0.5 - 10** keV
- Pulse length FWHM **5 - 500** fs (SXR only)
- Pulse energy up to **4** mJ

Short Wavelength SASE FEL

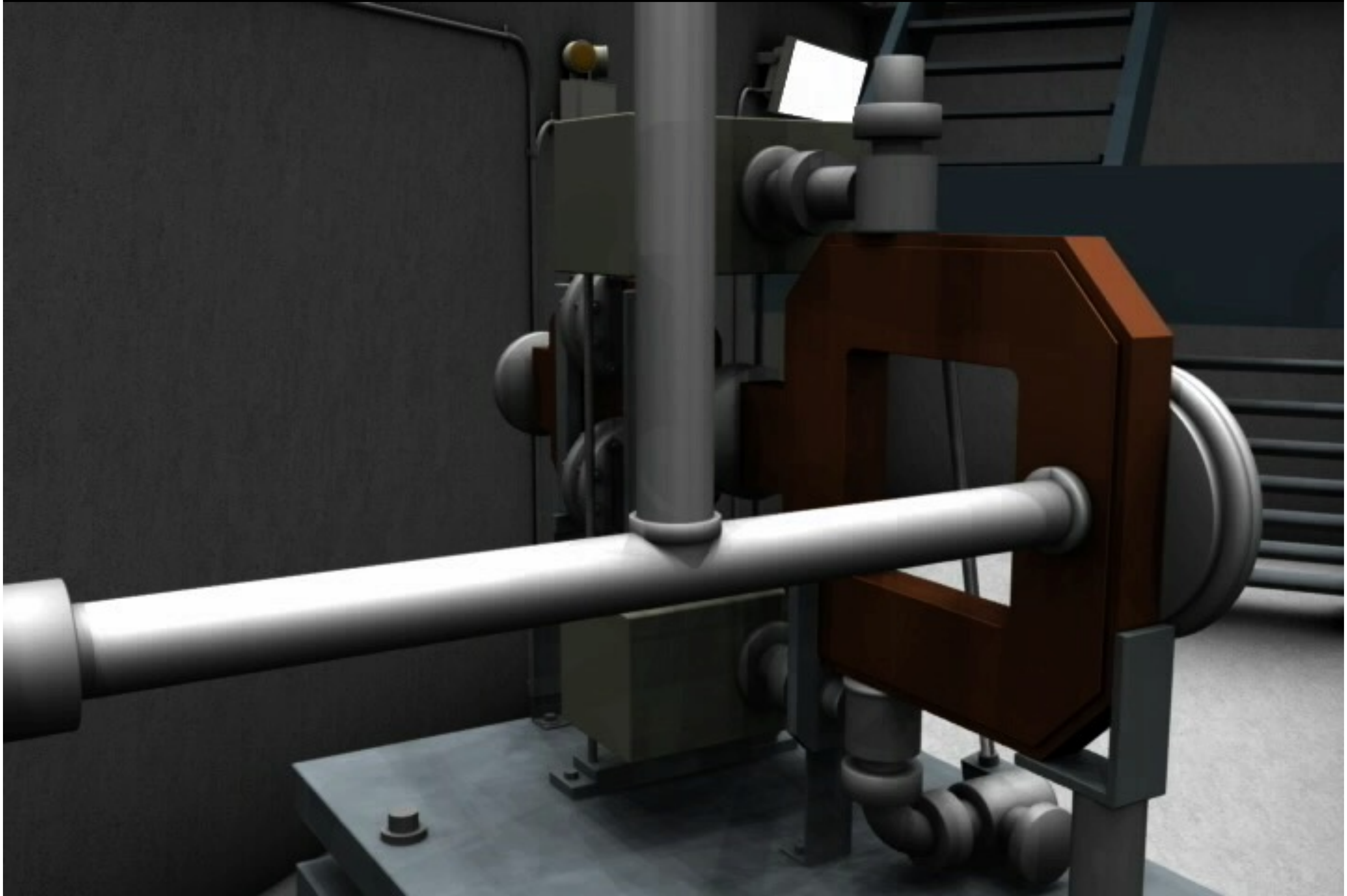


XFEL first lasing – Hamburg - May 2017

FELs Initiatives in Italy



Electron source and acceleration

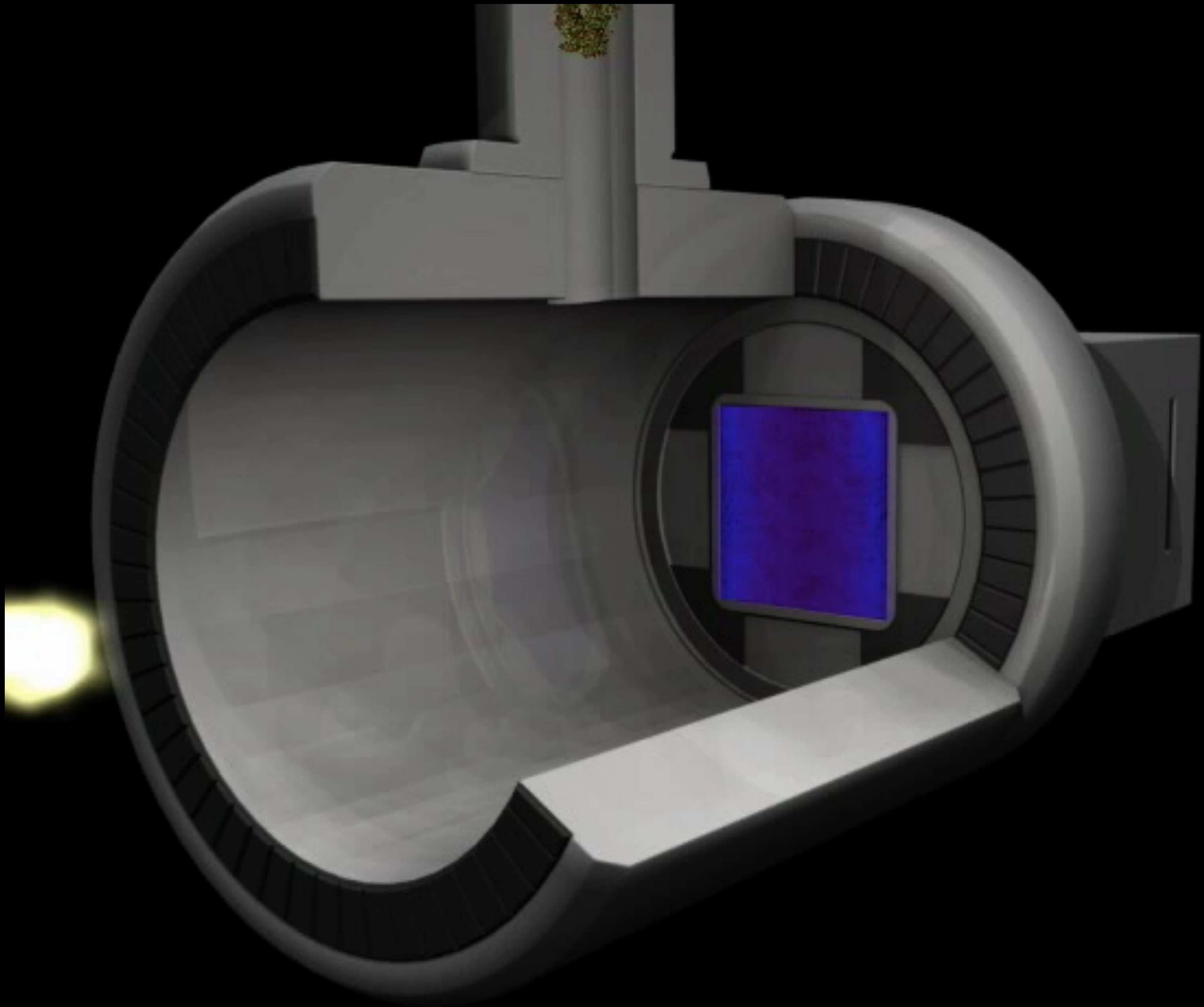


Magnetic bunch compressor (< 1 ps)

Long undulators chain

Beam separation

Experimental hall (Single Protein Imaging)



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

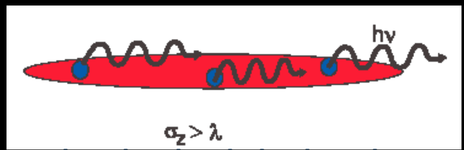
Peak power of one accelerated charge:

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

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

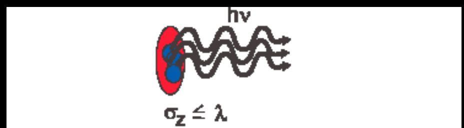
Incoherent Spontaneous Radiation Power:

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



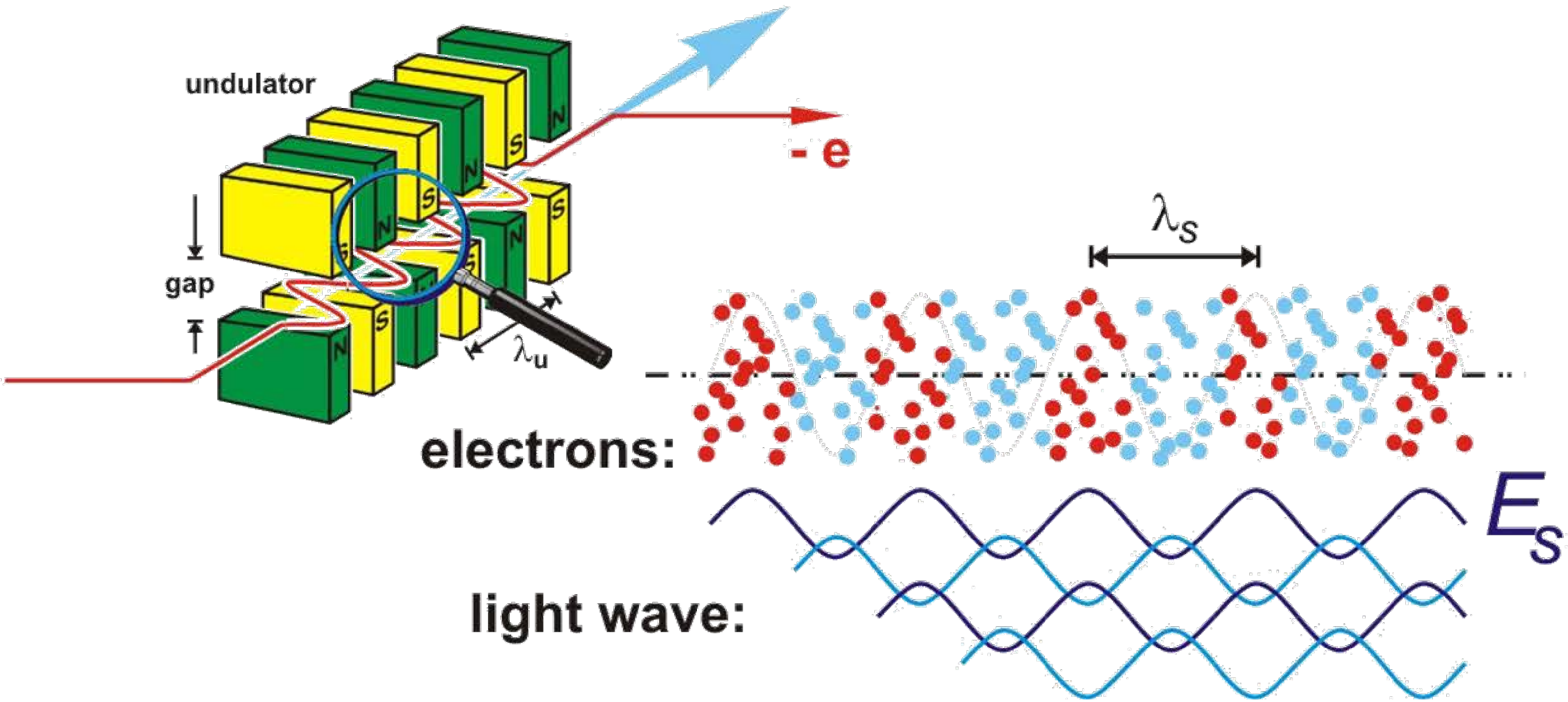
Coherent Stimulated Radiation Power:

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



Bunching on the scale of the wavelength:

Spontaneous Emission ==> Random phases



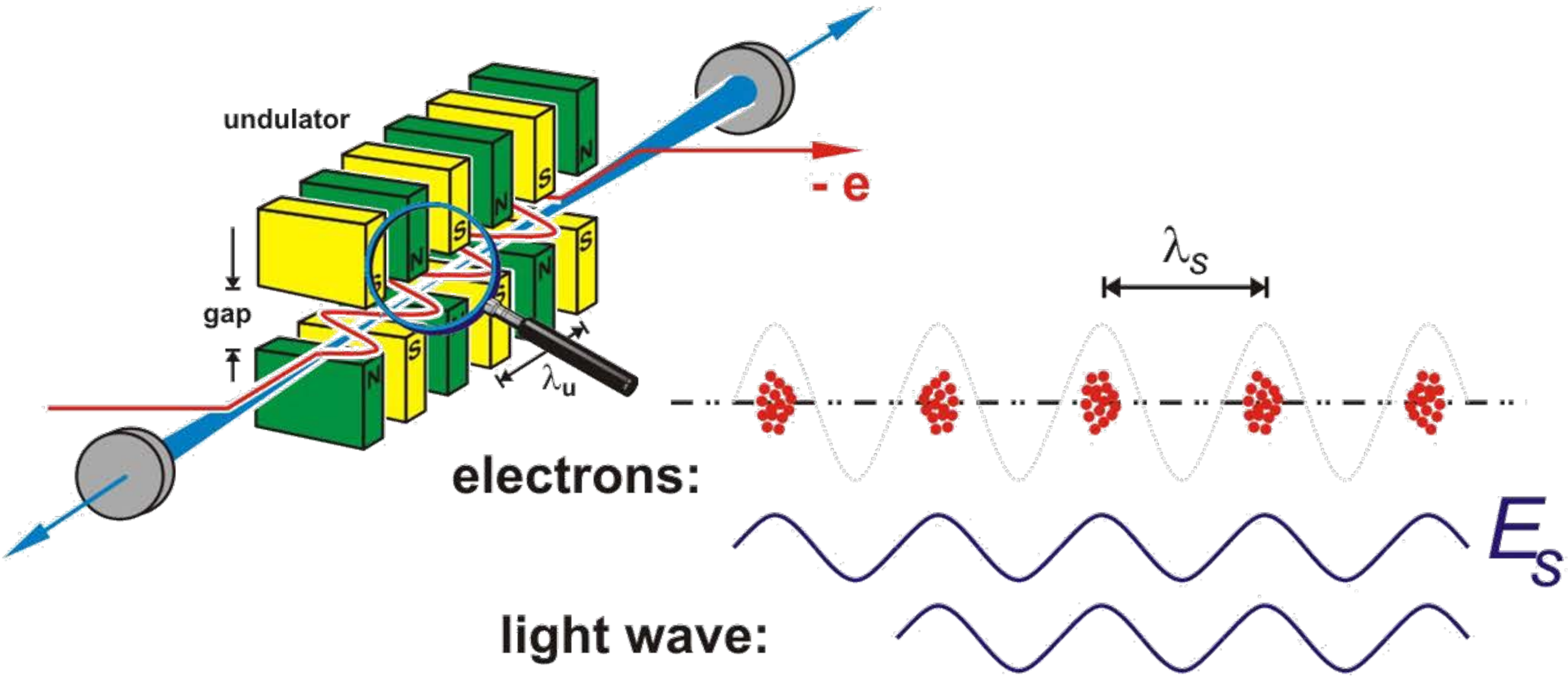
Radiated Power :

$P \propto N$

destructive interference

→ **shotnoise radiation**

Coherent Light ==> Stimulated Emission

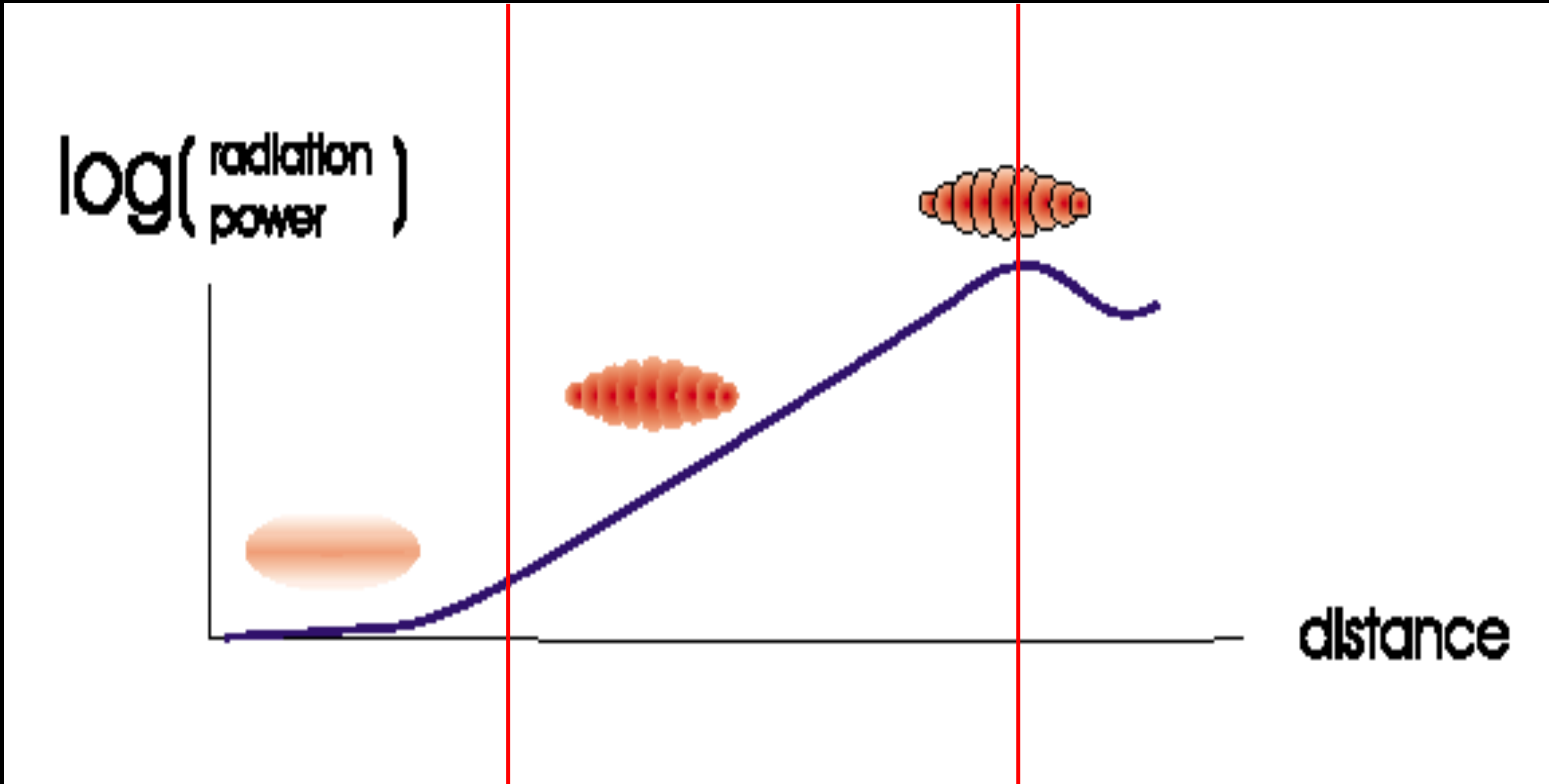


Radiated Power :

$P \propto N^2$

constructive interference

⟶ **enhanced emission**



Letargy

Spontaneous Emission

Low Gain

Slow Bunching

Exponential Growth

Stimulated emission

High Gain

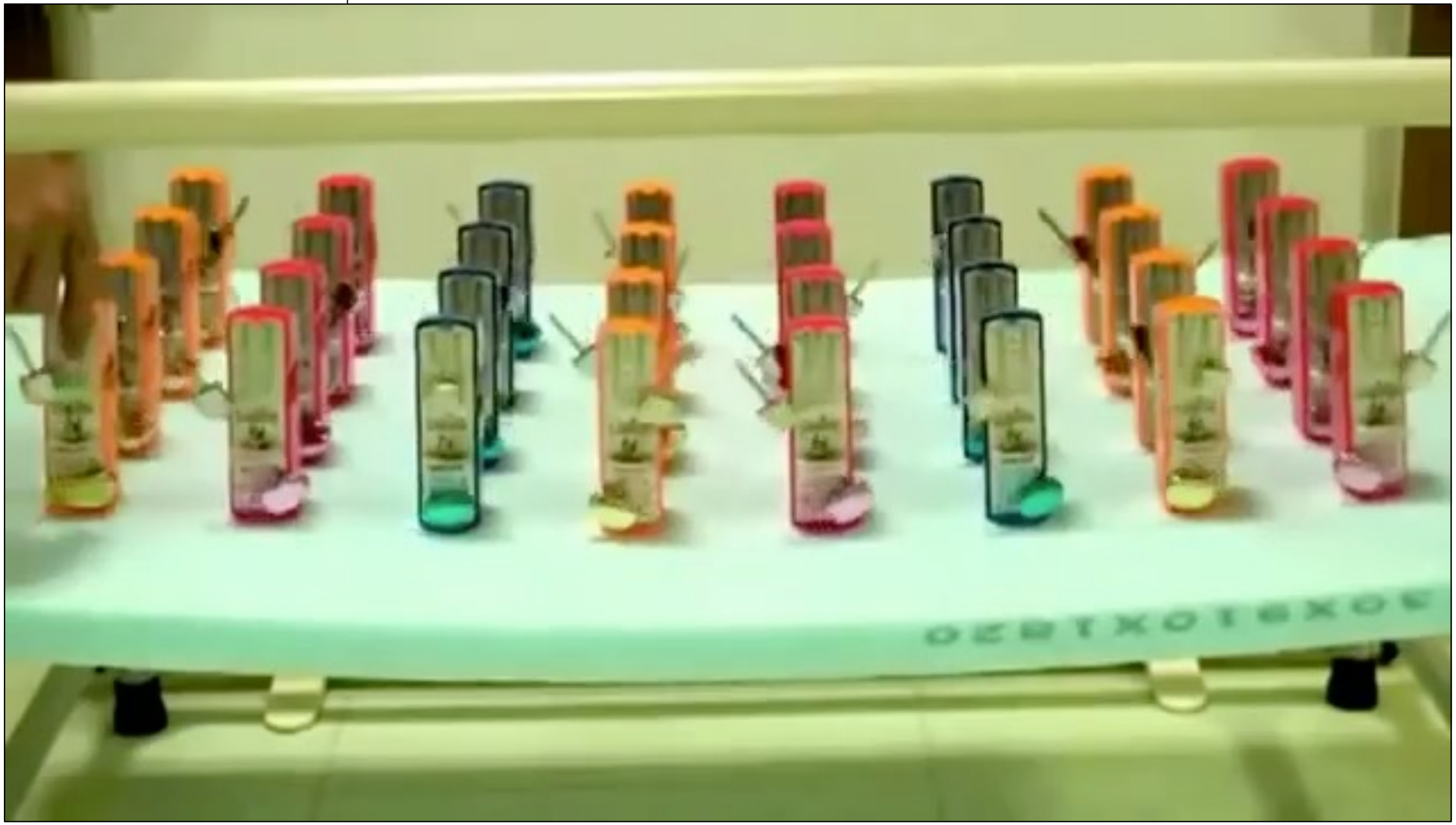
Enhanced Bunching

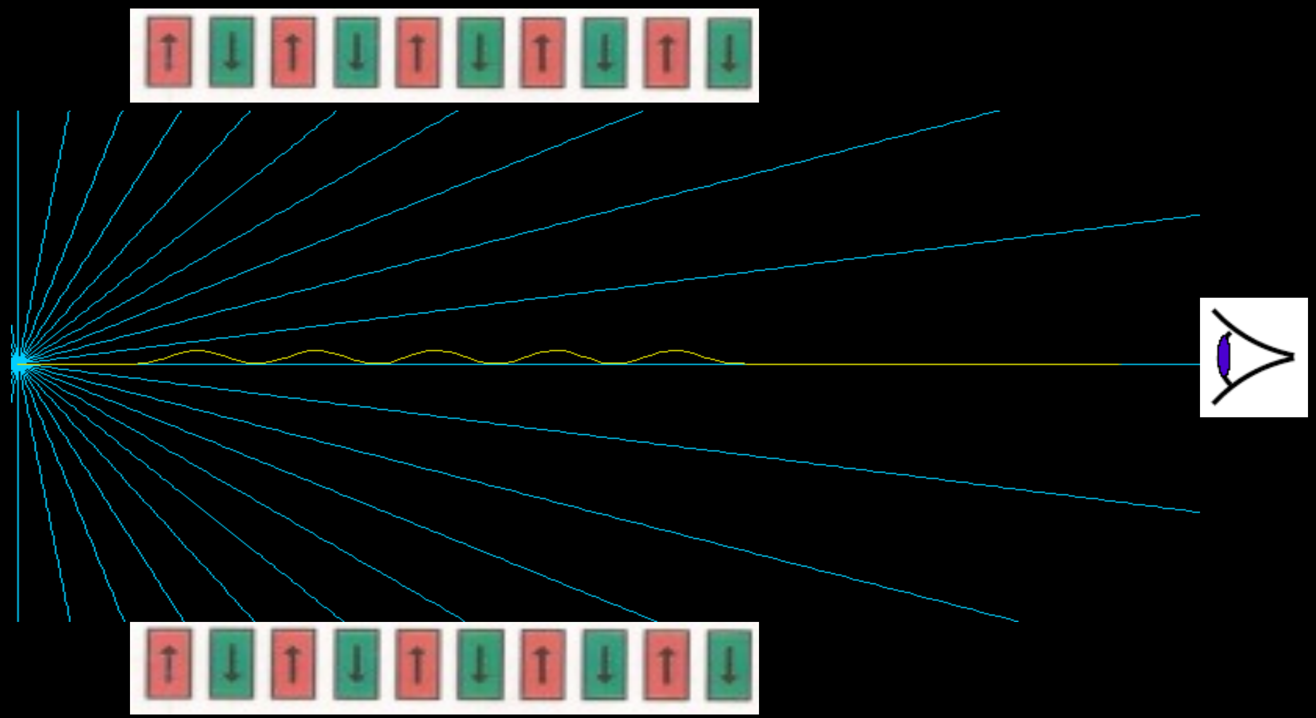
Saturation

Absorption

No Gain

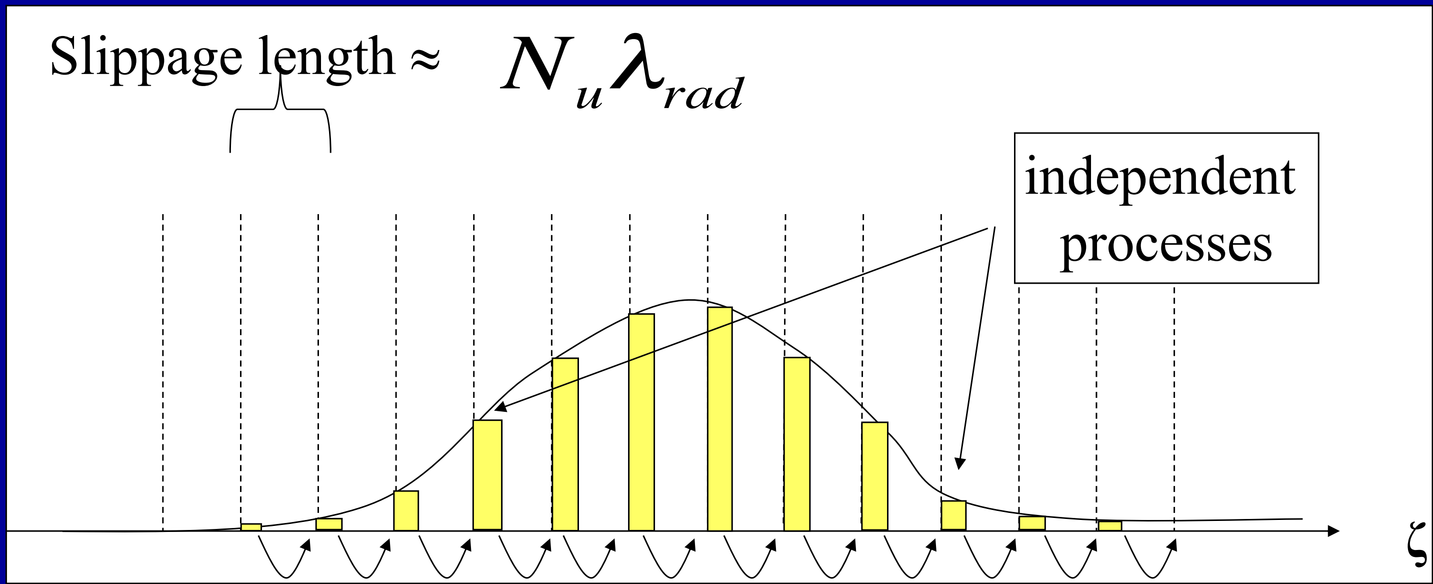
Debunching





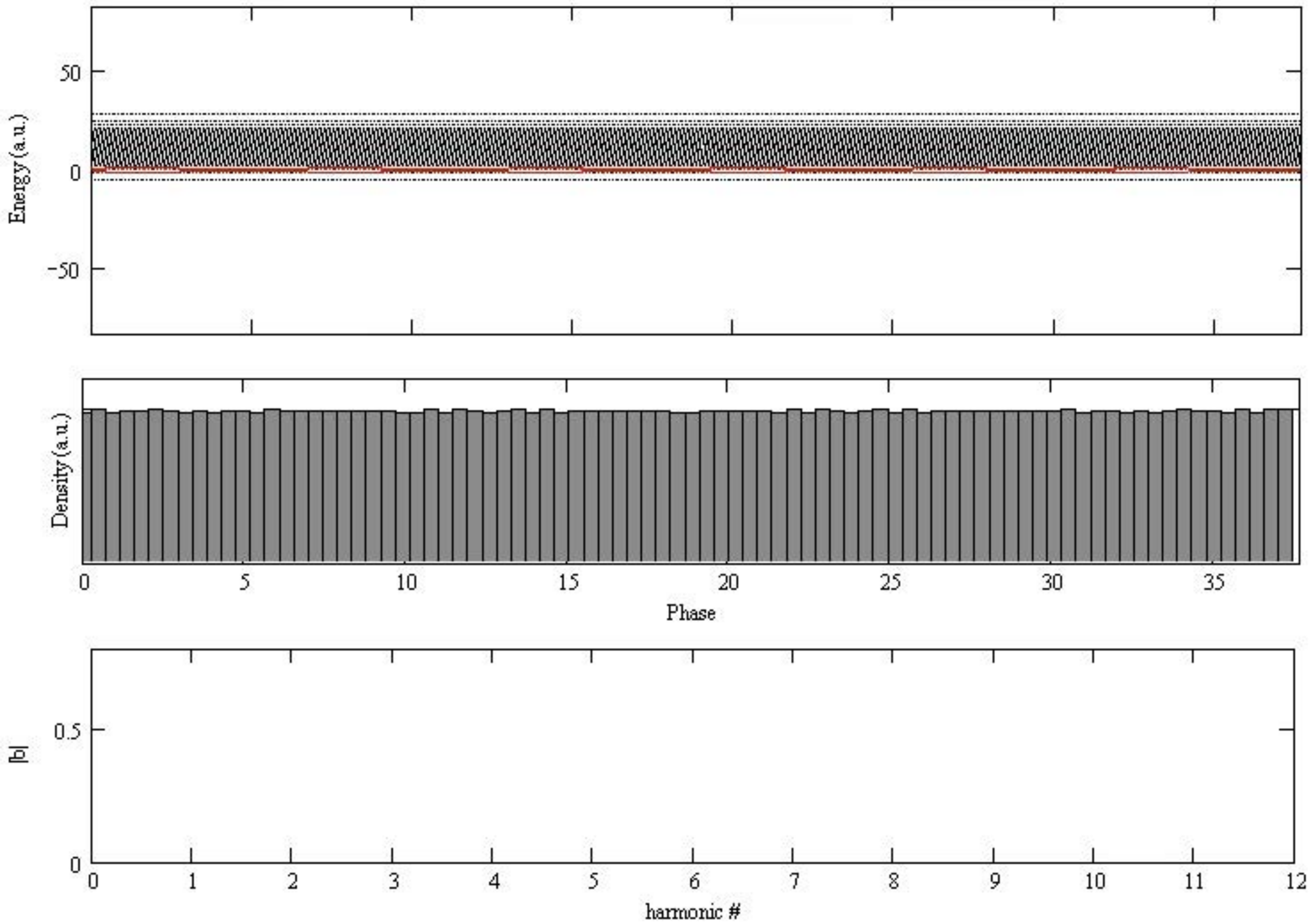
Radiation Simulator – T. Shintake, @ http://www-xfel.spring8.or.jp/Index.htm

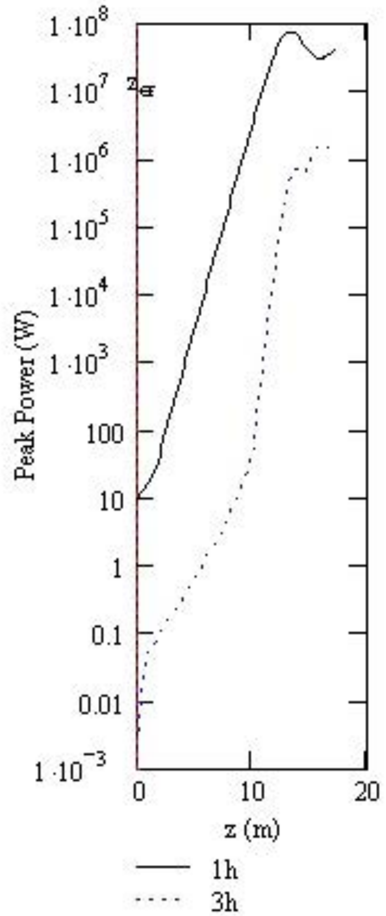
SASE Longitudinal coherence



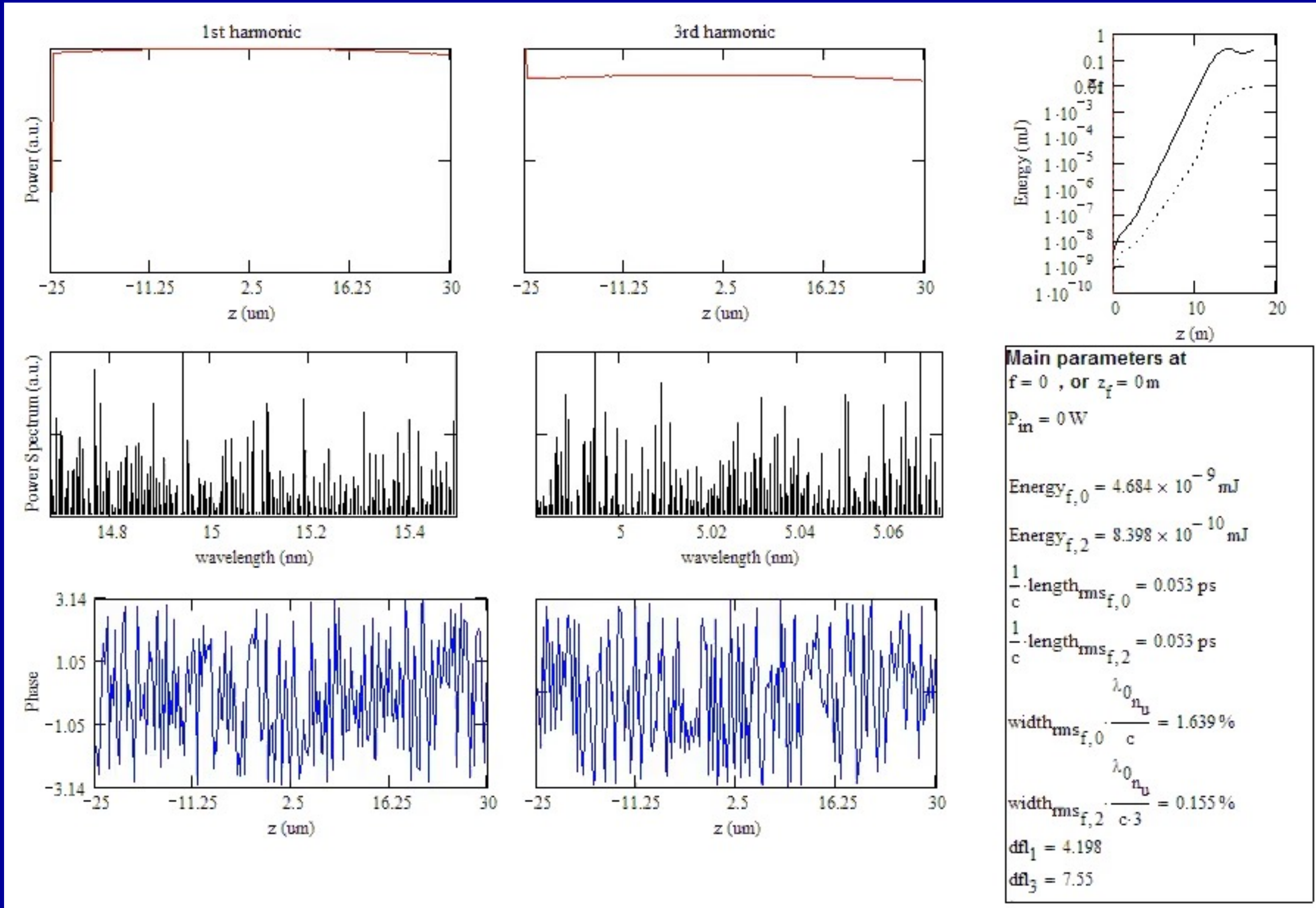
The radiation "slips" over the electrons for a distance $N_u \lambda_{rad}$

Bunching evolution



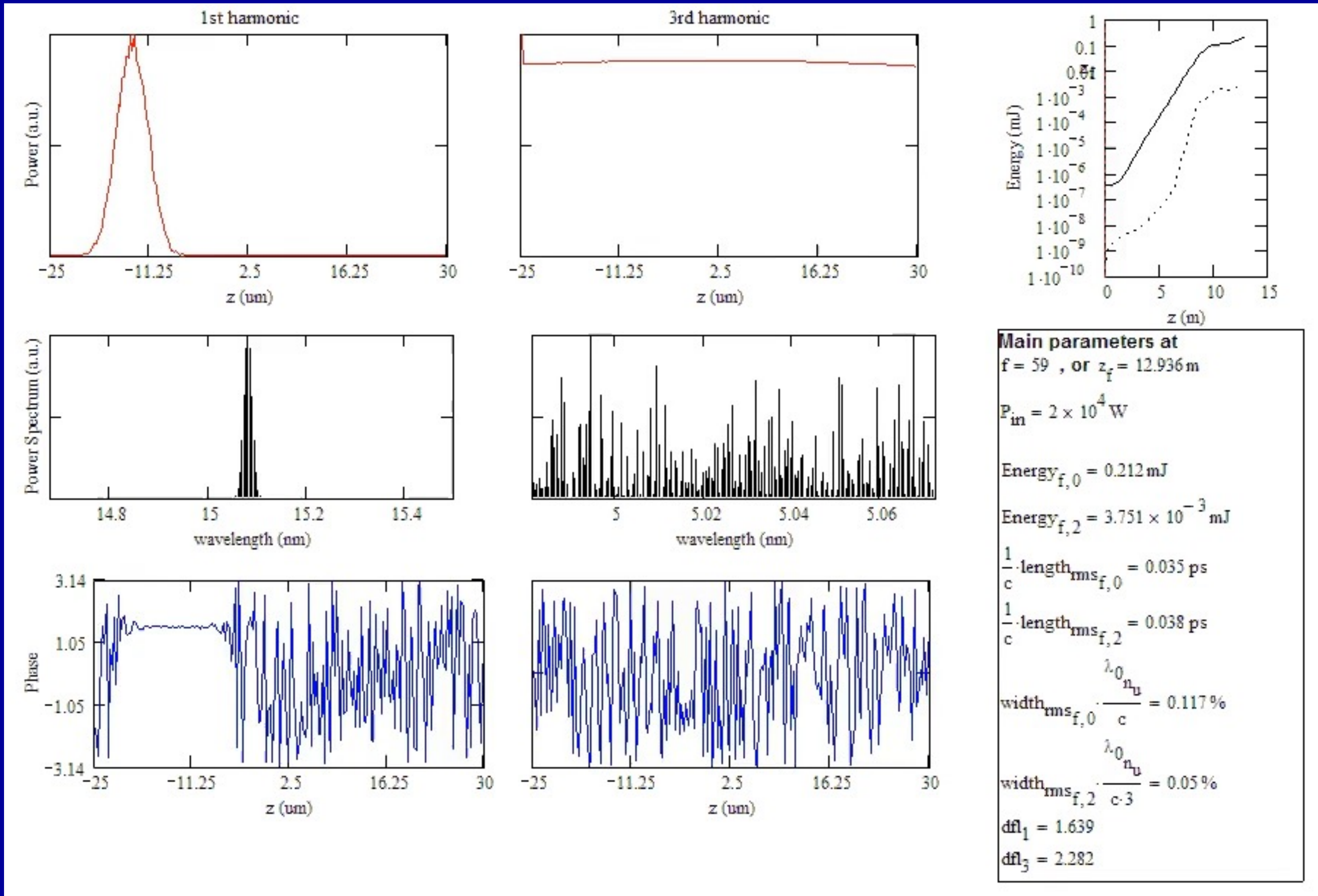


SASE



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

SEEDING



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

SASE FEL at short wavelengths require a very intense, high quality e-beam

- FEL Parameter $$\rho = 0.136 \frac{1}{\gamma_r} J^{1/3} B_u^{2/3} \lambda_u^{4/3}$$
- Exponential growth $$P(z) = \frac{P_0}{9} \exp\left(\frac{z}{L_G}\right)$$
- Gain Length $$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$
- Saturation power $$P_{sat} = \rho P_{beam} \propto N_e^{4/3}$$
- Constraint on emittance $$\varepsilon = \frac{\varepsilon_n}{\gamma} < \frac{\lambda_0}{4\pi}$$
- Constraint on energy spread $$\Delta\gamma/\gamma < \rho$$
- Relative bandwidth $$\frac{\Delta\omega}{\omega} = \sqrt{\frac{\rho}{N_u}}$$

Short-wavelength free-electron laser sources and science: a review

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

The physics of x-ray free-electron lasers

C. Pellegrini

Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, California 90095, USA and SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

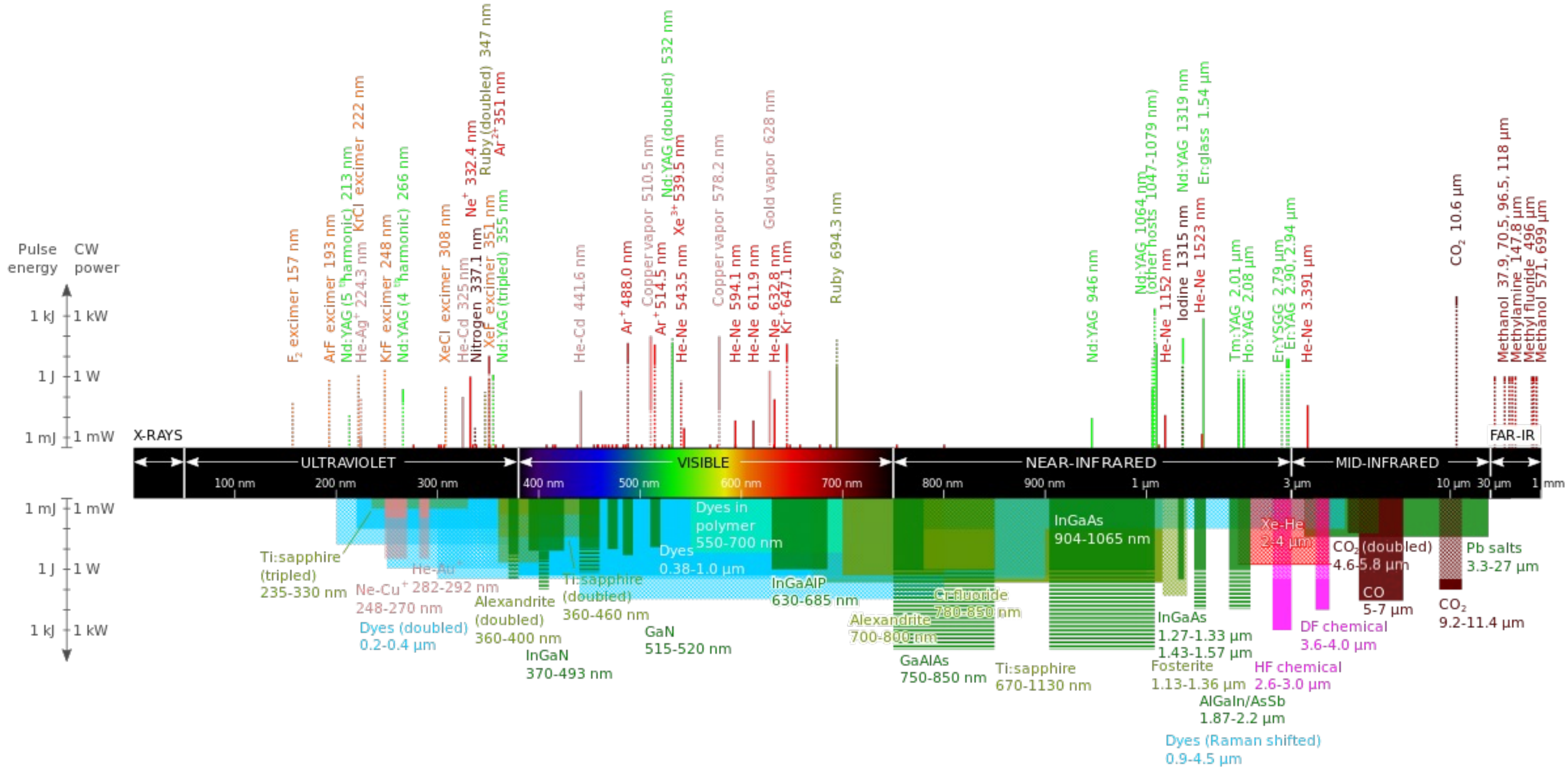
A. Marinelli

SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

S. Reiche

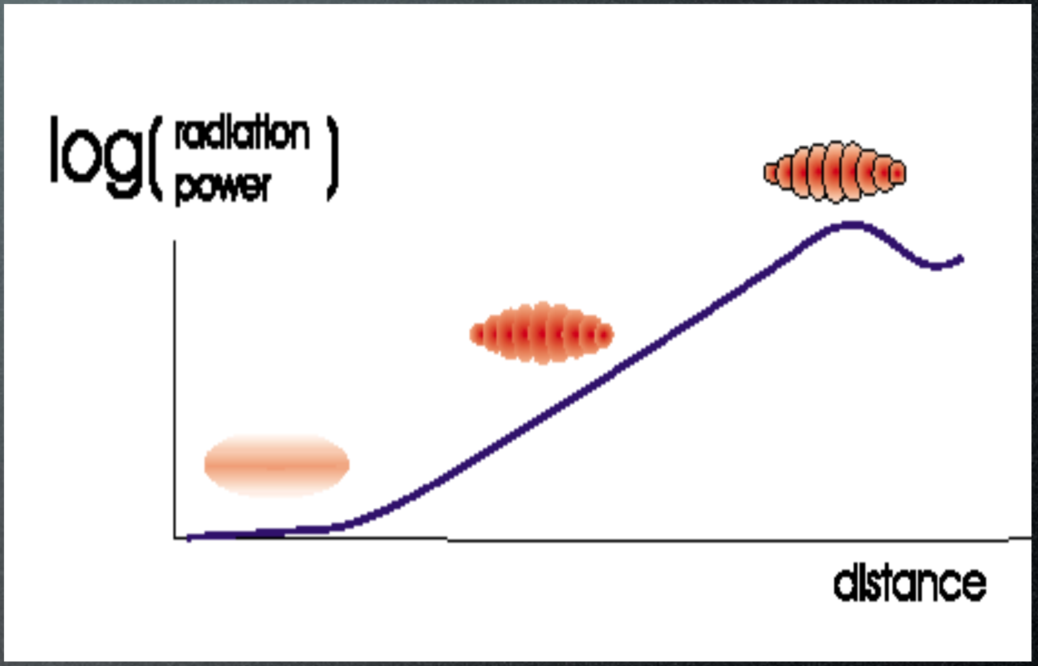
Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Wavelengths of commercially available atomic lasers



1. Well known and proven technology
2. One Laser One Color.
3. Limited by Mirrors ==> No X rays.

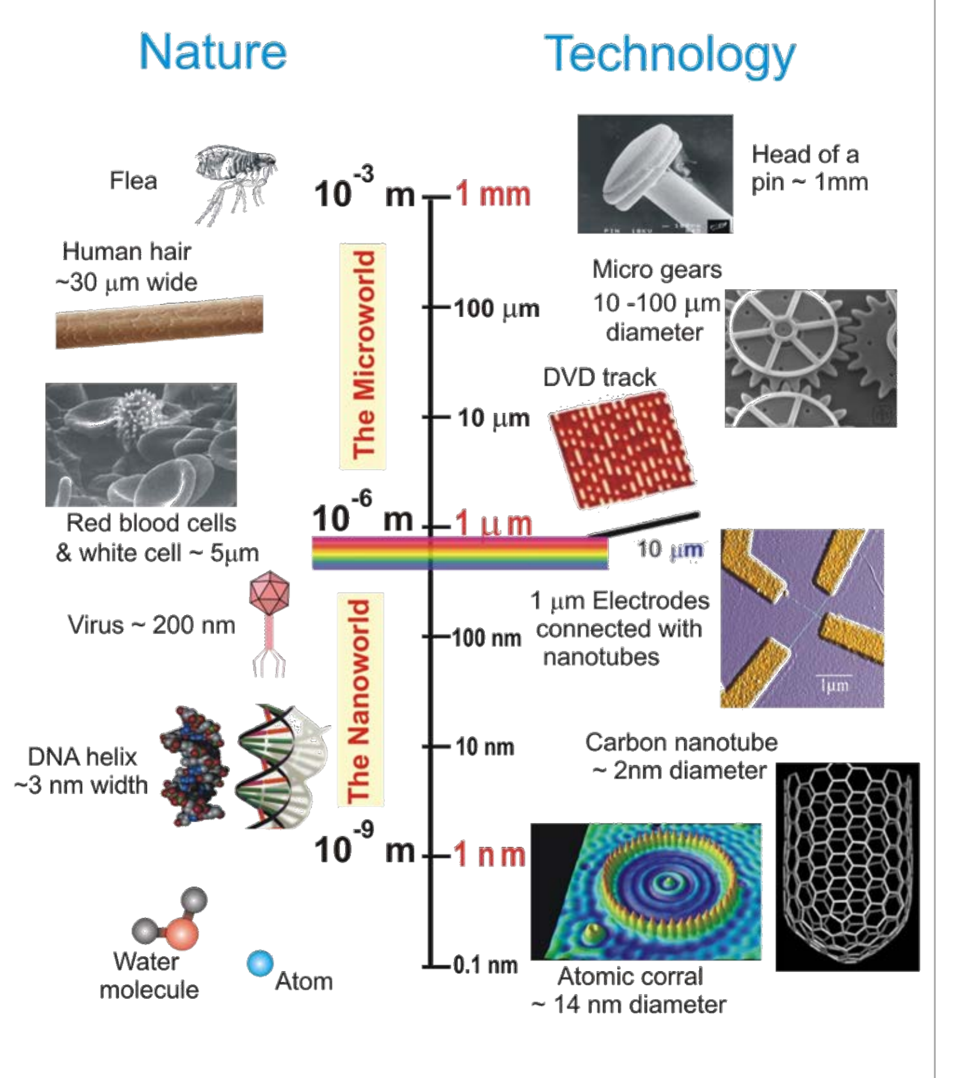
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



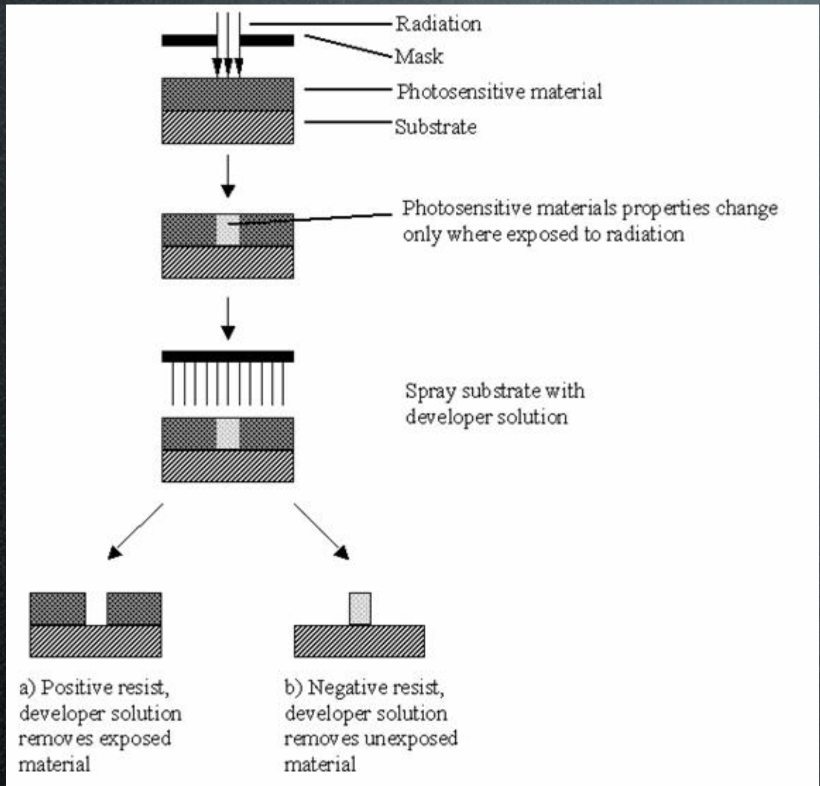
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)

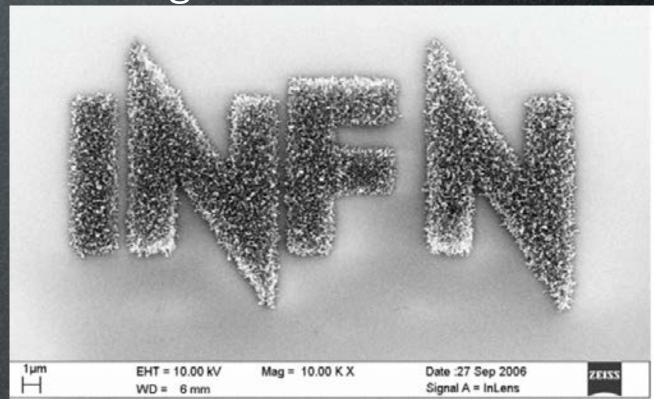
Ultra-Small


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



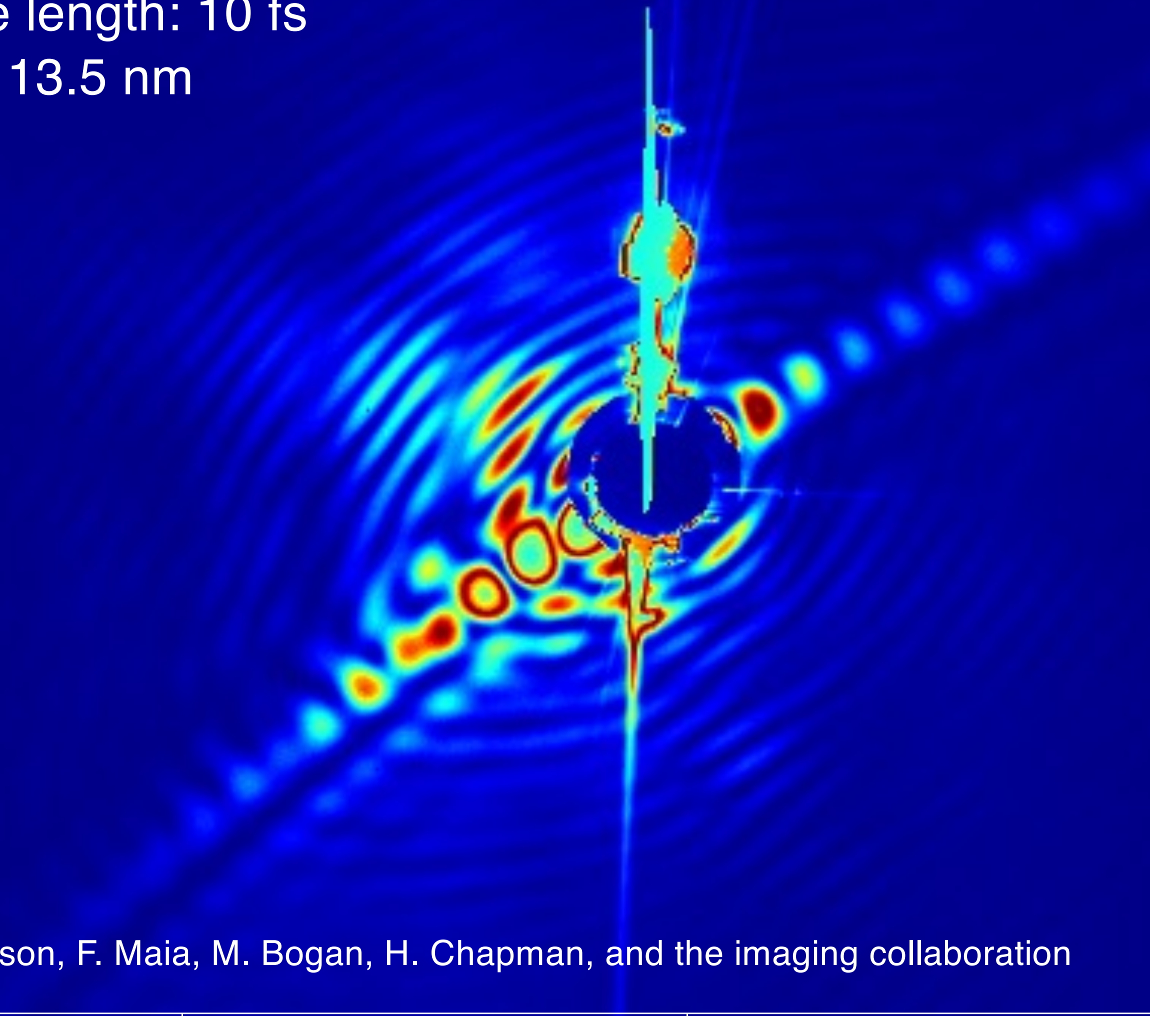
- Extreme UV Lithographt is the candidate technology with <50-35 nm

- Cost effective solutions based on FEL sources can be foreseen

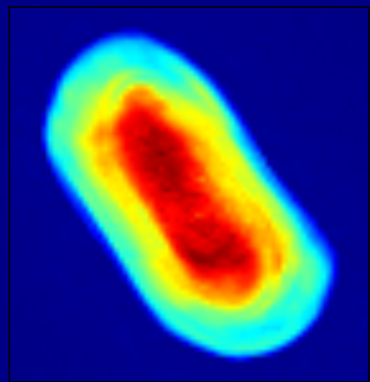
FIRST FLASH DIFFRACTION IMAGE OF A LIVING CELL

FLASH soft X-ray laser, Hamburg, Germany

FLASH pulse length: 10 fs
Wavelength: 13.5 nm



RECONSTRUCTED
CELL STRUCTURE



Filipe Maia, Uppsala

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

30 60 ∞ 60 30

Resolution length on the detector (nm)

cluster and nanoparticle

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

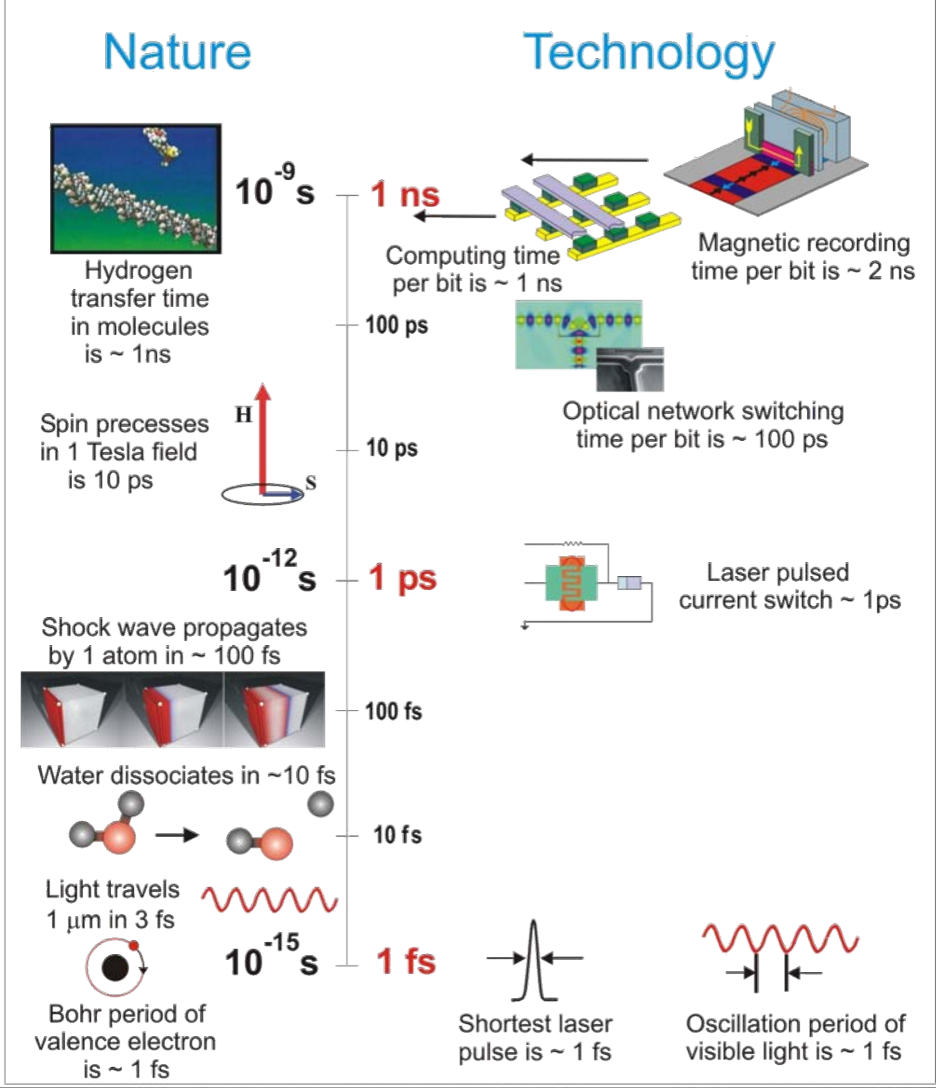
Small particles are different from bulk matter; finite size effects influence all properties of matter.

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

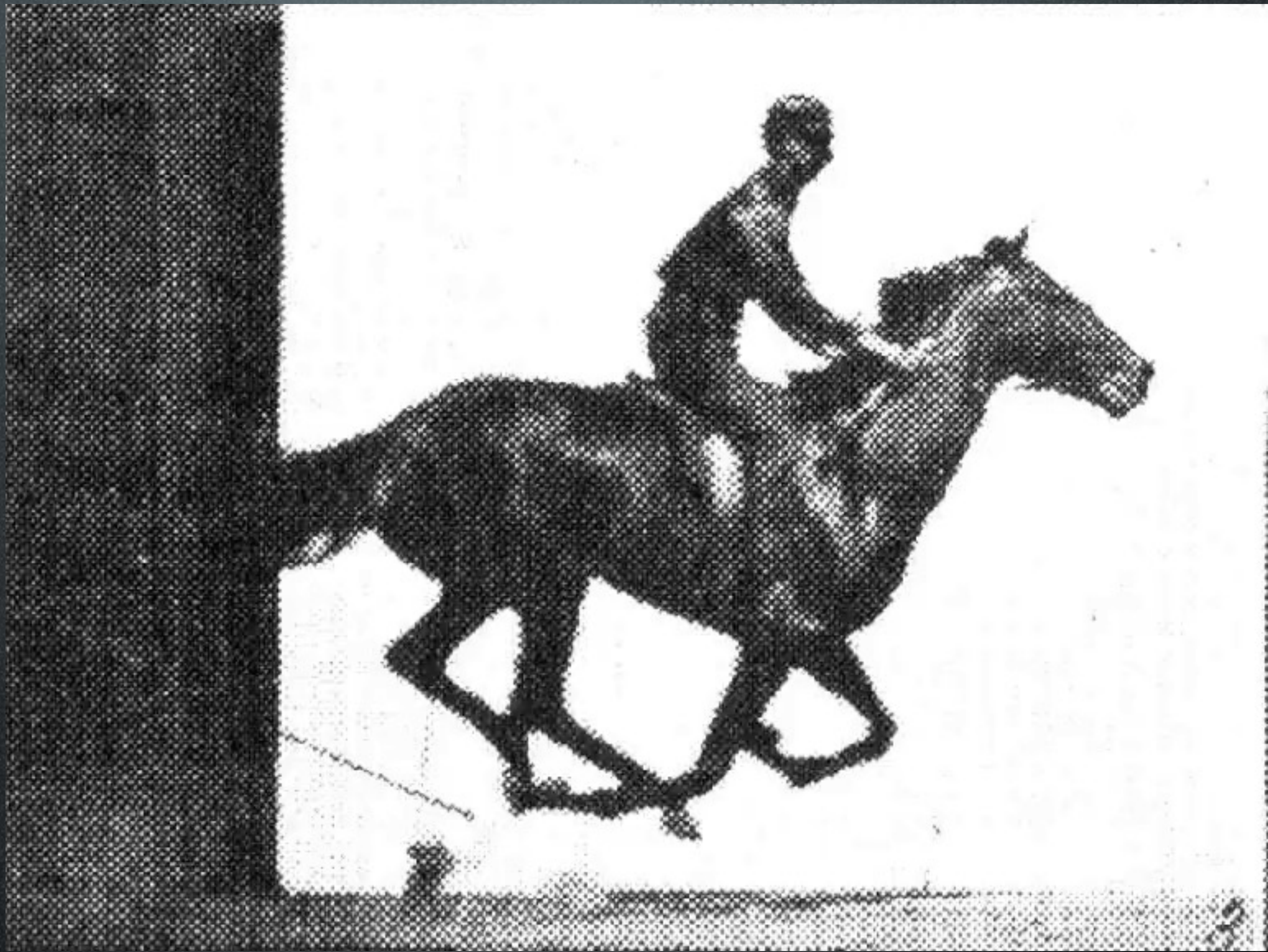


Nature
Technology
10^-9 s
1 ns
Hydrogen transfer time in molecules is ~ 1ns
Computing time per bit is ~ 1 ns
Magnetic recording time per bit is ~ 2 ns
100 ps
Optical network switching time per bit is ~ 100 ps
Spin precesses in 1 Tesla field is 10 ps
H
S
10 ps
10^-12 s
1 ps
Laser pulsed current switch ~ 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

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

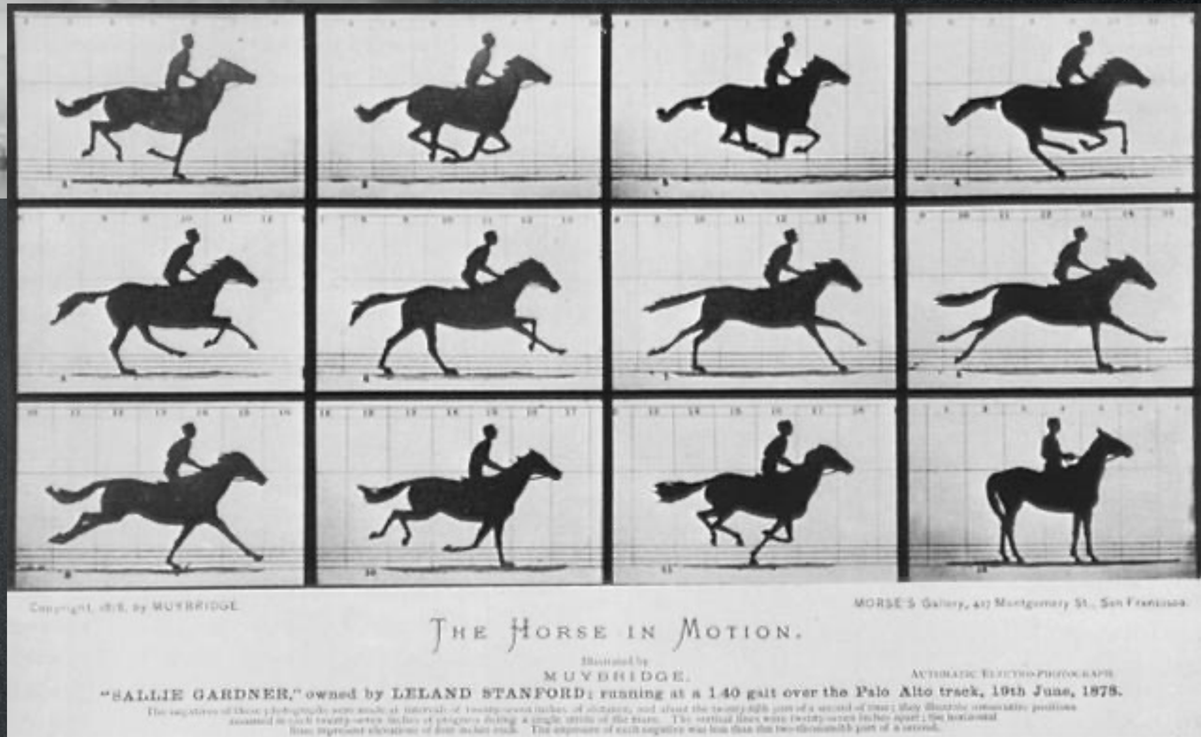
disagree whether all feet leave the ground during gallop...



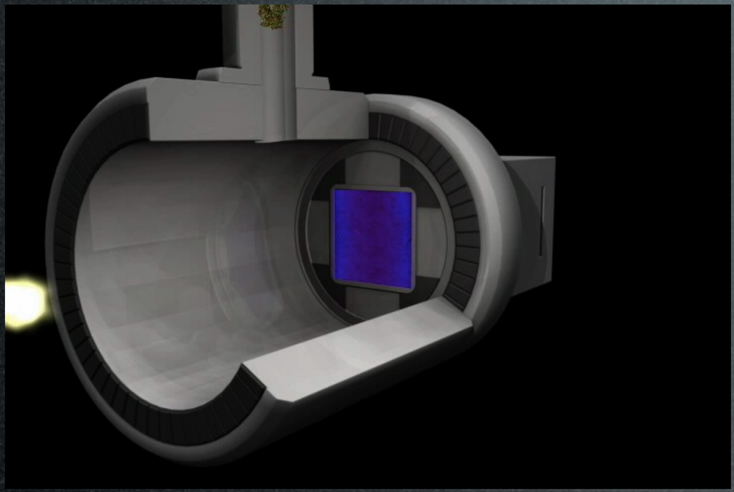
used spark photography to freeze this 'ultra-fast' process

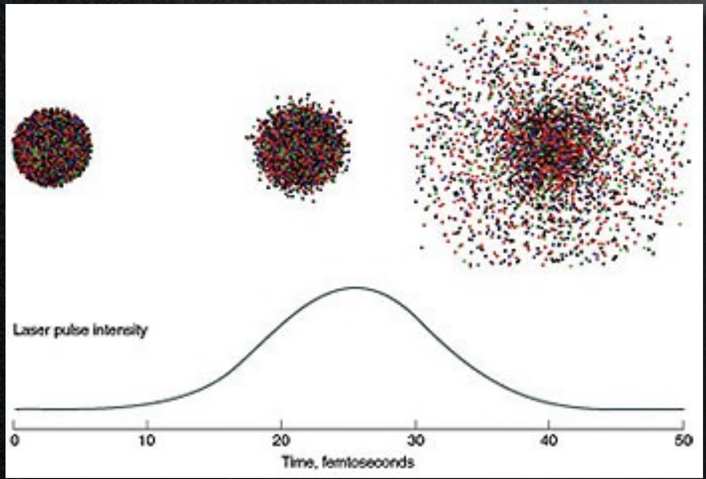
E. Muybridge, *Animals in Motion*, ed. L. S. Brown (Dover Pub. Co., New York 1957)
Courtesy Paul Emma (SLAC).


WILDFILMHISTORY


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





Lawrence Livermore National Laboratory (LLNL)

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.

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

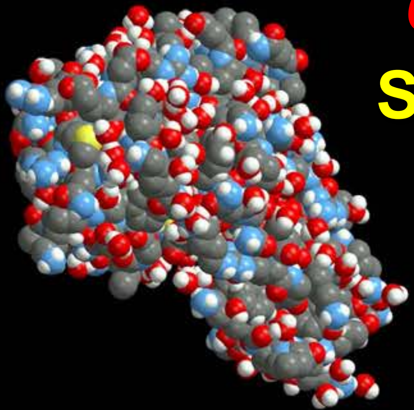
The patterns are combined to form an atomic-resolution image of the molecule.

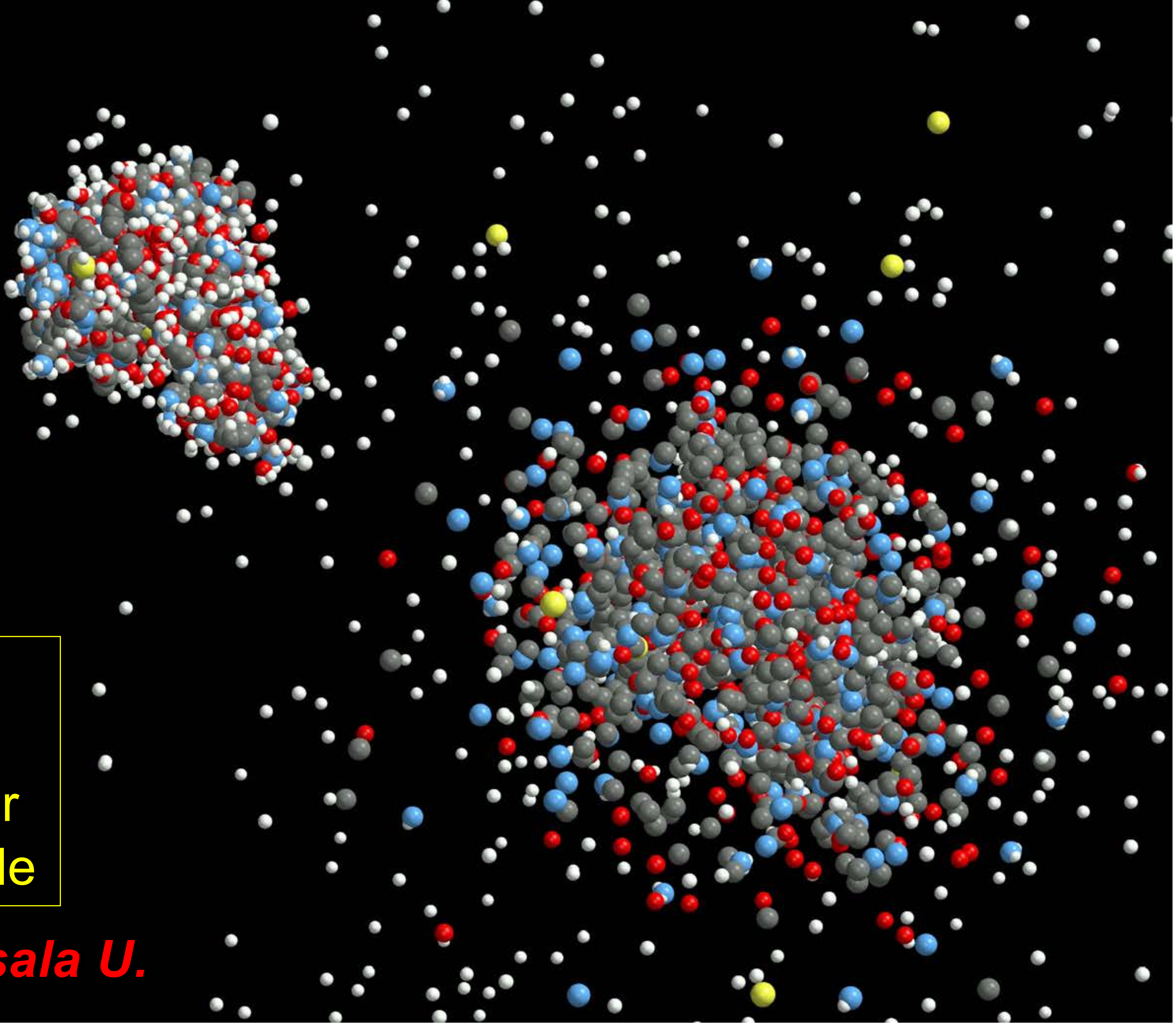
The speed record of 25 femtoseconds for flash imaging was achieved.

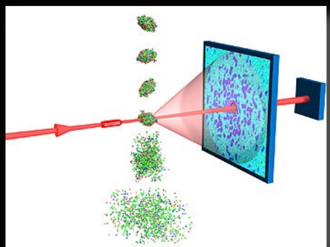
Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

Coulomb Explosion of Lysozyme (50 fs)

Single Molecule Imaging with Intense X-rays







Atomic and molecular dynamics occur at the *fsec*-scale

J. Hajdu, *Uppsala U.*

make a movie of chemical reactions

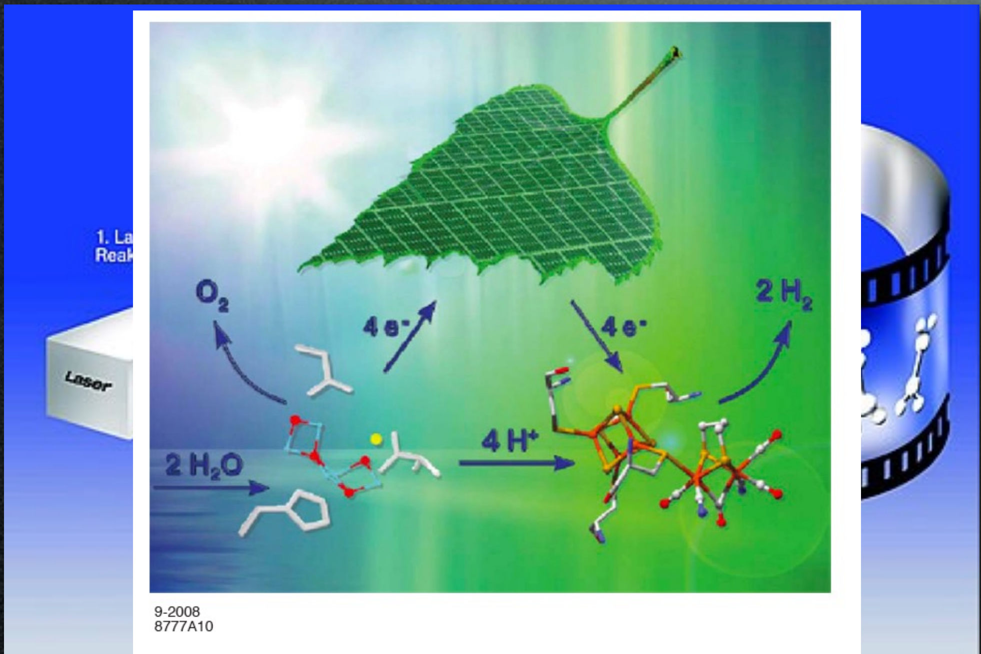


Figure 3.3. Photosynthetic water splitting and a hydrogenase powered by a light-harvesting antenna complex. [Source: W. Lubitz, E.J. Reijerse and J. Messinger, *Energy Environ. Sci.* **1**, 15 (2008)]

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.

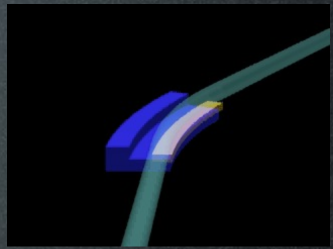
The first flash in each pair triggers the chemical reaction. With the second flash, a snapshot is then made.

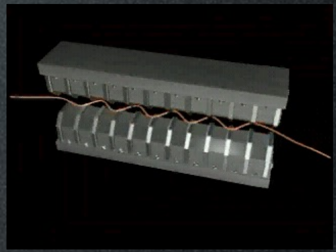
The delay between the two flashes can be precisely modified to within femtosecond and a series of snapshots can be made at various times following the start of the reaction.

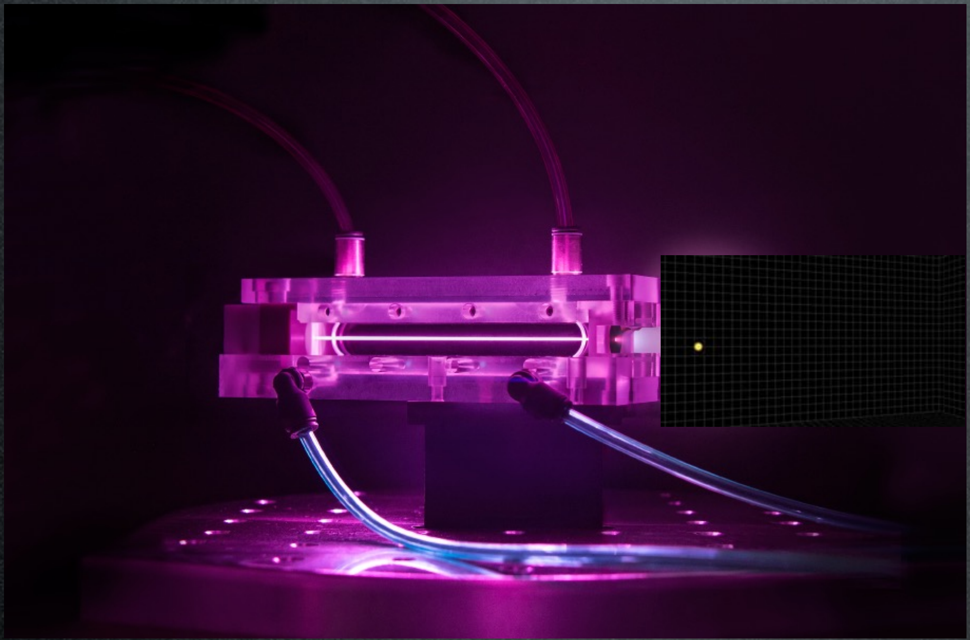
In each case, the images are of different molecules, but these images can be combined into a film.

Generations of Synchrotron Light Sources

I. Bending magnets in HEP rings







II. Compact Sources

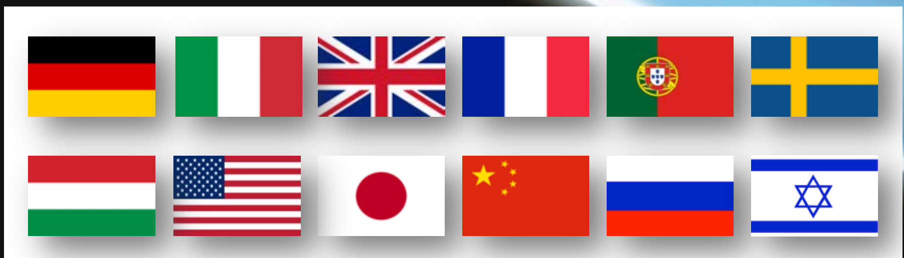
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

http://eupraxia-project.eu

A New European High-Tech User Facility

1

Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

Shrink down the facility size
Improve Sustainability

2

Producing particles and photons to support several urgent and timely science cases

Drive short wavelength FEL
Pave the way for future Linear Colliders

https://www.eupraxia-facility.org/

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

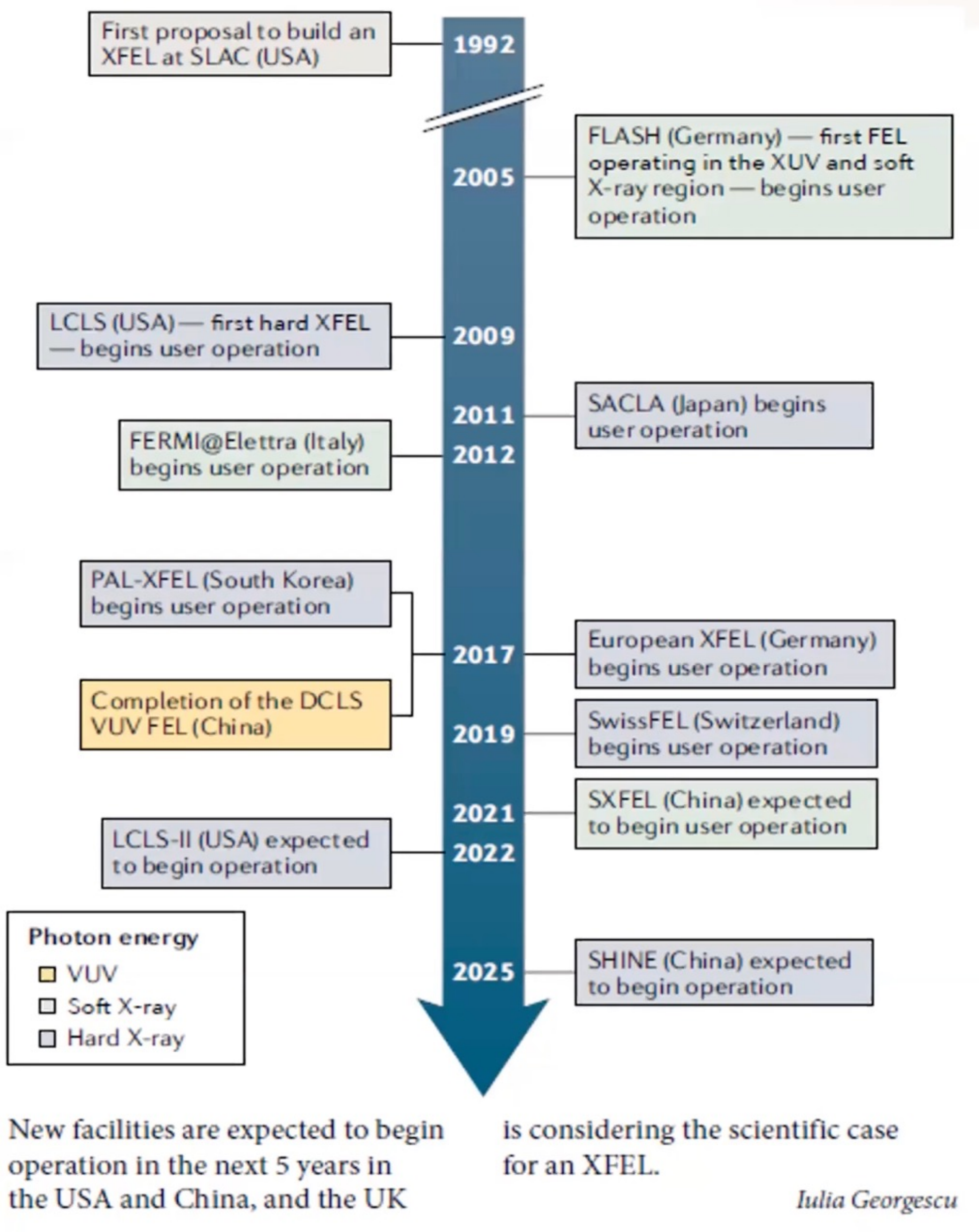
This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

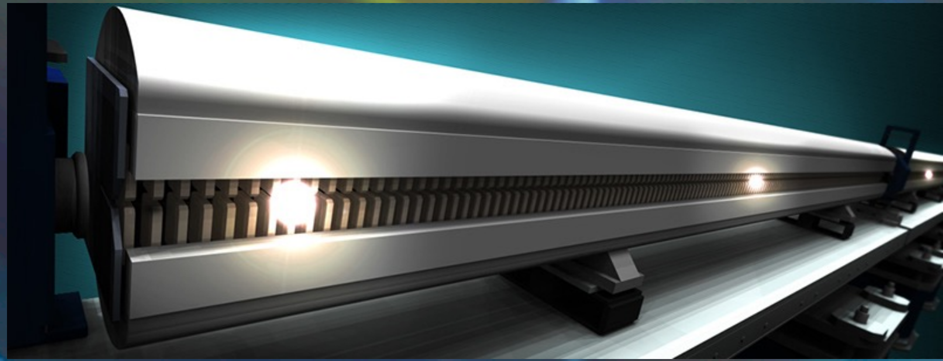
However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

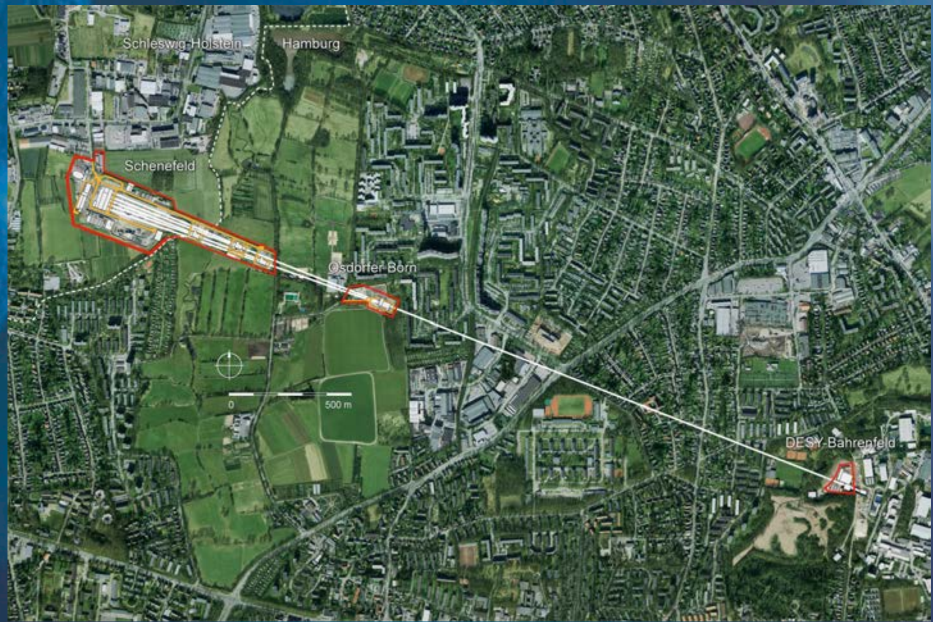
THE AUTHORS
Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

FEL is a well established technology

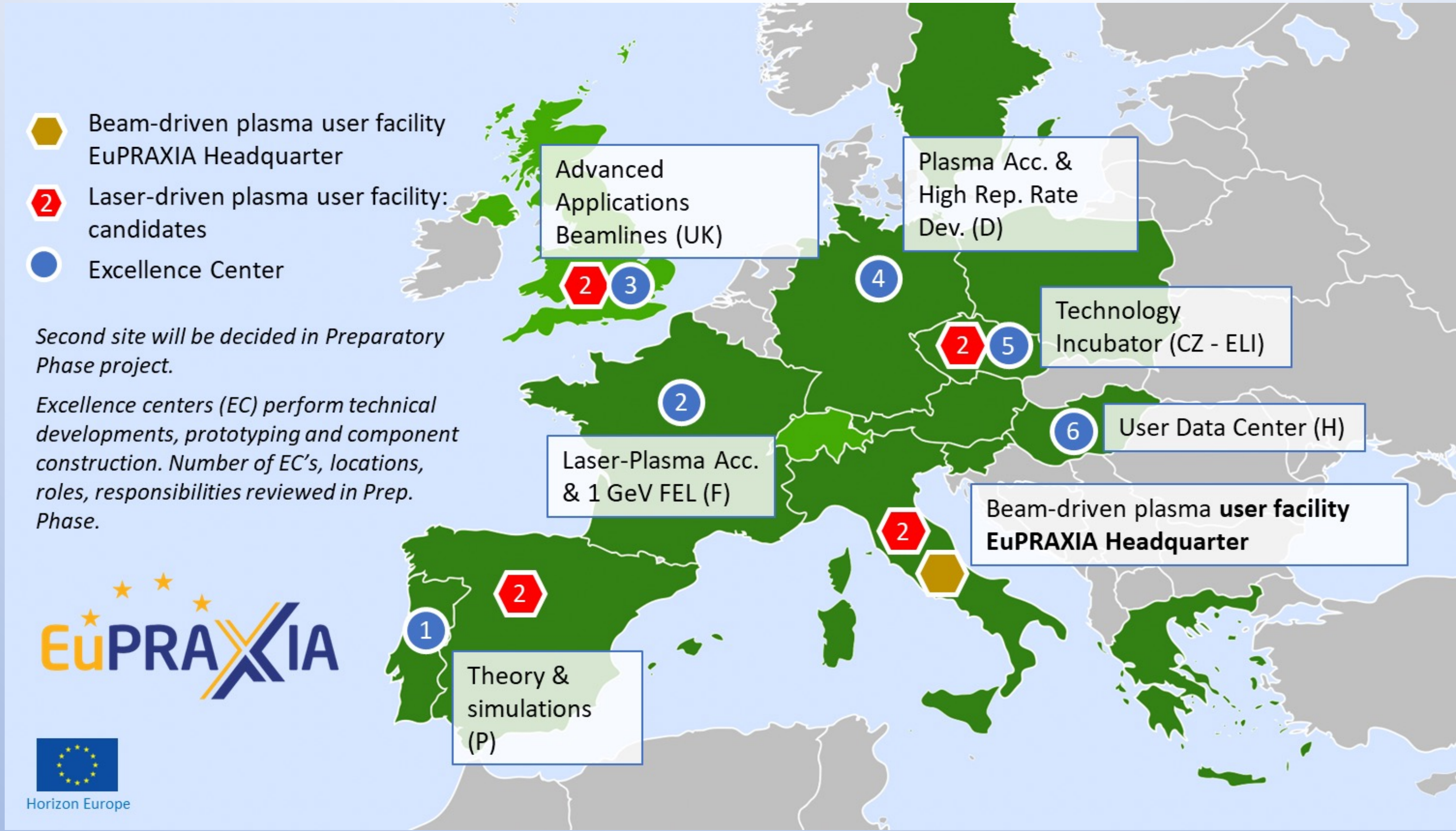
(But a widespread use of FEL is partially limited by size and costs)







Distributed Research Infrastructure

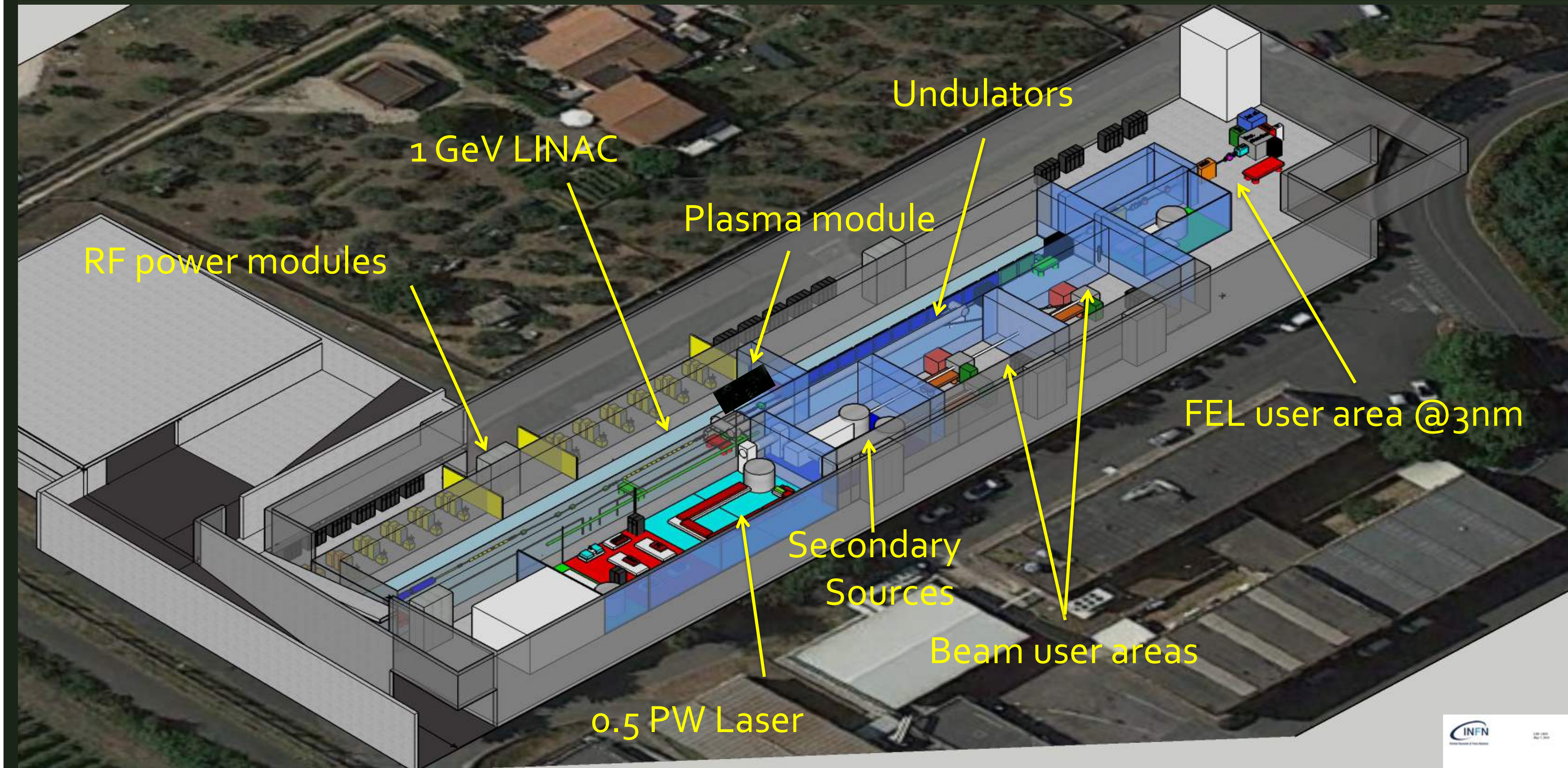


- **54 institutes** *(in addition > 2 asked to join us presently)* from **18 countries** plus CERN
  - **ESFRI** consortium (funding in-kind)
  - **Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - **Doctoral Network** (funding EU, UK, in-kind)

Il Progetto EuPRAXIA ai Laboratori Nazionali di Frascati

http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

EuPRAXIA@SPARC_LAB



http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

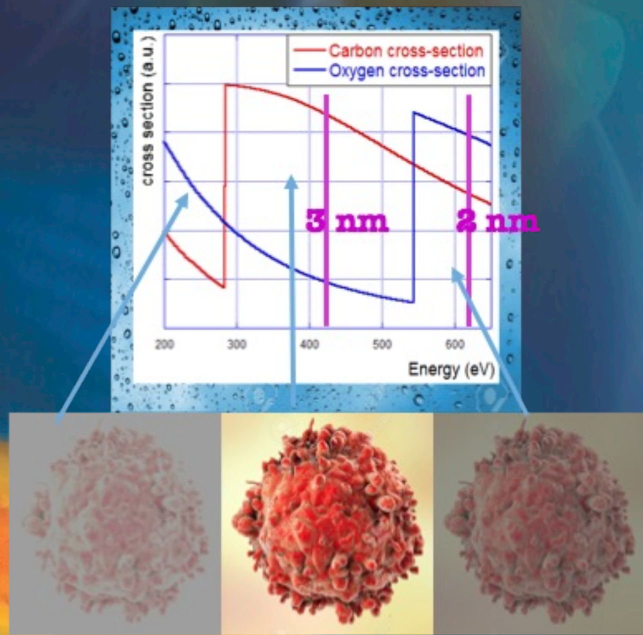
Expected SASE FEL performances

54 Chapter 2. Free Electron Laser design principles

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	$x\ 10^{-3}$	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	µJ	83.8	11.7
Photons per pulse	$x\ 10^{11}$	11	1.5

Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



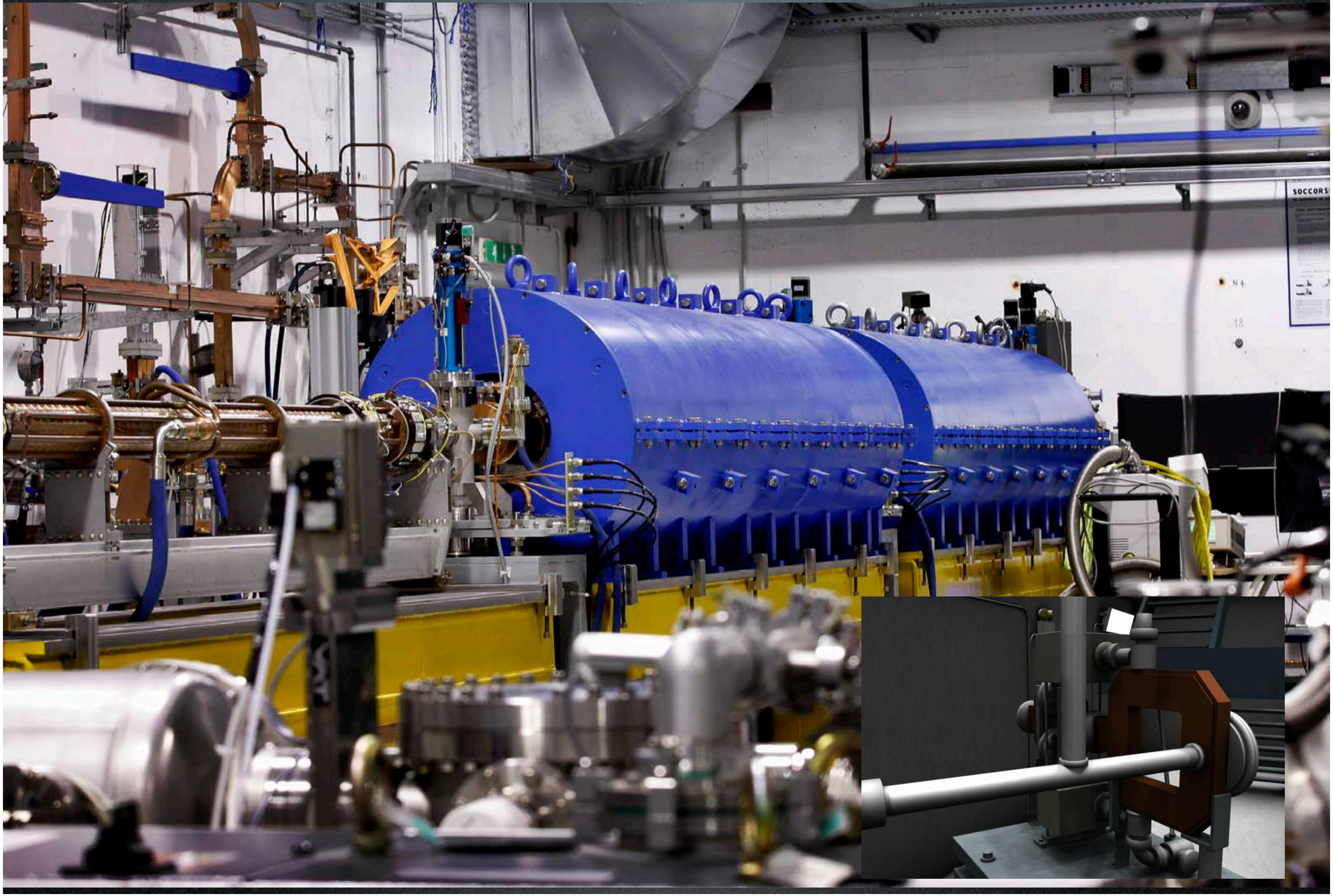
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

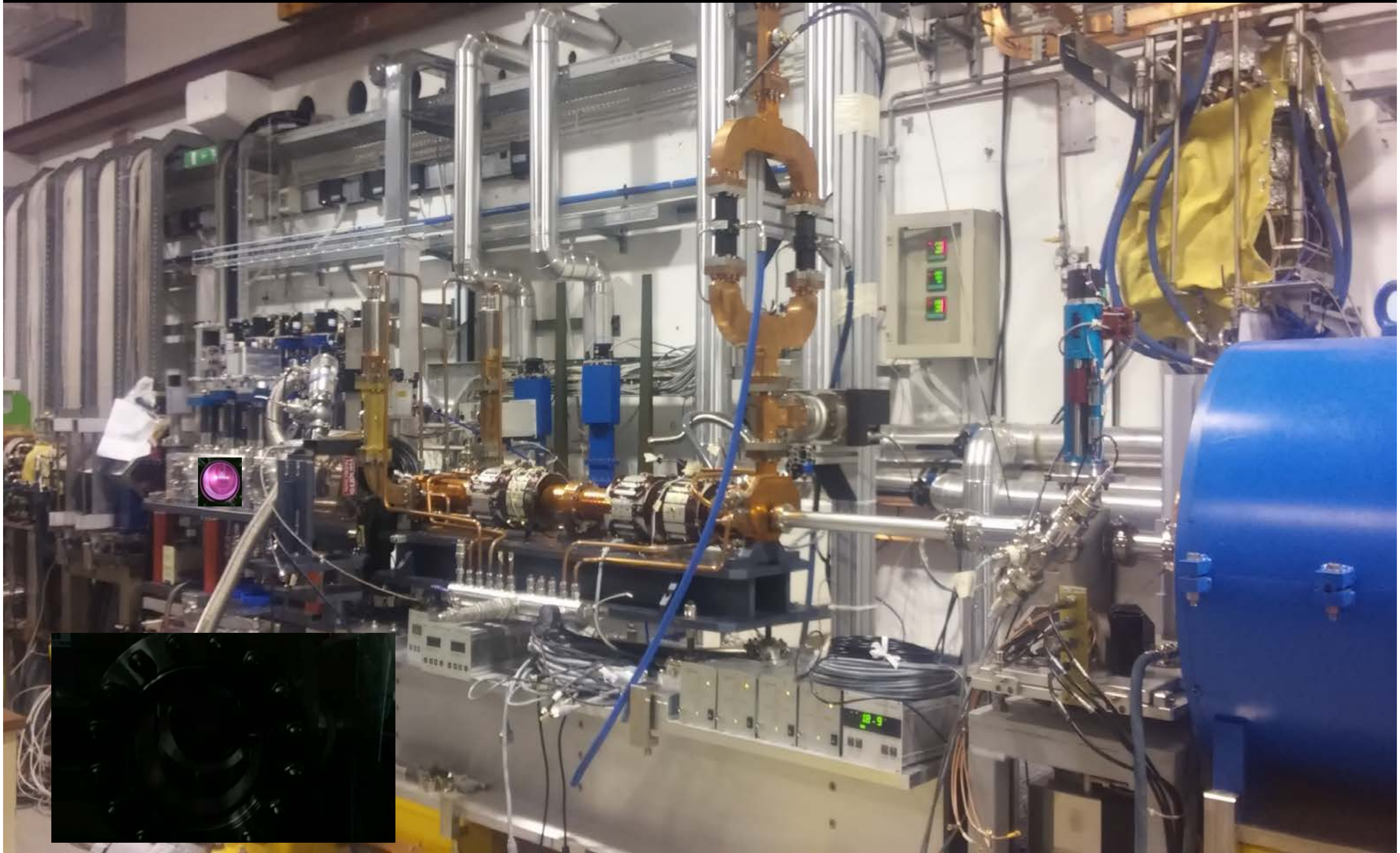
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

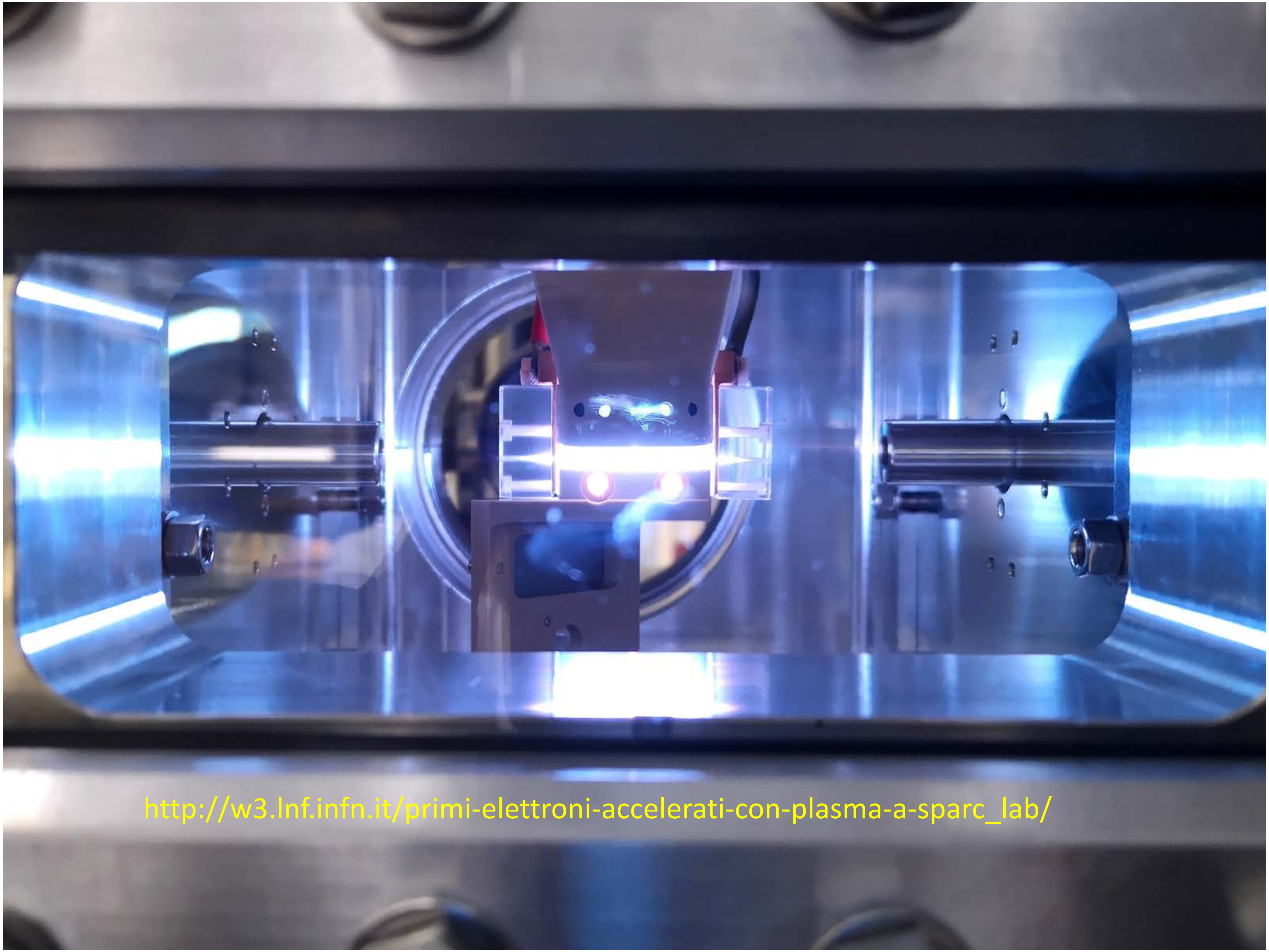

High harmonics in a single pass seeded FEL amplifier

High Brightness Photo-injector with Velocity Bunching



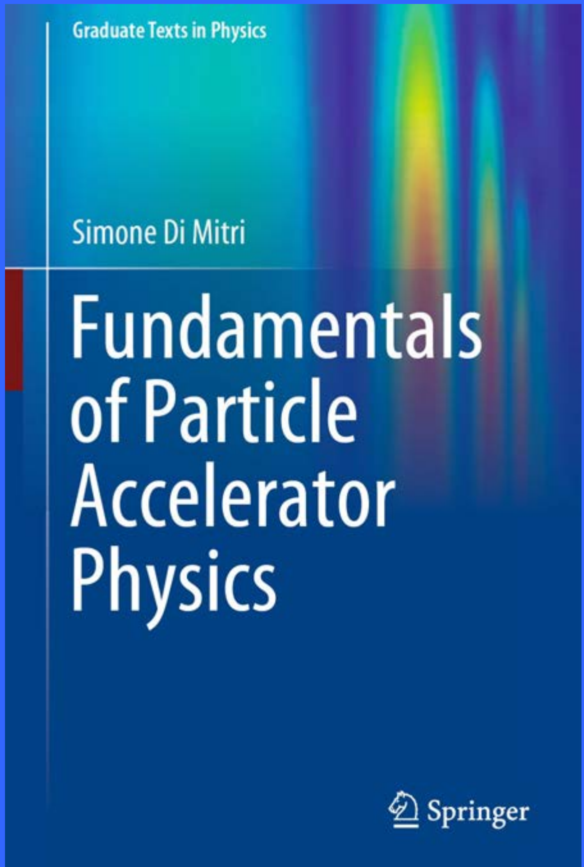
PWFA vacuum chamber at SPARC_LAB

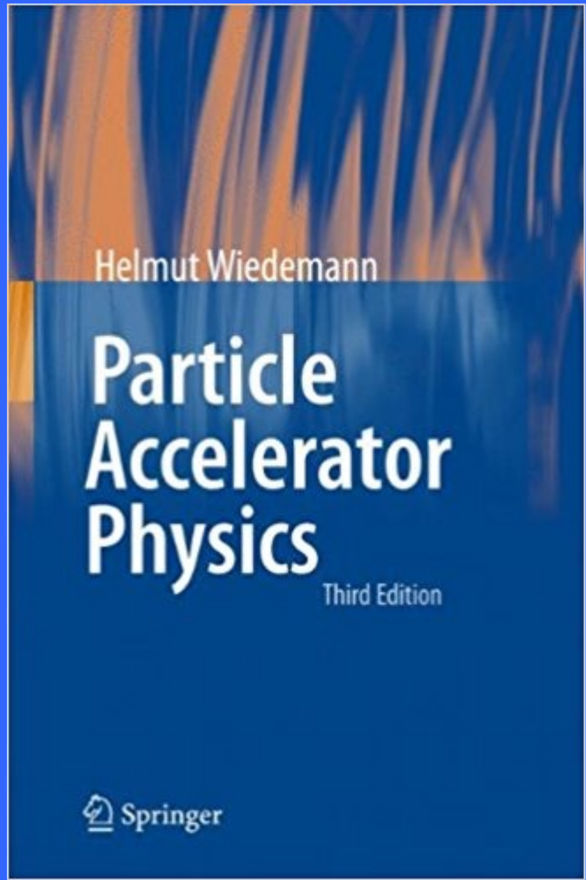


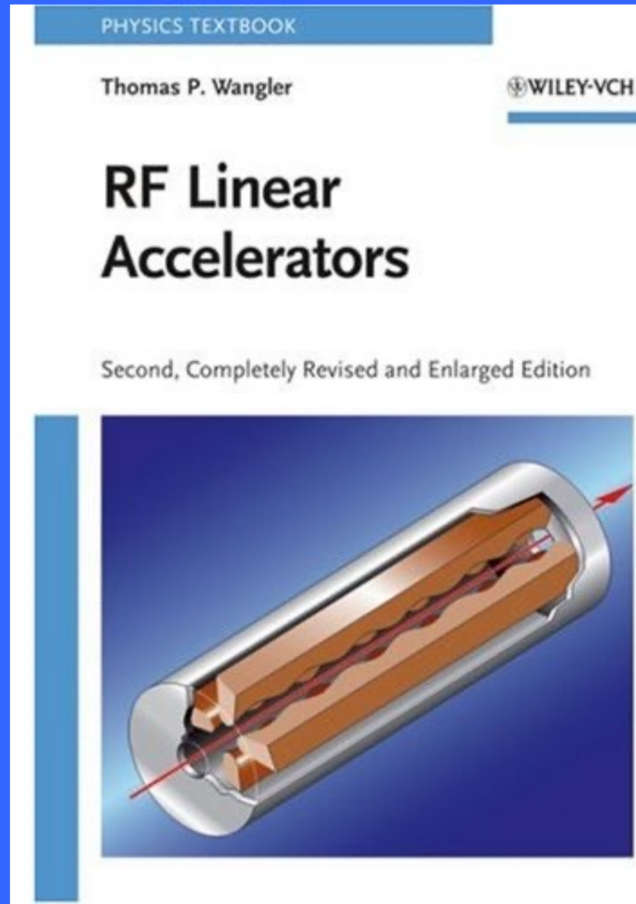


http://w3.lnf.infn.it/primi-elettroni-accelerati-con-plasma-a-sparc_lab/

https://www.asimmetrie.it/


Graduate Texts in Physics
Simone Di Mitri
Fundamentals of Particle Accelerator Physics
Springer


Helmut Wiedemann
Particle Accelerator Physics
Third Edition
Springer


PHYSICS TEXTBOOK
Thomas P. Wangler
WILEY-VCH
RF Linear Accelerators
Second, Completely Revised and Enlarged Edition

The CERN Accelerator School

http://cas.web.cern.ch/previous-schools

2015	Intensity Limitations	Geneva	Switzerland	CERN-2017-006-SP
2015	Advanced Accelerator Physics	Warsaw	Poland	
2015	Accelerators for Medical Applications	Vösendorf	Austria	CERN-2017-004-SP
2014	Plasma Wake Acceleration	Geneva	Switzerland	CERN-2-16-001
2014	Introduction to Accelerator Physics	Prague	Czech Republic	
2014	Power Convertors	Baden	Switzerland	CERN-2015-003
2014	Basics of Accelerator Science and Technology at CERN	Chavannes de Bogis	Switzerland	
2013	Basics of Accelerator Science and Technology at CERN	Chavannes de Bogis	Switzerland	
2013	Advanced Accelerator Physics	Trondheim	Norway	CERN-2014-009
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