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Instruments of discovery:
from Adone to the X-ray free-electron laser

Claudio Pellegrini
Department of Physics and Astronomy
UCLA

Introduction

High-energy electron and positron beams play an important role in the exploration of the properties of matter at molecular, atomic and subatomic levels.

Adone, and the following e^+-e^- colliders, explored the structure of subatomic matter, leading to the standard model of elementary particles.

Electron beams also drive free-electron lasers, to produce coherent X-ray beams that are opening, for the first time, the exploration of atomic and molecular processes at their characteristic length and time scales of about 1 Ångstrom-1 femtosecond.

In this talk I review the complex collective and self-organization phenomena, whose study started at the Frascati National Laboratory in the 1960s with a small accelerator, AdA, and later with Adone, that make these instruments of discovery possible.


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THE RISE OF COLLIDING BEAMS,

Burton Richter, SLAC-PUB-6023, June 1992.

“The first step in the electron-positron direction was taken in Italy, and the key personality was Bruno Touschek. There is a seminal moment in this story that occurred at a seminar by Touschek at Frascati on March 7, 1960, in which Touschek outlined the scientific potential of electron-positron annihilation studies. Giorgio Salvini, then director of the Frascati laboratory, and the high-energy physics community in Italy were immediately convinced by Touschek’s arguments and began to work to bring e^+e^- colliders to life. The first machine was called AdA, and it was brought into operation less than a year after Touschek’s seminar.”


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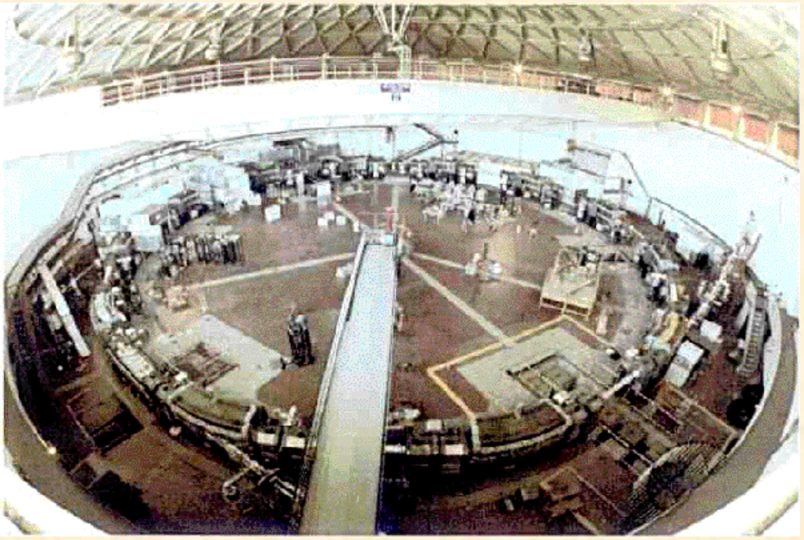
The legacy of Bruno Touschek,

E. Amaldi, CERN 81-19, 1981.

All of the arguments discussed by Touschek and their brilliant exposition , made a considerable impression on everyone present, including the then Director of the Laboratory Nazionali di Frascati, Giorgio Salvini, and Carlo Bernardini, Gianfranco Corazza and Giorgio Ghigo.

During the same day, the three last mentioned persons began to work with Touschek on a project for the first e^+e^- storage ring, essentially designed as a prototype for checking the feasibility of accelerators based on the ideas set forth by Touschek during the seminar.

AdA, the first electron-positron collider: 2 m diameter, 250 MeV.



30 m diameter, 1.5GeV.

THE RISE OF COLLIDING BEAMS, Burton Richter :“ADONE was to be the first of the high-energy electron-positron colliders capable of getting into the region where many different kinds of hadrons could be produced …”

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ELECTRON POSITRON STORAGE RINGS: STATUS AND PRESENT LIMITATIONS.

F. Amman, 1969 Particle Accelerator Conference

The first electron beam was successfully stored in ADA, the Frascati 250 MeV e+e- ring in the spring of 1961; in the years 1962-64 the Princeton-Stanford 550 MeV e^-e^- ring and VEP-I, a 130 MeV, e^-e^- ring, in Novosibirsk, came into operation; the second Novosibirsk ring, VEPP-II, 700 MeV, began to produce high-energy physics data in 1966, and shortly afterwards was followed by ACO, a 500 MeV e^+e^- ring built at Orsay. ADONE, the 1.5 GeV e+e- ring in Frascati, is not yet running for high energy physics: the first beam was stored in December 1967. The modification of the CEA electron synchrotron as a 3 GeV e^+e^- ring is well along and it is supposed to be ready for tests with the two beams during 1969; VEP-III, a 3. 5 GeV e^+e^- ring, will be in operation in Novosibirsk probably next year.

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Amman, PAC 69: “ADONE, after the first year of troubleshooting (talking of a storage ring it would be better to say instability-shooting), should start high energy physics experiments during 1969. It may seem strange that eight years after the initial operation of a storage ring, only one e^-e^- (the Princeton-Stanford 550 MeV) and two e^+e^- rings, VEPP-II and ACO, have produced high energy physics results, and these are limited to experiments with very high cross section. I would like to remark that the first beam instabilities observed on the Princeton-Stanford ring, and interpreted as being due to the resistance of the walls, opened a new era in the accelerator field: **it has been realized for the first time that the interaction of the beam with its environment makes a circular accelerator an essentially unstable system,** that can become stable, in virtue of the Landau damping, when the beam density is not too high and the non linearities in the focusing forces give a frequency distribution of the particles large enough to compete with the instabilities.”

Adone and beam instabilities

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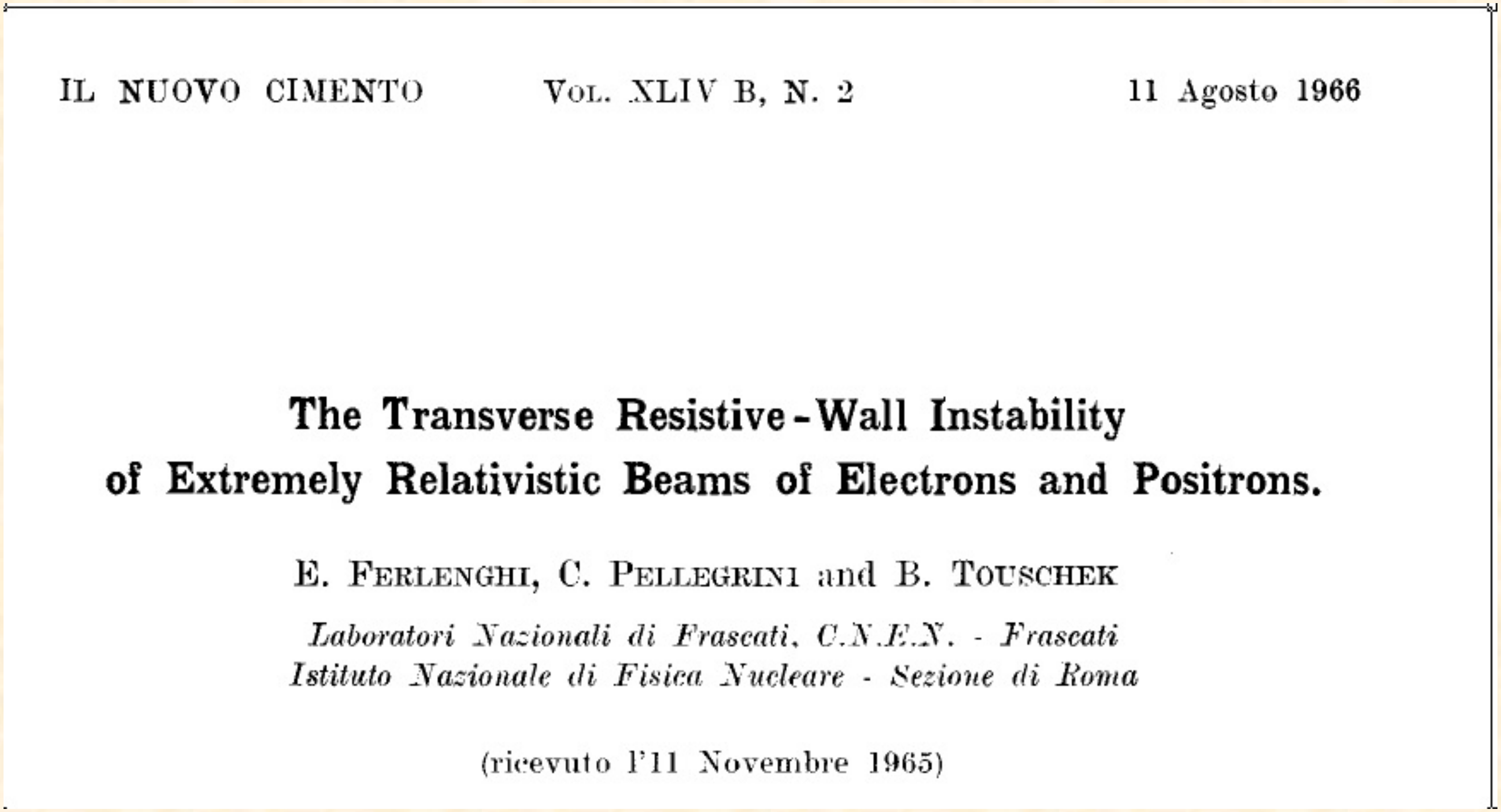
The resitive wall instability was observed on the Stanford-Princeton ring. We extended the theory at Frascati, and evaluated its effect on Adone. We were ready for it.



IL NUOVO CIMENTO   VOL. XLIV B, N. 2   11 Agosto 1966

The Transverse Resistive-Wall Instability of Extremely Relativistic Beams of Electrons and Positrons.

E. FERLENGHI, C. PELLEGRINI and B. TOUSCHEK

Laboratori Nazionali di Frascati, C.N.E.N. - Frascati
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto l'11 Novembre 1965)

Surprises and new effects

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Amman, PAC 1969 paper.

“c) Transverse instabilities.
2) the threshold current is very low: In ADONE, at 300 MeV, the injection energy, with the natural beam dimensions, the threshold positron current is about 0.150 mA per bunch;” (The design value to reach the desired luminosity of 10^{30} cm^{-2} s^{-1} was 0.1 A)

A new class of collective instabilities

The problem was solved, and the current and luminosity increased, by the understanding and the theoretical description of the new effects. I remember discussing with Touschek and Matt Sands, in the control room of Adone, what could be the explanation of what we were seeing. These discussions led to the head-tail instability theory, which needed the combination of synchrotron oscillations, betatron oscillations, wake fields in the ring vacuum chamber.

IL NUOV0 CIMENT0 VOL. LXIV A, N. 2 21 Novembre 1969

On a New Instability in Electron-Positron Storage Rings (The Head-Tail Effect).

C. PELLEGRINI

Laboratori Nazionali del CNEN - Frascati (Roma

Amman PAC 69:“A peculiar behavior of the “head-tail” instability theory has been tested on ADONE: the rise time turns out to be approximately proportional to (1 - Chromaticity/momentum compaction) ..Tests with different values of the chromatism have been done on ADONE using a very crude sextupole; the results are in qualitative agreement with the theory.”

Richter, The rise of colliding beams: “The instability was driven by what the accelerator physicists called the “chromaticity,” i.e., the variation of betatron oscillation frequency with momentum. Their analysis also indicated the cure, and the ADONE machine was soon equipped with sextupole magnets with which the chromaticity could be adjusted to the proper sign to cure the problem.”

Adone: some initial results

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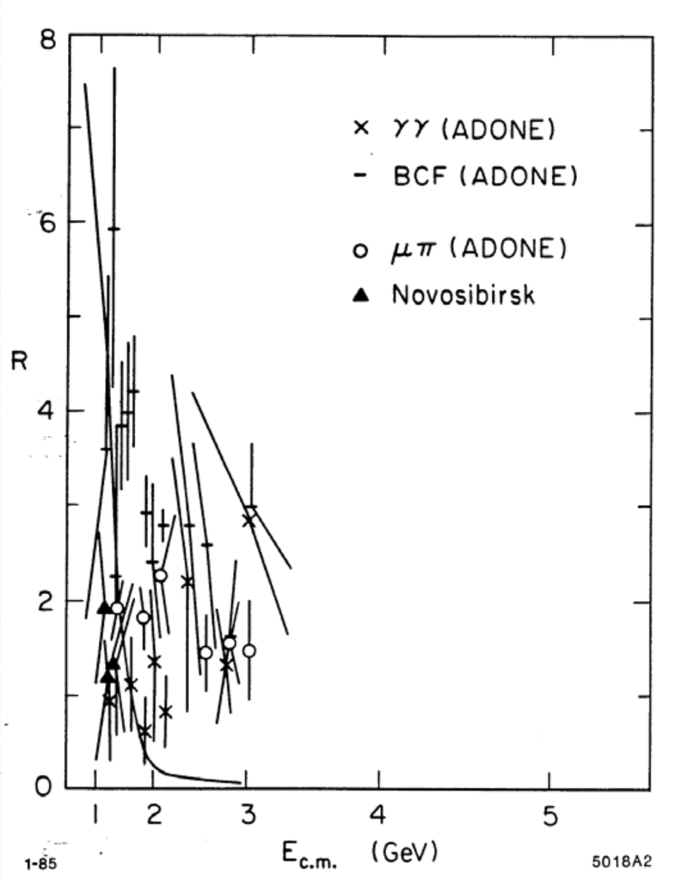
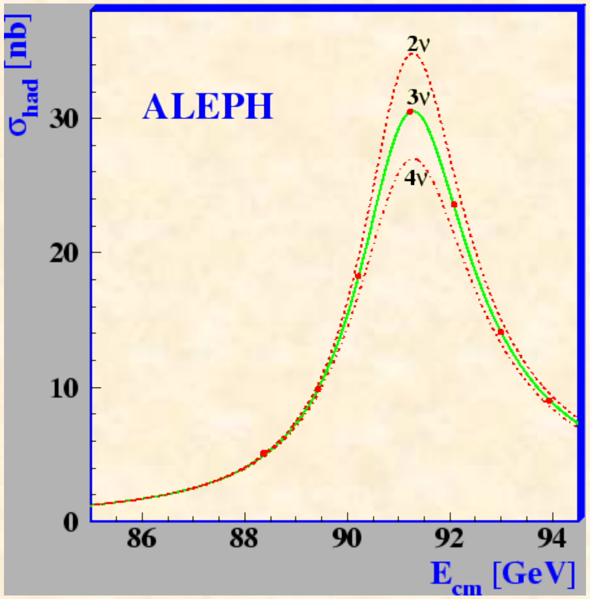
Controlling the head-tail and other longitudinal instabilities raised the current and luminosity to the value need to explore the e^+-e^- interactions, and to new surprises.



The ratio R of the inclusive cross section for hadron production to the cross section for μ-meson pair production versus center-of-mass energy. The results from the three ADONE experiments differed, but all of them were very large compared to the theoretical expectations of that time, shown by the solid line.

Colliders evolution:LEP 4.2 km diameter, 100 GeV

Measuring the mass of the Z_0 and its width. The measure agrees with the existence of only three families of leptons and quarks.



Why is a particle beam is unstable?

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A particle beam is an ensemble of many (typically 10^9-10^{11}) particles subject to elastic forces, moving near a reference trajectory, and occupying a small phase space volume. Calling x,y, z the 3 coordinates identifying a particle position transversely and along the trajectory, and p_x,p_y,p_z, the corresponding momenta, the simplest system Hamiltonian is

$$H_0 = p_x^2 + \omega_x^2 x^2 + p_y^2 + \omega_y^2 y^2 + p_z^2 + \omega_z^2 z^2$$

Any function of H_0 is an equilibrium function, and the ideal beam is such that all particles occupy a small phase space volume. This is the beam we try to create in colliders and other accelerators. However this description is only valid if we neglect the interaction between the particles in the beam.

Beam instabilities

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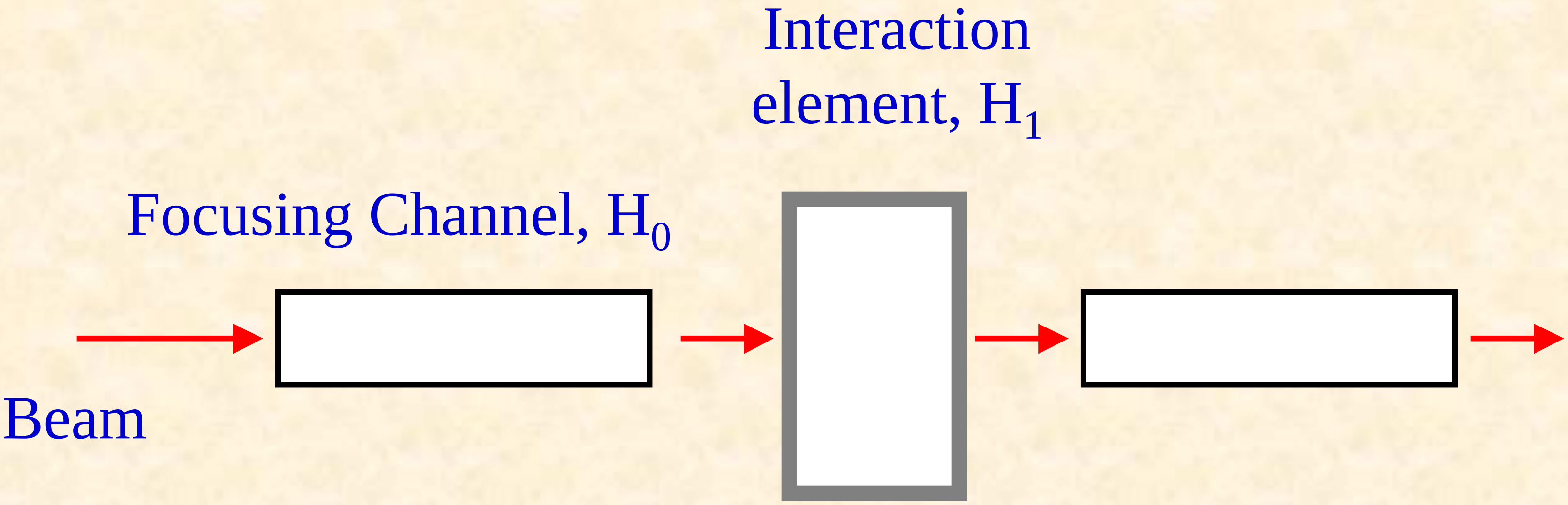
The interaction can take many forms. In general the system can be described as consisting of two parts: a linear focusing transport channel, described by H_0, and one additional element inserted at some point, described by H_1, the element that introduces an interaction between the particles in the beam.


Interaction element, H_1

Focusing Channel, H_0

Beam

Beam instabilities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When the interaction is considered the system is no more in equilibrium and it will evolve toward a new state, which depends on the characteristics of the dominant interaction term. The number of degrees of freedom of the beam is very large and so is the number of possible final states.

To understand what happens we need to answer two questions:

1. Given the dominant interaction forces, what is the final state;
2. What is the time scale characterizing the transition.

For one dominant collective interactions of the particles, the final state has also well defined collective properties. Some time these collective properties can prevent us from reaching our goal, as in the Head-tail case; some other time they can be used to obtain new interesting physical conditions,as in the free-electron case.


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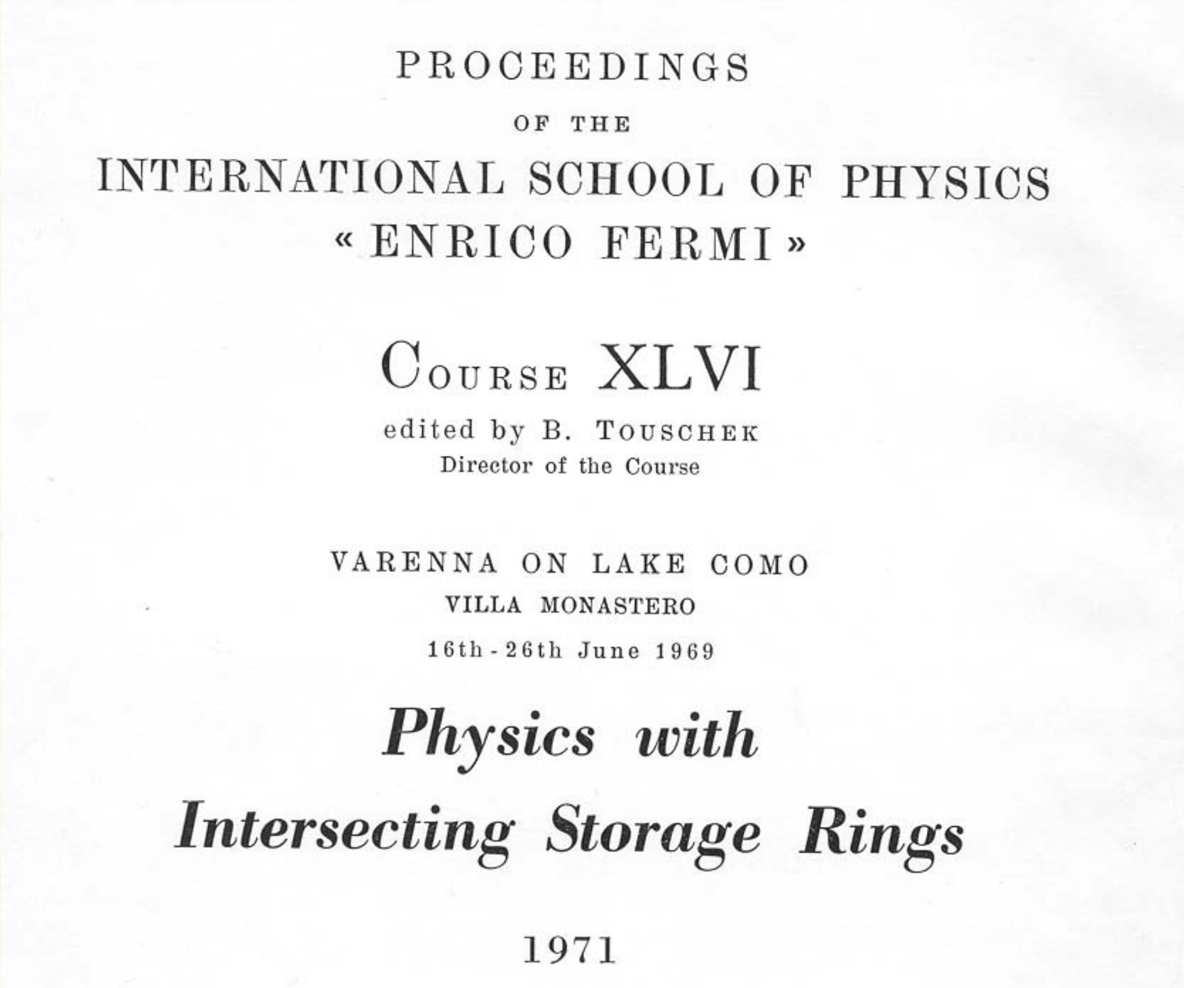
The Head-tail and other instabilities were discussed at length in a Varenna school directed by Touschek in 1969.


PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS
« ENRICO FERMI »

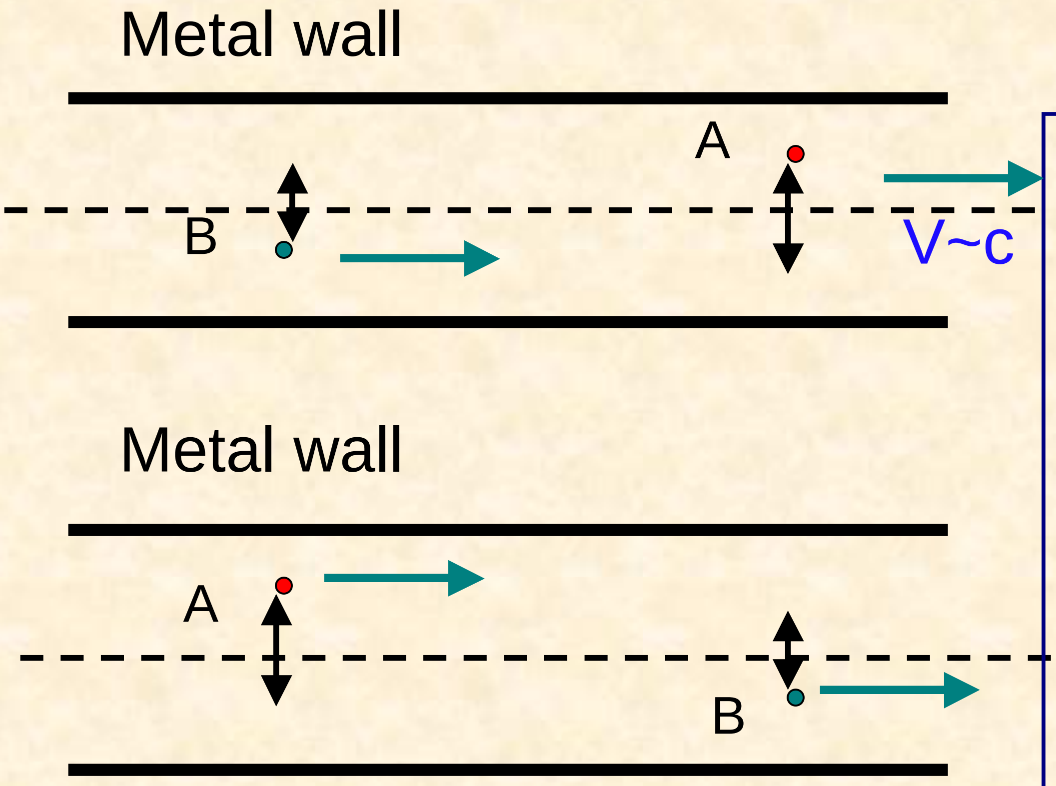
COURSE XLVI

edited by B. TOUSCHEK
Director of the Course

VARENNA ON LAKE COMO
VILLA MONASTERO
16th - 26th June 1969

Physics with
Intersecting Storage Rings

1971



The moving and oscillating particle A induces currents in the metallic pipe. The induced currents generate a field inside the pipe. If the wall resistivity is non zero, the wakefields decay slowly and act on particle B with a longitudinal and transverse force.

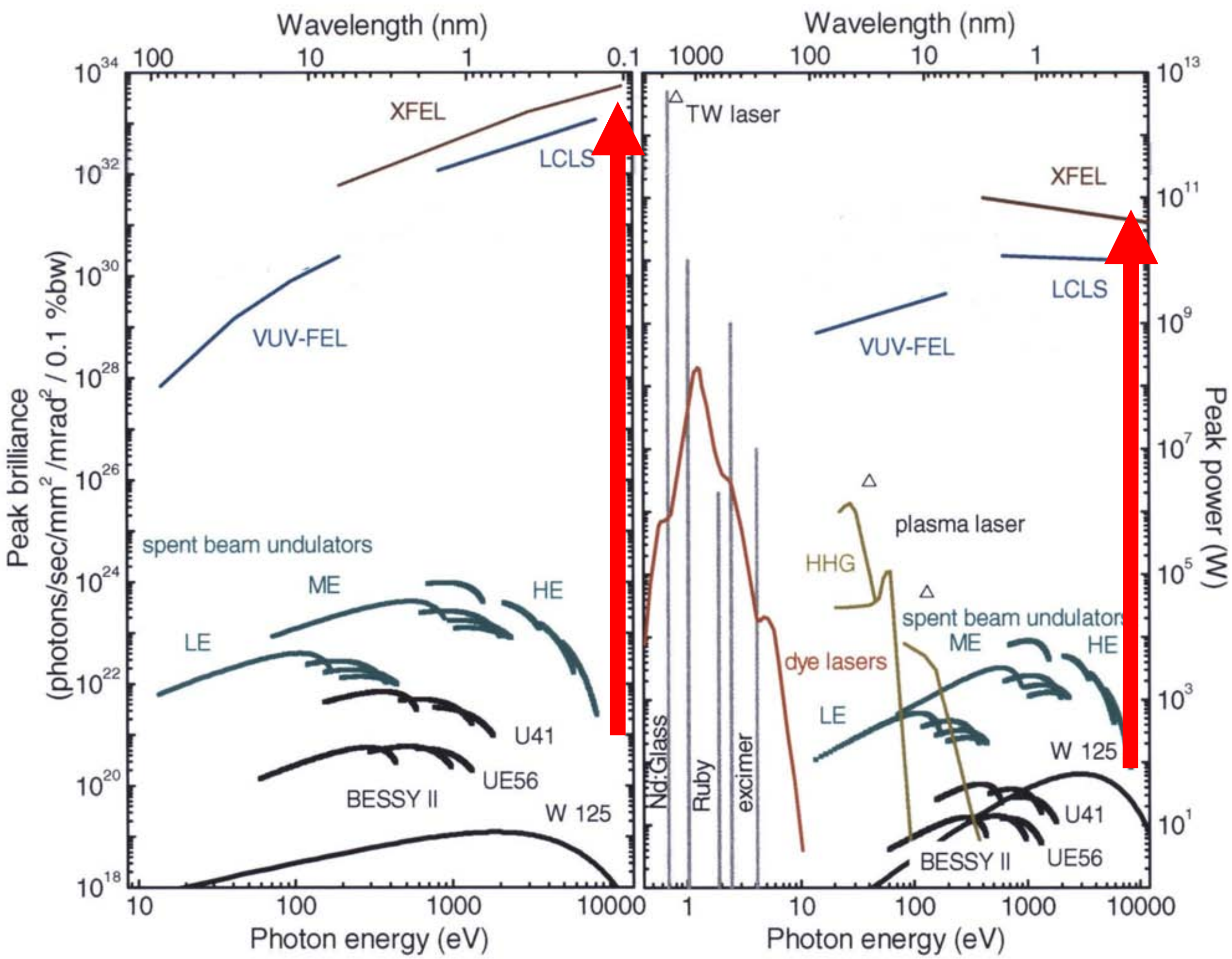
The head particle A starts to oscillate and it induces an oscillation of the tail particle B. After half synchrotron period the situation is reversed, introducing a strong regenerative effect, and exponentially growing transverse oscillations.

Instabilities and collider luminosity

The control of instabilities and other improvements developed from the 1960, has made possible to increase the luminosity of an e^+e^- collider from about 10^{30} $cm^{-2}s^{-1}$ of Adone to 10^{34} $cm^{-2}s^{-1}$ of the B-factories. A further increase to about 10^{36} $cm^{-2}s^{-1}$ is expected in the next generation of B-factories!

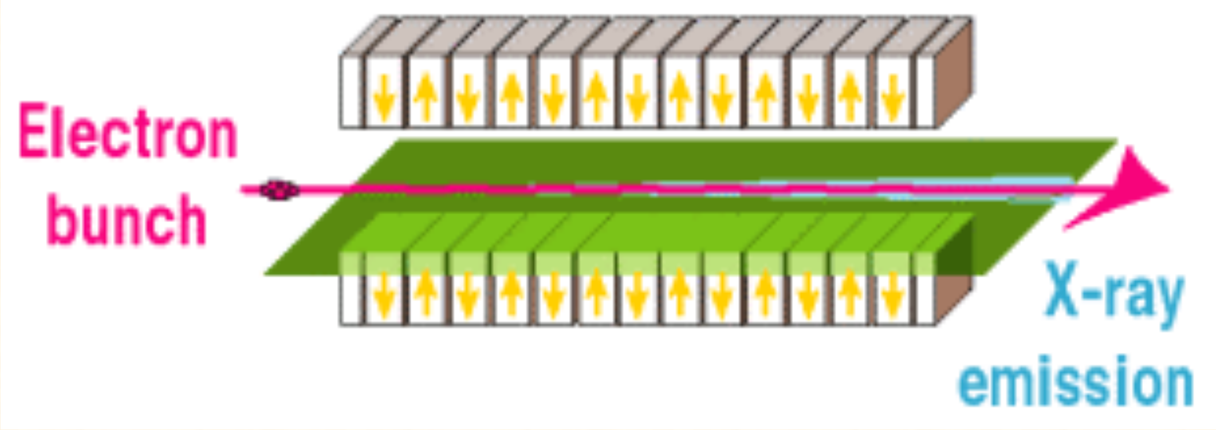
But sometimes instabilities are good …

On April, 2009 the peak power of coherent X-ray beams at 1.5 Å jumped by 11 order of magnitudes.



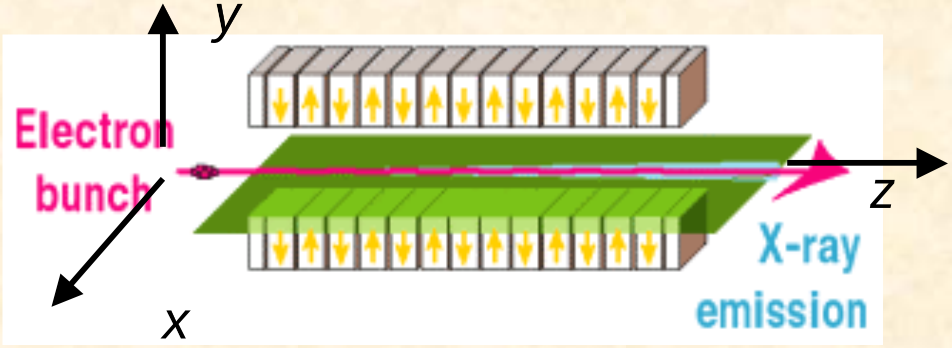
LCLS results, in good agreement with theory.

FELcollective instability



An electron beam moves through an undulator magnet and executes an oscillation transverse to the direction of propagation. Each electron is accelerated and radiates an electromagnetic field. The radiation acts on other electrons and modulates their energy, establishing a collective interaction. The interaction produces a transition of the beam to a novel state, in which the electron distribution consists of micro-bunches separated by the radiation wavelength, and the radiation emitted is coherent and has large intensity.

FEL physics: radiation from one electron, no collective interaction.



Electron energy γmc^2, $\gamma >> 1$

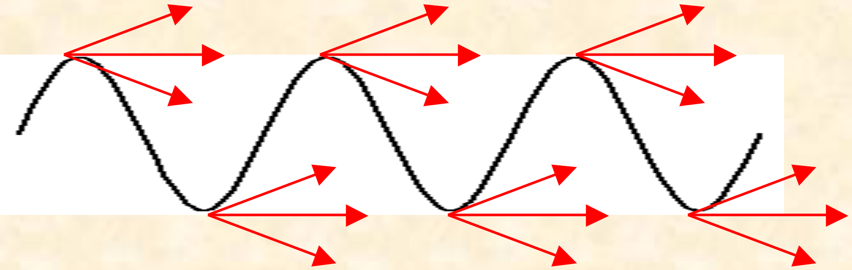
Electron velocity:

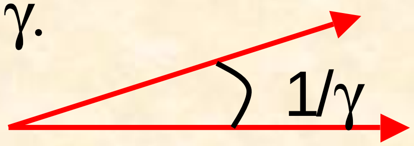
$$\beta_x = \frac{K}{\gamma}\cos\left(\frac{2\pi}{\lambda_U}z\right),\ K = \frac{eB_U c}{2\pi mc^2}$$

Electron trajectory: $x = a\sin(2\pi z/\lambda_U)$

The quantity K, the "undulator parameter", is the normalized vector potential for the undulator magnetic field. Typically $K \sim 1$,

The radiation is mostly emitted in an angle $1/\gamma$.





FEL physics: radiation from one electron

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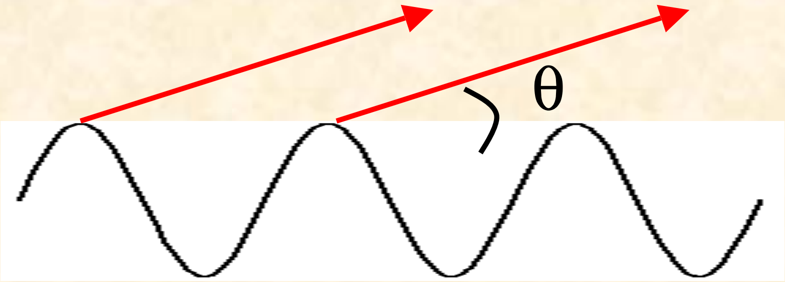


Time delay between the photons emitted at two successive peaks

$$\Delta T = \left(\frac{\lambda_U}{\beta_z c} - \frac{\lambda_U}{c\cos\theta}\right)$$

The waves add in phase at a wavelength λ such that

$$\Delta T = \lambda / c$$

giving

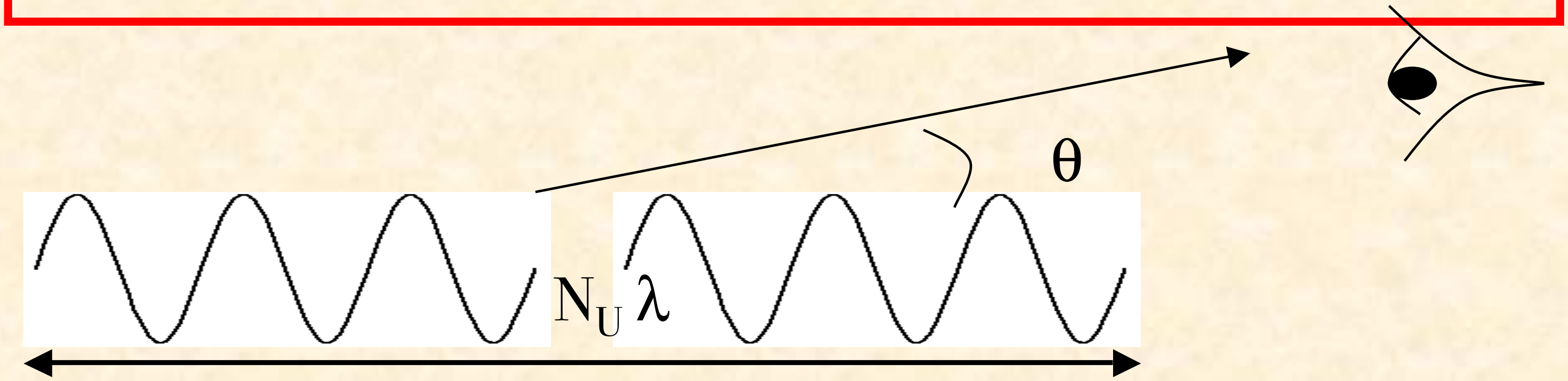
$$\lambda = \lambda_U\left(\frac{1}{\beta_z} - \frac{1}{\cos\theta}\right)$$

For small angles and large energy we have approximately

$$\lambda \approx \lambda_U (1 - \beta_z + \theta^2 / 2)$$

$$\approx \lambda_U (1 + K^2 / 2 + \gamma^2\theta^2) / 2\gamma^2$$

FEL physics: radiation from one electron



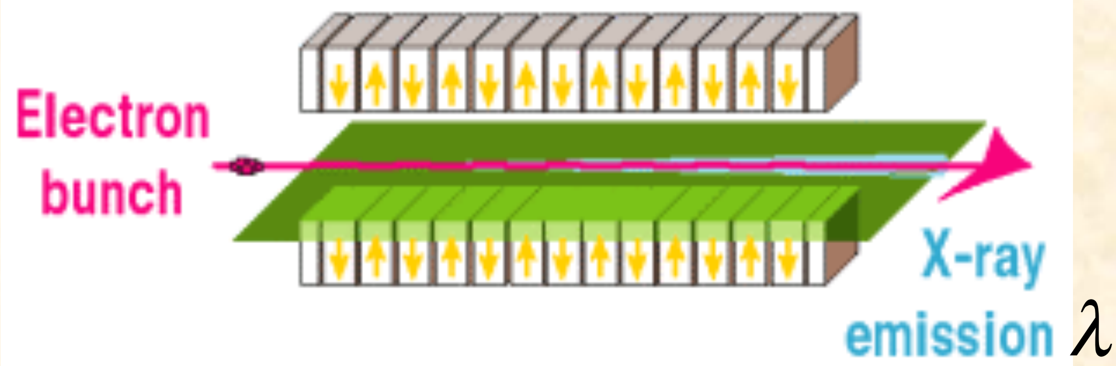
For an undulator with N_U periods, each electron emits a wave train with N_U waves. For an observer on axis the duration of the wave train is given by the difference in arrival time of photons emitted at the entrance and exit of the undulator

$$c\Delta T = N_U \lambda_U / \beta_z - N_U \lambda_U / \cos\theta = N_U \lambda$$

Approximation for the electron velocity β_z

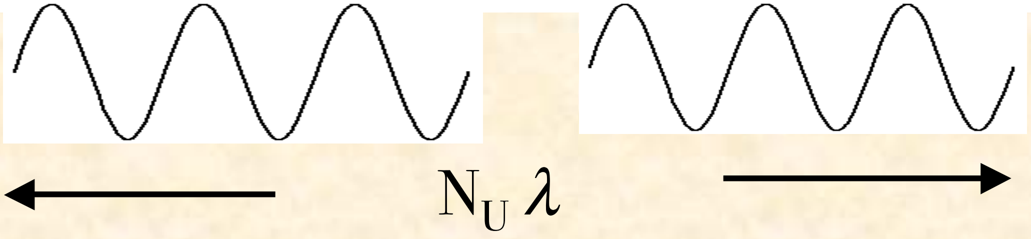
$$\beta_z = \sqrt{1 - \frac{1}{\gamma^2} - \beta_x^2} \approx 1 - \frac{1 + K^2}{2\gamma^2}$$

FEL physics: radiation from one electron



Undulator with
N_U periods.

$$\lambda = \lambda_U \frac{1 + K^2/2 + \gamma^2\theta^2}{2\gamma^2}$$



Each electron emits a wave train with N_U waves $\Delta\lambda/\lambda = 1/N_U$

For: $\gamma=3x10^4$, $\lambda_U = 3$ cm, $K=3$, $N_U \sim 3300$, we obtain
$\lambda \sim 0.1$ nm, $\Delta\lambda/\lambda \sim 3x10^{-4}$, $N_U\ \lambda \sim 0.3\ \mu m$.

FEL physics: radiation from one electron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Because of dependence of the wavelength on the emission angle, the "coherent angle", corresponding to $\Delta\lambda/\lambda<1/N_U$, is

$$\boldsymbol{\theta_c=(\lambda/N_U\lambda_U)^{1/2}}$$

the effective, diffraction limited, source radius is

$$\boldsymbol{a_c=(\lambda N_U \lambda_U)^{1/2}/4\pi}$$

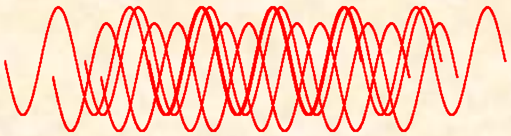
with $\boldsymbol{a_c\,\theta_c=\lambda/4\pi}$**. For the X-ray FEL** $\boldsymbol{\theta_c\sim 1\,\mu\mathrm{rad}}$**,** $\boldsymbol{a_c\sim 10\,\mu\mathrm{m}}$**.**

The average number of coherent photons/electron in $\Delta\Omega=\pi\theta_c^2/2$, $\Delta\lambda/\lambda=1/N_U$, in the absence of a collective interaction, is

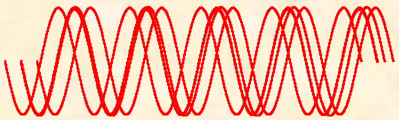
$$\boldsymbol{N_{ph}=\pi\alpha K^2/(1+K^2)\sim 0.01},$$

a small number.

Many, N_e, electrons. A picture of their emitted wave trains



Disordered state, the single electron wave trains superimpose with random phases: noise. **Intensity ~ N_e**



Ordered state, all wave trains are in phase. **Intensity ~ N_e^2**

The order parameter is the "Bunching factor", *B*. ϕ is the relative phase of the wave and the electron oscillation. *B=1* perfect order.

$$B = \frac{1}{N_e}\sum_{n=1}^{N_e}\exp(i\phi_n)$$

N_e is about 10^9- 10^{10} . Large possible gain. How do we go from disorder to order?

Answer: FEL Collective Instability

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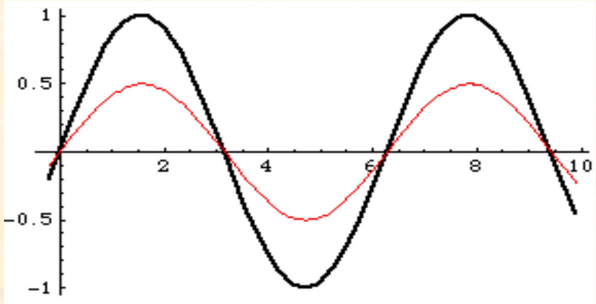
I. e-beam+undulator +EM field (initially spontaneous radiation)-> electron energy modulation, scale λ;

$$\frac{d\gamma}{dt} \sim eE \bullet V_T \cos\Phi$$

$$\Phi = \frac{2\pi}{\lambda}(z - ct) + \frac{2\pi}{\lambda_w} z$$

Φ is the relative phase of the field and electron oscillation.

II. energy modulation + undulator -> electron bunching, scale λ;



$$\frac{d\Phi}{dt} \sim \gamma - \gamma_0$$

III. larger bunching factor B->higher EM field intensity ->go back to step I

FEL Collective Instability

- Because of the instability the bunching, B, and the field grow exponentially, starting from the initial noise -the spontaneous radiation- and saturate when $B \sim 1$.
- The field grows exponentially along the undulator, the exponentiation length is the *gain length* L_G

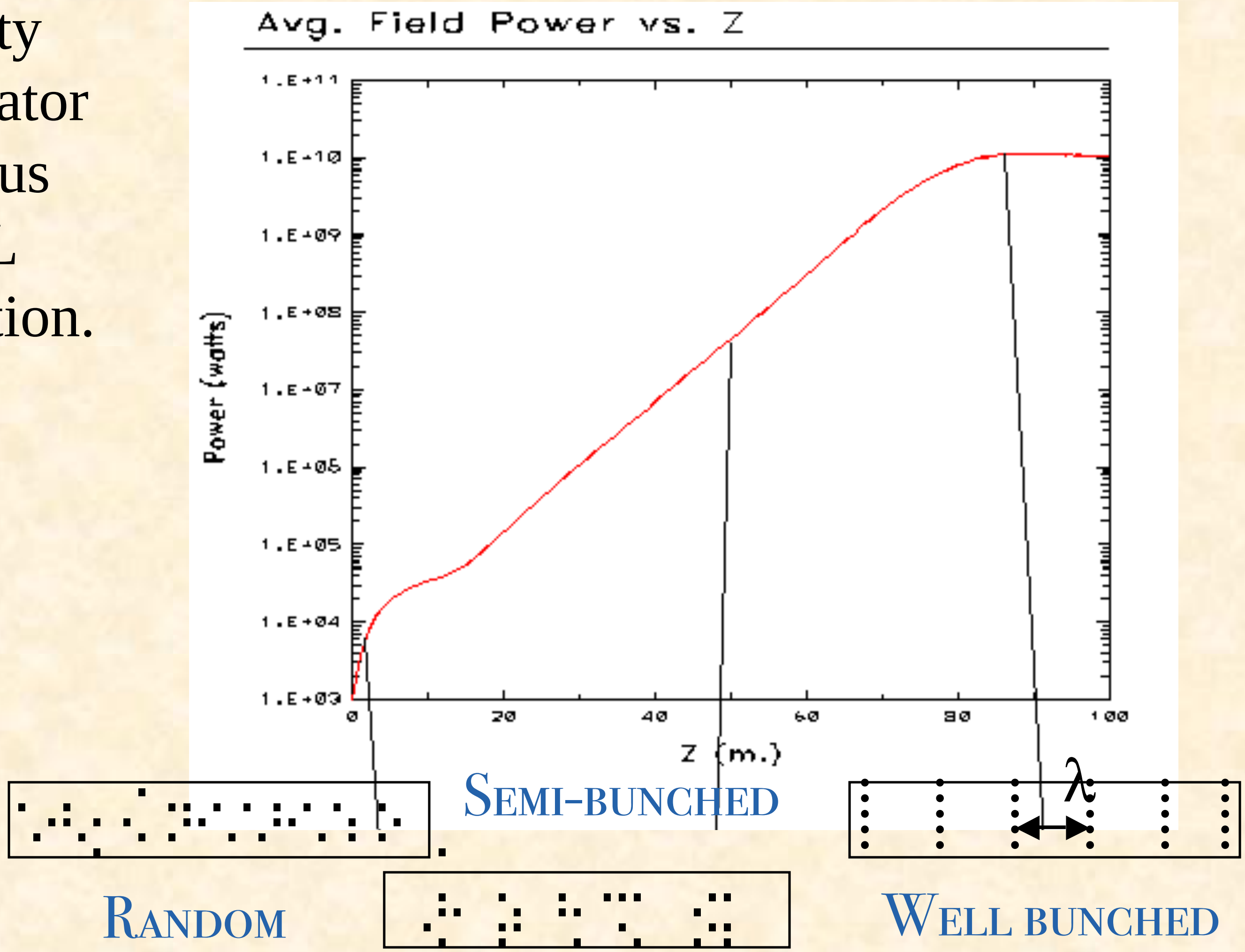
An FEL operating in this mode is called a

Self Amplified Spontaneous Emission (SASE) FEL.

SASE: a beam self-organization effect.

Evolution of power and beam density along the undulator from spontaneous radiation to FEL amplified radiation.

The interaction produces an ordered distribution in the beam, similar to a 1-D relativistic crystal.



X-rays Coherence properties

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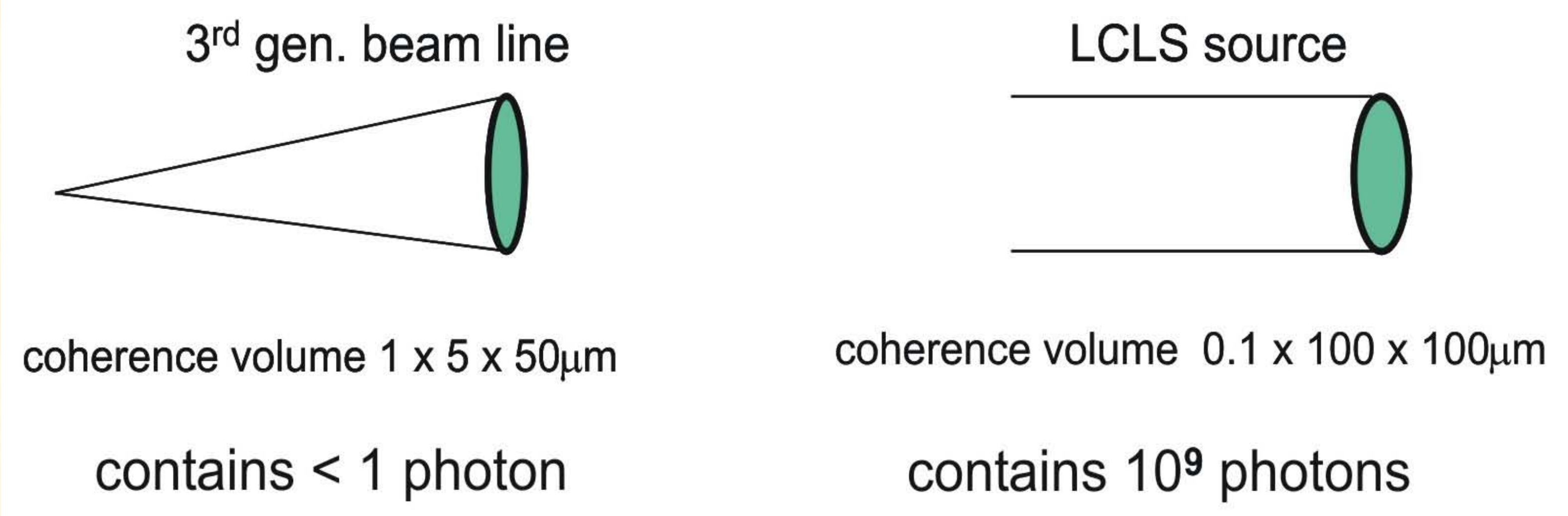
The X-ray FEL radiation has unprecedented coherence, about 10^9 photons in the coherence volume. The energy of coherent photons can be pooled to create multi-photons excitations and carry out non-linear X-ray experiments. This is a largely unexplored area of science.



3rd gen. beam line

coherence volume 1 x 5 x 50μm

contains < 1 photon

LCLS source

coherence volume 0.1 x 100 x 100μm

contains 10^9 photons

The study of the free-electron laser instability led to a proposal of a new instrument, the X-ray FEL, later called the LCLS.

A 4 to 0.1 nm FEL Based on the SLAC Linac* ^.
C. Pellegrini
UCLA Physics Department, 405 Hilgard Avenue, Los Angeles
CA 90024
March 2, 1992

^Published in Proceedings of the Workshop on Fourth Generation Light Sources, February 24-27, 1992, M. Cornacchia and H. Winick, Chairmen, SSRL 92/02.

Why X-ray FELs

The large number of photons per pulse allows to determine the structures of complex molecules or nano-systems in a single shot; to study non linear phenomena; to study high energy density systems.

The transverse coherence gives new possibilities of imaging at the nanometer and sub-nanometer scale. Using fast, single shot imaging, one can follow the dynamics of these phenomena.

Short pulses open new ways of following electron dynamics in molecular processes.

Using all these properties X-ray FELs enable the exploration of matter at the atomic and molecular level with unprecedented space-time resolution.

X-ray FELs Main Characteristics

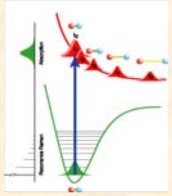
- Peak power, about 10 Gigawatt or more
- Pulse length, a few to 100 femtosecond
- Transversely coherent, diffraction limited
- Line width < 0.001
- Tunable from 15 to 1 Å, or less

The X-ray FELs are a powerful tool to explore matter and the dynamic of atomic and molecular processes.

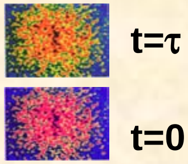
- SLAC-PUB-611

Program developed by international team of scientists working with accelerator and laser physics communities

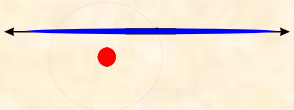
“the beginning.... not the end”



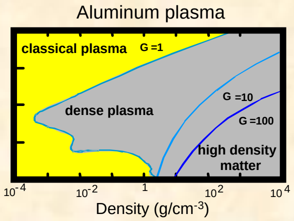
Femtochemistry



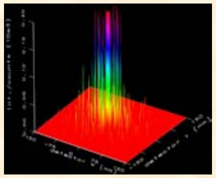
Nanoscale Dynamics in Condensed matter



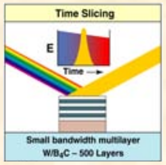
Atomic Physics



Plasma and Warm Dense Matter



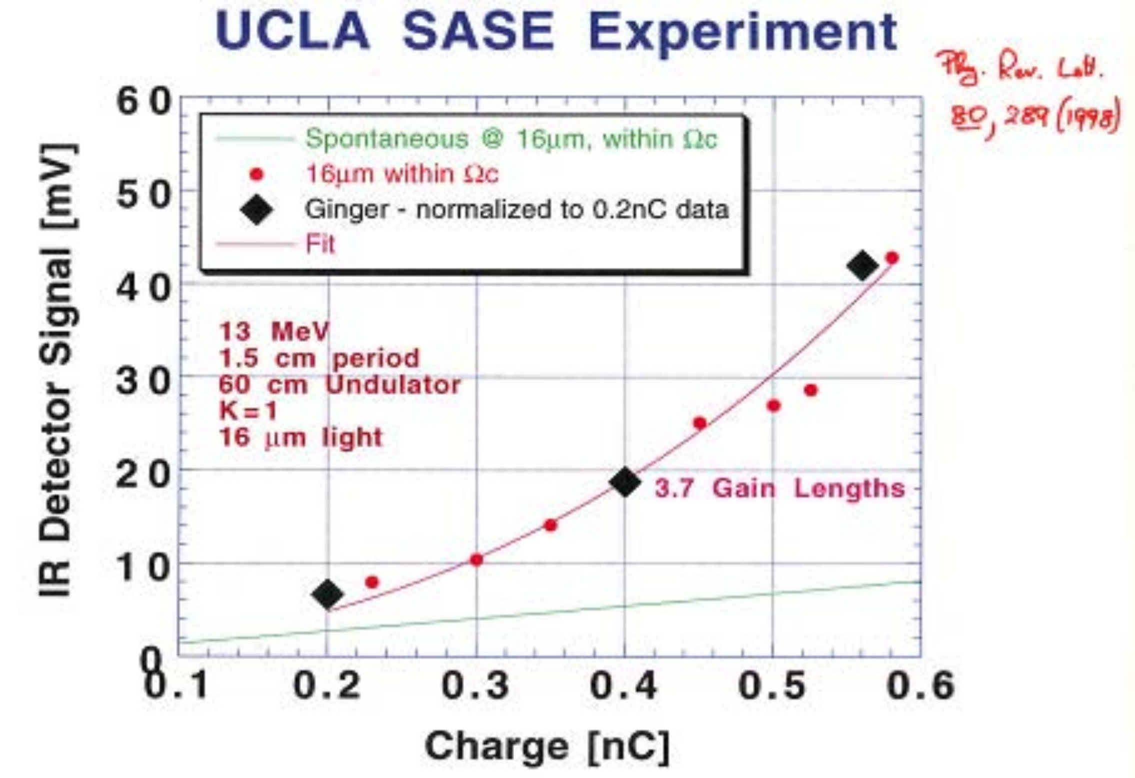
Structural Studies on Single Particles and Biomolecules



FEL Science/Technology

Of course we need an experimental verifications of the theory.

First experimental demonstration of SASE theory:
UCLA/Kurchatov, M. Hogan et al. Phys. Rev. Lett. 80, 289 (1998).



Experimental verifications of theory

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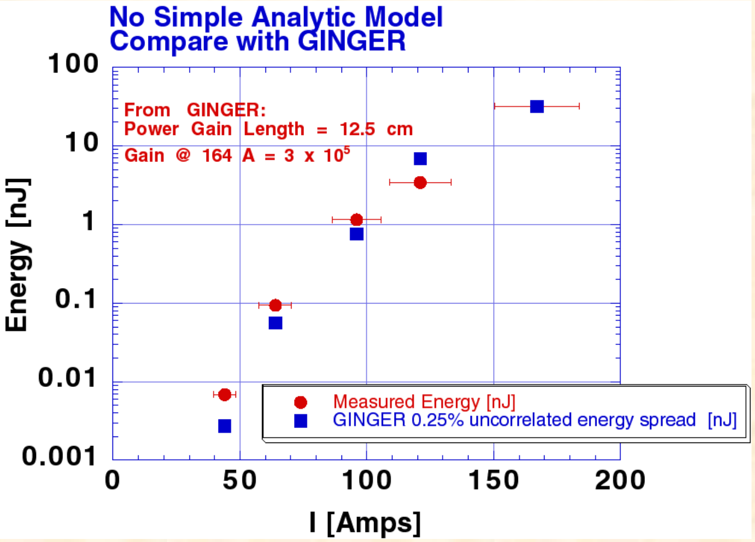
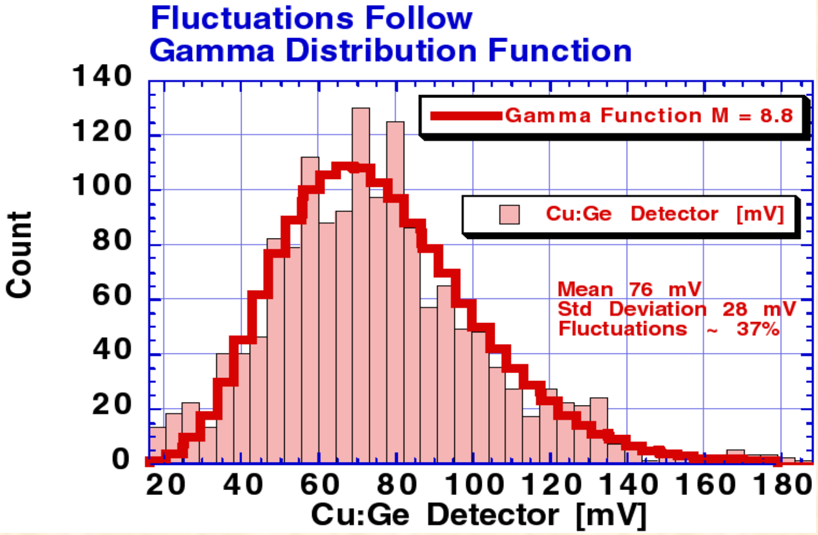
Gain of 3x105 at 12 mm. Demonstration of fluctuations and spikes, good agreement with theory.

UCLA/Kurchatov/LANL/SSRL

M. Hogan et al. Phys. Rev. Lett. 81, 4897 (1998).





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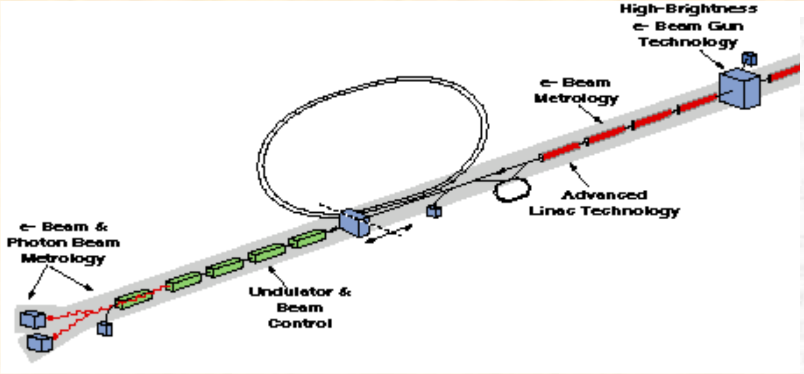
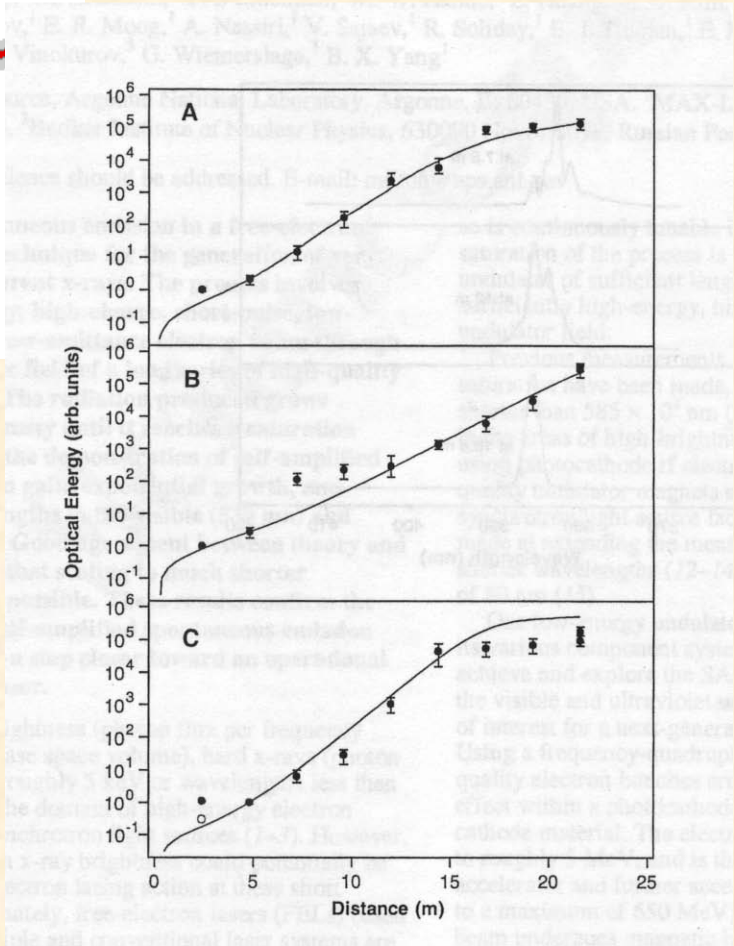
LEUTL, APS





LEUTL exponential gain and saturation at 530 nm, A &B, and 385 nm, C. The gain reduction for case B was obtained by reducing the peak current.

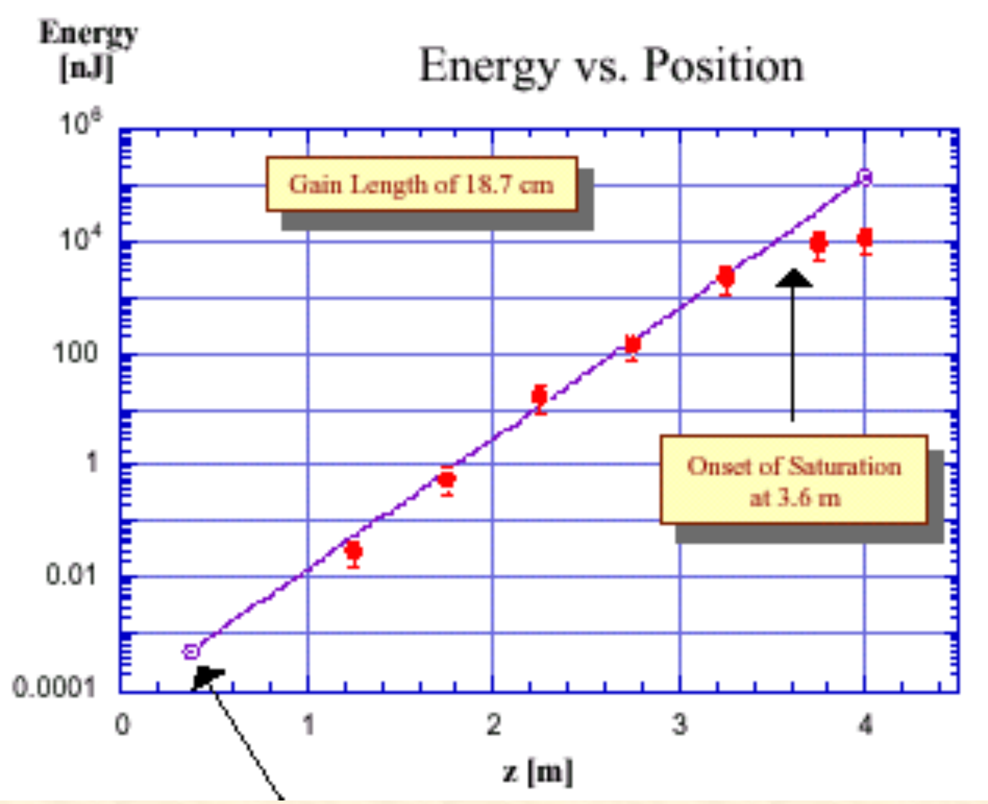
Milton et al., Science*xpress*, May 17, 2001.

http://www.aps.anl.gov/aod/mcrops/leutl/Steve.html

VISA:Visible to Infrared SASE Amplifier

UCLA

BNL-SLAC-LLNL-UCLA



Wavelength 830nm

Average Charge:170 pC

Gain Length 18.5 cm

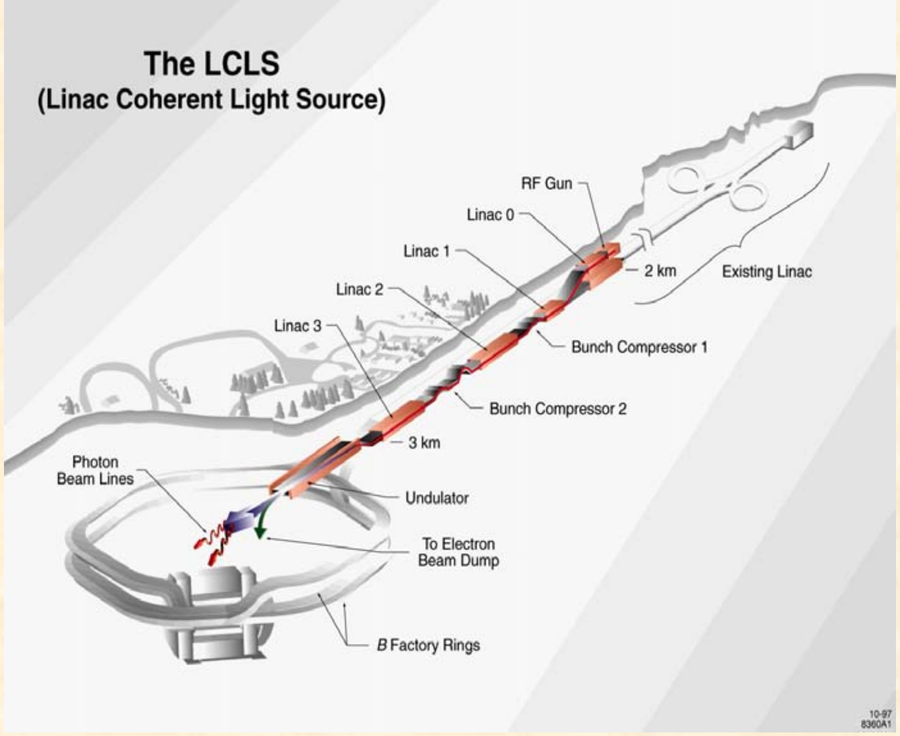
Peak SASE Energy:10 mJ

Total Gain: 2×10^7


UCLA

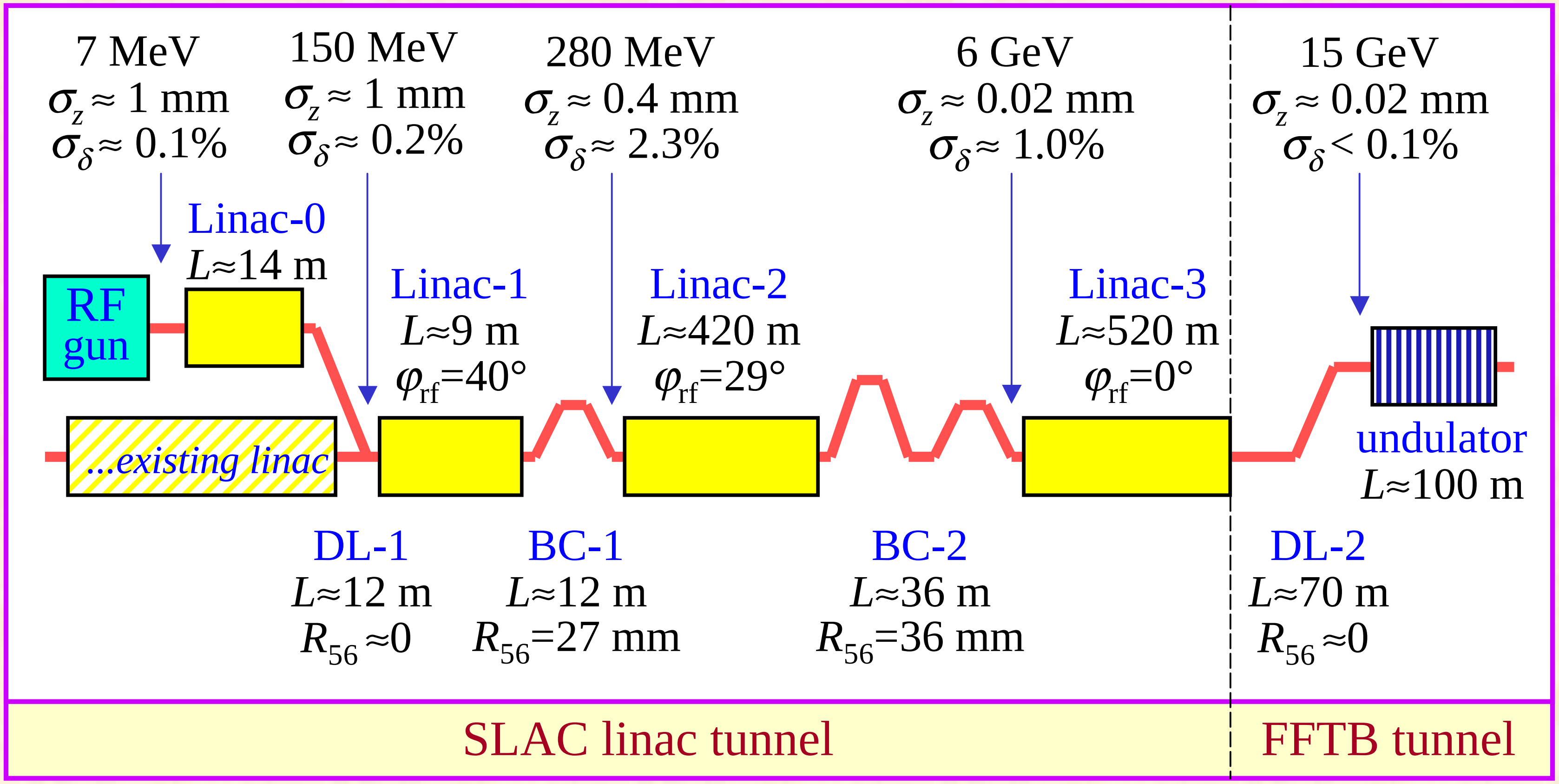
The development of LCLS

Following the 1992 proposal a study group, initially led by H. Winick and later by M. Cornacchia, was formed at SLAC, with collaborators from many institutions.
Thde group developed a design report, which was the base for the DOE decision to fund the project.



LCLS

LCLS schematic



7 MeV
$\sigma_z \approx 1$ mm
$\sigma_\delta \approx 0.1\%$

150 MeV
$\sigma_z \approx 1$ mm
$\sigma_\delta \approx 0.2\%$

280 MeV
$\sigma_z \approx 0.4$ mm
$\sigma_\delta \approx 2.3\%$

6 GeV
$\sigma_z \approx 0.02$ mm
$\sigma_\delta \approx 1.0\%$

15 GeV
$\sigma_z \approx 0.02$ mm
$\sigma_\delta < 0.1\%$

RF gun

Linac-0
$L \approx 14$ m

...existing linac

Linac-1
$L \approx 9$ m
$\varphi_{\mathrm{rf}} = 40°$

Linac-2
$L \approx 420$ m
$\varphi_{\mathrm{rf}} = 29°$

Linac-3
$L \approx 520$ m
$\varphi_{\mathrm{rf}} = 0°$

undulator
$L \approx 100$ m

DL-1
$L \approx 12$ m
$R_{56} \approx 0$

BC-1
$L \approx 12$ m
$R_{56} = 27$ mm

BC-2
$L \approx 36$ m
$R_{56} = 36$ mm

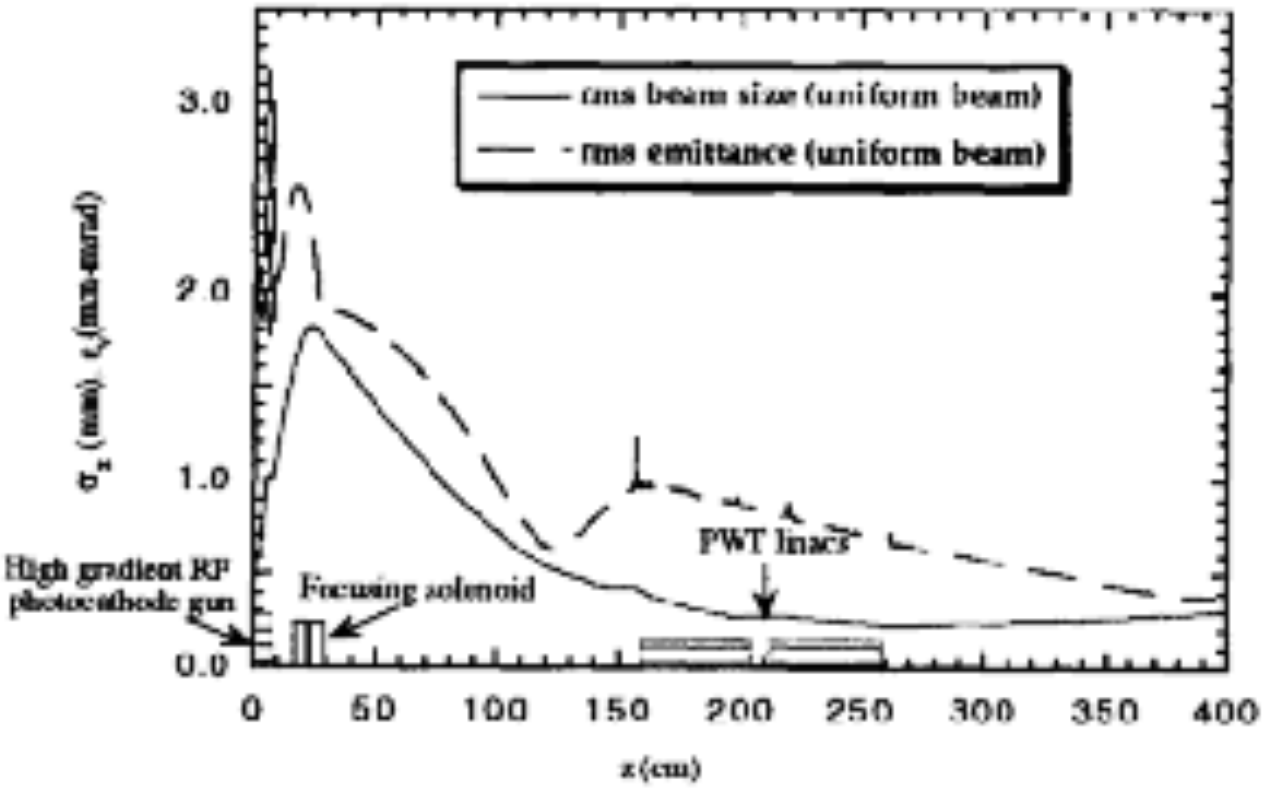
DL-2
$L \approx 70$ m
$R_{56} \approx 0$

SLAC linac tunnel

FFTB tunnel

LCLS Injector: Parmela simulation

M. Ferrario et al. LCLS-TN-00-04, March 2000



LCLS characteristics

Electron Beam	**λ=15**	λ=0.15	nm
Electron energy	4.313	13.64	GeV
Normal. Emittance, slice	2	1.2	μm rad
Charge	0.2-1	0.2-1	nC
Peak current	1920	3400	A
Pulse form, long. flat top, trans. Gaussian			
RMS bunch duration	136	73	fs
Energy spread, slice rms	0.03	0.01	%
Energy spread, Proj. rms	0.09	0.03	%

LCLS characteristics


UCLA

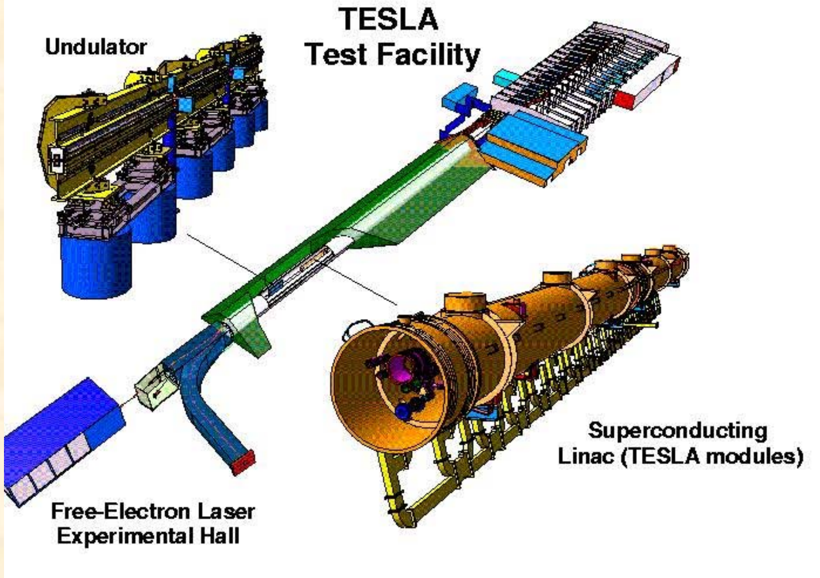
Wavelength (fundamental)	1.5	0.15	nm
FEL parameter	8.5	4.2	
Power gain length	2.6	5.1	m
Peak saturation power	4	8	GW
Average saturation power	0.23	0.23	W
Cooperation length	280	57	nm
Photons per pulse	10.6	1.1	x 10^{12}
Peak brightness	0.28	15	x 10^{32*}

FLASH at DESY: a UV-soft X-ray FEL

UCLA

Following the LCLS proposal and study, B. Wiik proposed to develop a UV-Soft X-ray, in preparation of a 1Å FEL (now the European XFEL) that would have been part of the TESLA e^+e^-collider.

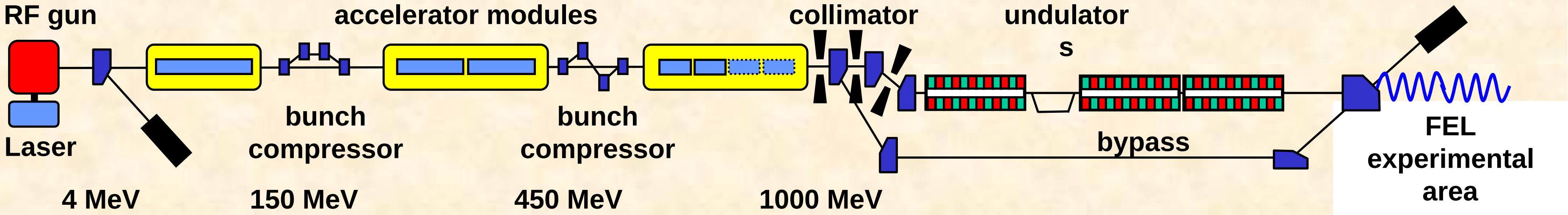
1 GeV – 6 nm
Norm. emittance: 2 mm mrad
FWHM FEL pulse length: <50 fs
Peak current 2500 A
Linac rep. rate 10 Hz
Max. pulse rate 72 000



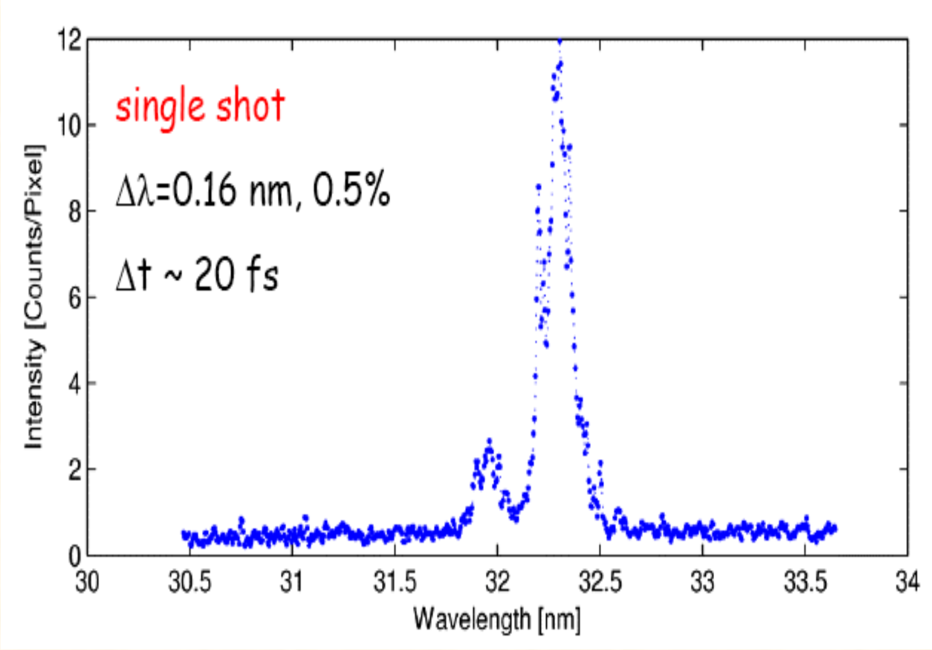
Courtesy J. Rossbach, Desy

VUV-FEL → FLASH

Free Electron LASer in Hamburg



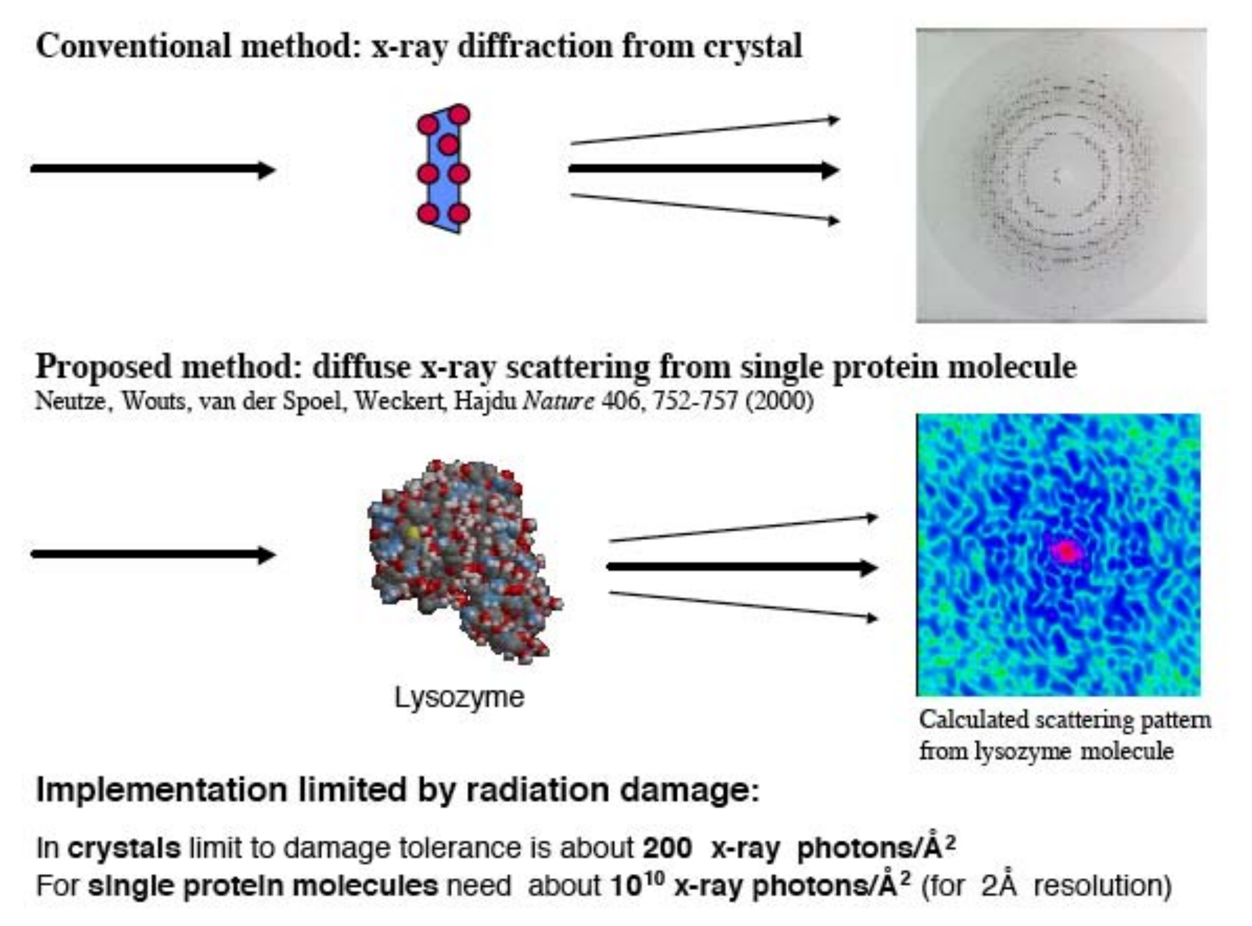
Jan. 14, 2005: lasing at 32 nm



More recently Flash lased at 6 nm.

Courtesy J. Rossbach, Desy

Single molecule (nanocrystal, biomolecule) imaging using short-pulse, coherent x-rays from FELs



Conventional method: x-ray diffraction from crystal

Proposed method: diffuse x-ray scattering from single protein molecule

Neutze, Wouts, van der Spoel, Weckert, Hajdu *Nature* 406, 752-757 (2000)

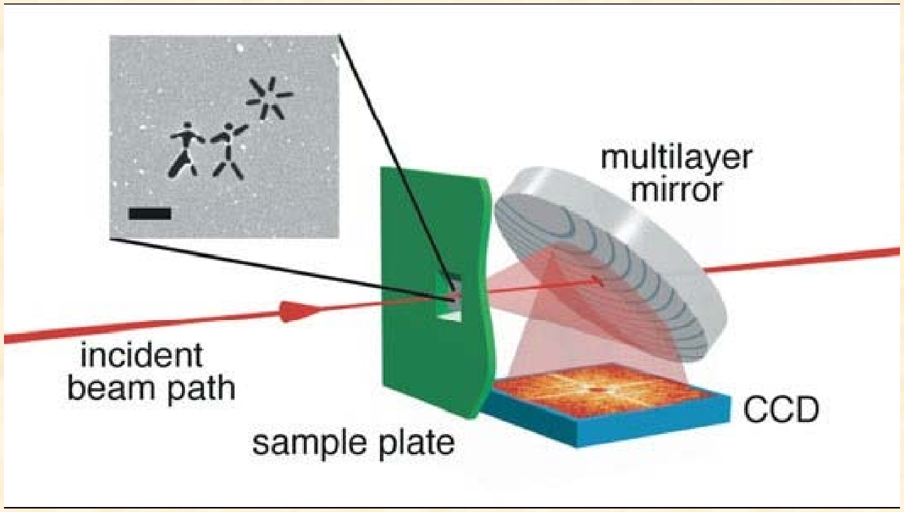
Lysozyme

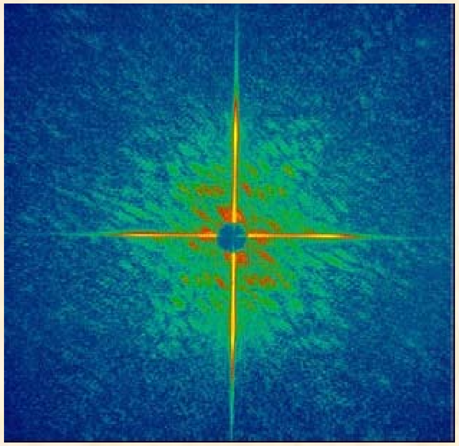
Calculated scattering pattern from lysozyme molecule

Implementation limited by radiation damage:

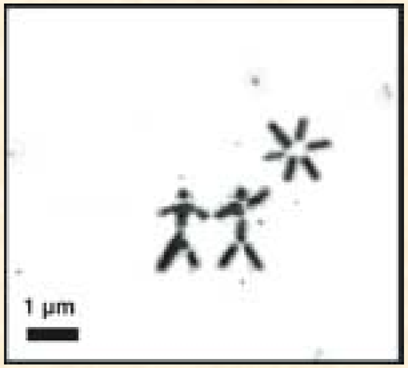
In **crystals** limit to damage tolerance is about **200 x-ray photons/Å^2**

For **single protein molecules** need about **10^{10} x-ray photons/Å^2** (for 2Å resolution)





Ultrafast Coherent Diffractive Imaging at FLASH, H.N. Chapman et al. Nature Physics 2, 839 (2006).



(a) Coherent diffraction pattern recorded from a single 25 fs pulse. (b) Reconstructed X-ray image, which shows no evidence of the damage caused by the pulse.

The beginning of microscopy

The earliest records of microscopic observations, mostly of a bee, date from 1625 and 1630 and were the work of Francesco Stelluti (1577-1653). They were published in Stelluti's Apiarium by the Accademia dei Lincei

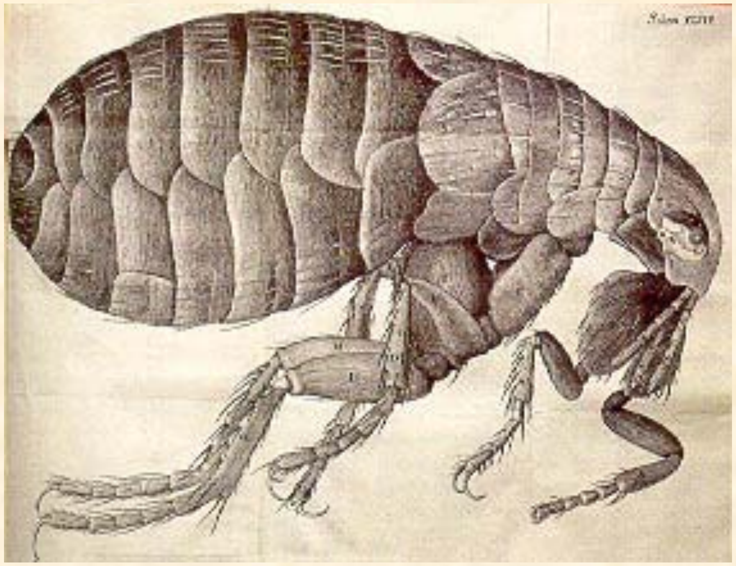
Academia da Lincei: “Microscopium“

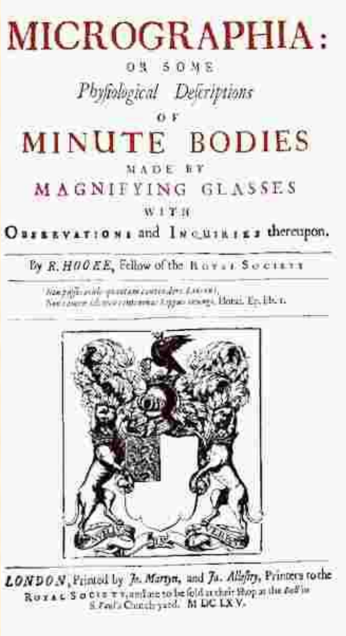
Francesco Stelluti
1577- ca 1651

8

Hooke Microscopic Studies

The microscope developed rapidly. Robert Hooke (1635-1703) published his studies in Micrographia, its most well known work, in 1665. Hooke’s himself made the beautiful drawings of his observations. The book was published by the Royal Society.





MICROGRAPHIA:
OR SOME
Phyſiological Deſcriptions
OF
MINUTE BODIES
MADE BY
MAGNIFYING GLASSES
WITH
OBSERVATIONS and INQUIRIES thereupon.

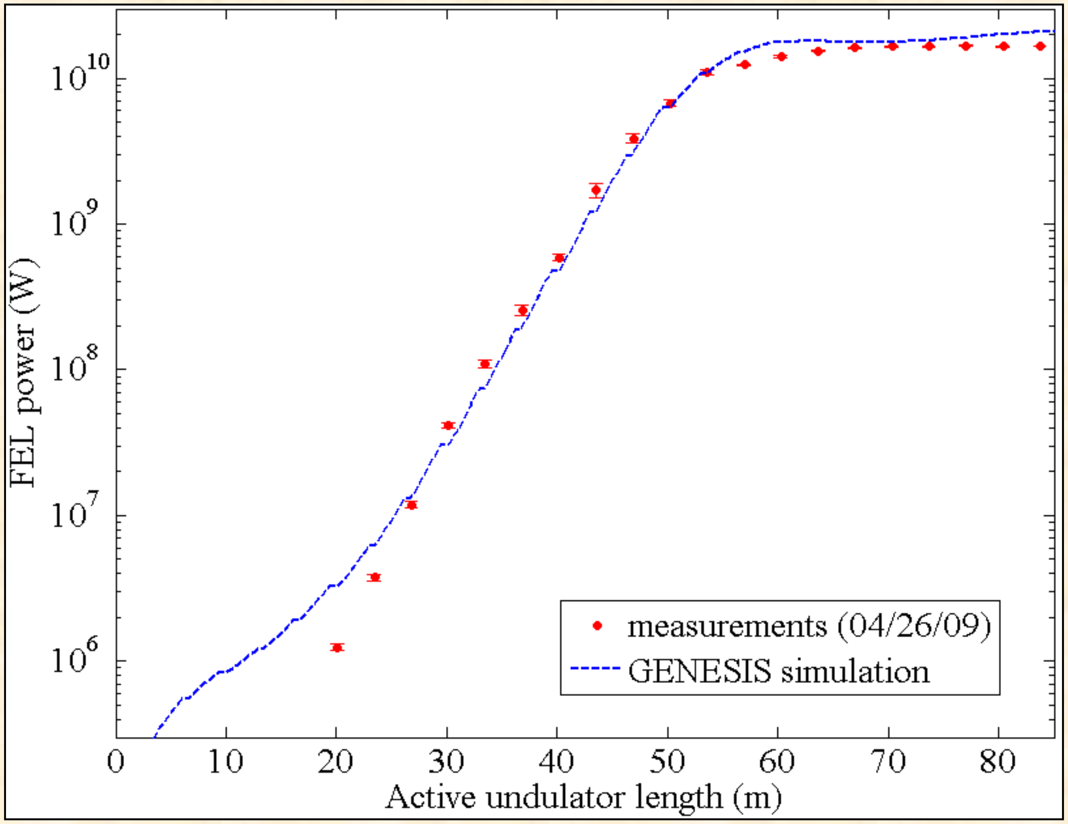
By *R. HOOKE*, Fellow of the ROYAL SOCIETY.

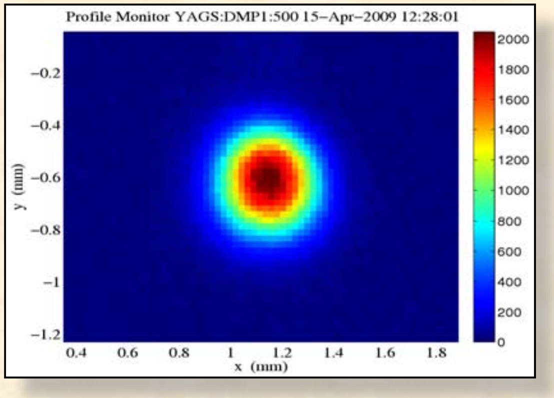
LONDON, Printed by *Jo. Martyn*, and *Ja. Alleſtry*, Printers to the ROYAL SOCIETY, and are to be ſold at their Shop at the *Bell* in S. *Paul's* Church-yard. M DC LXV.

X-Ray FELs

After many years of research and development an X-ray free-electron laser (FEL) operating in the Å spectral region, the LCLS, first proposed in 1992, is now in operation. Another X-ray FEL operating at the same wavelength is being developed at DESY as a European project. Other similar projects, SCSS, in Japan and the Suisse-FEL at PSI are being developed. Several FELs operating in the few to 100 nm region, are being developed and built in Europe, the US and Asia.

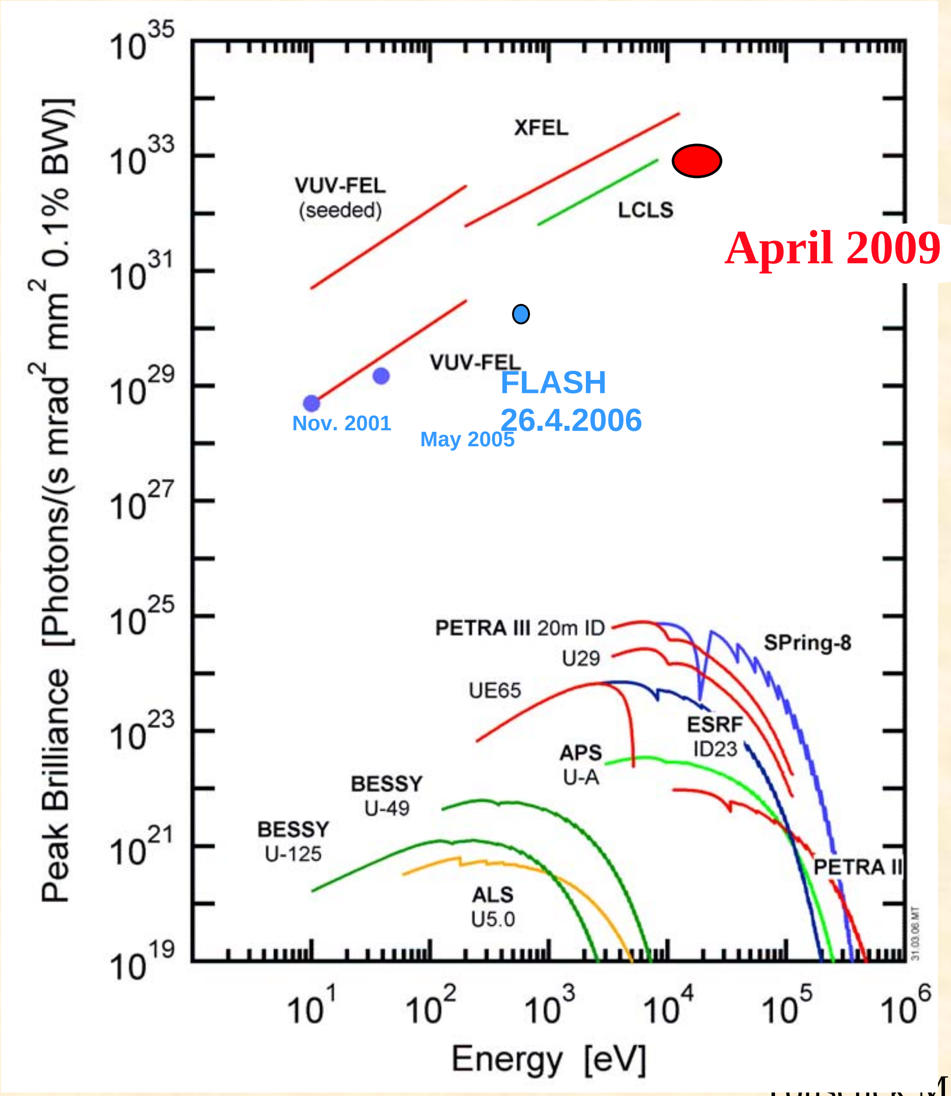
LCLS lasing at 1.5 Å, April 2009





Pulse length likely <50 fs.

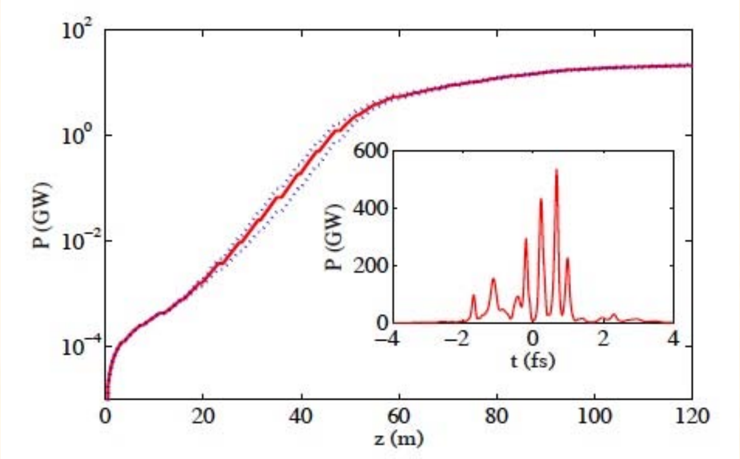
Peak brightness for synchrotron radiation sources and X-ray FELs.



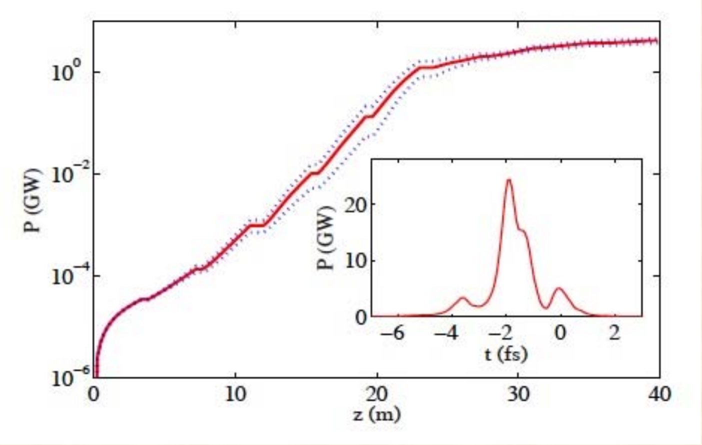
April 2009

Brightness is a very useful quantity to measure the capability of a radiation source. It is a measure of the photon density in the 6-D transverse and longitudinal phase space. From the best synchrotron radiation source to LCLS we gain 10to 11 orders of magnitude

LCLS at low charge, femtosecond pulses



20, pC, λ=0.15 nm, FWHM 2 fs



20, pC, λ=1.5 nm, single spike, full coherence, FWHM 2 fs

Simulations by Y. Ding and the LCLS group, SLAC, and C. Pellegrini, UCLA, 2009 Part. Acc. Conf. .
Measured and in reasonably good agreement with simulations during the last few weeks.

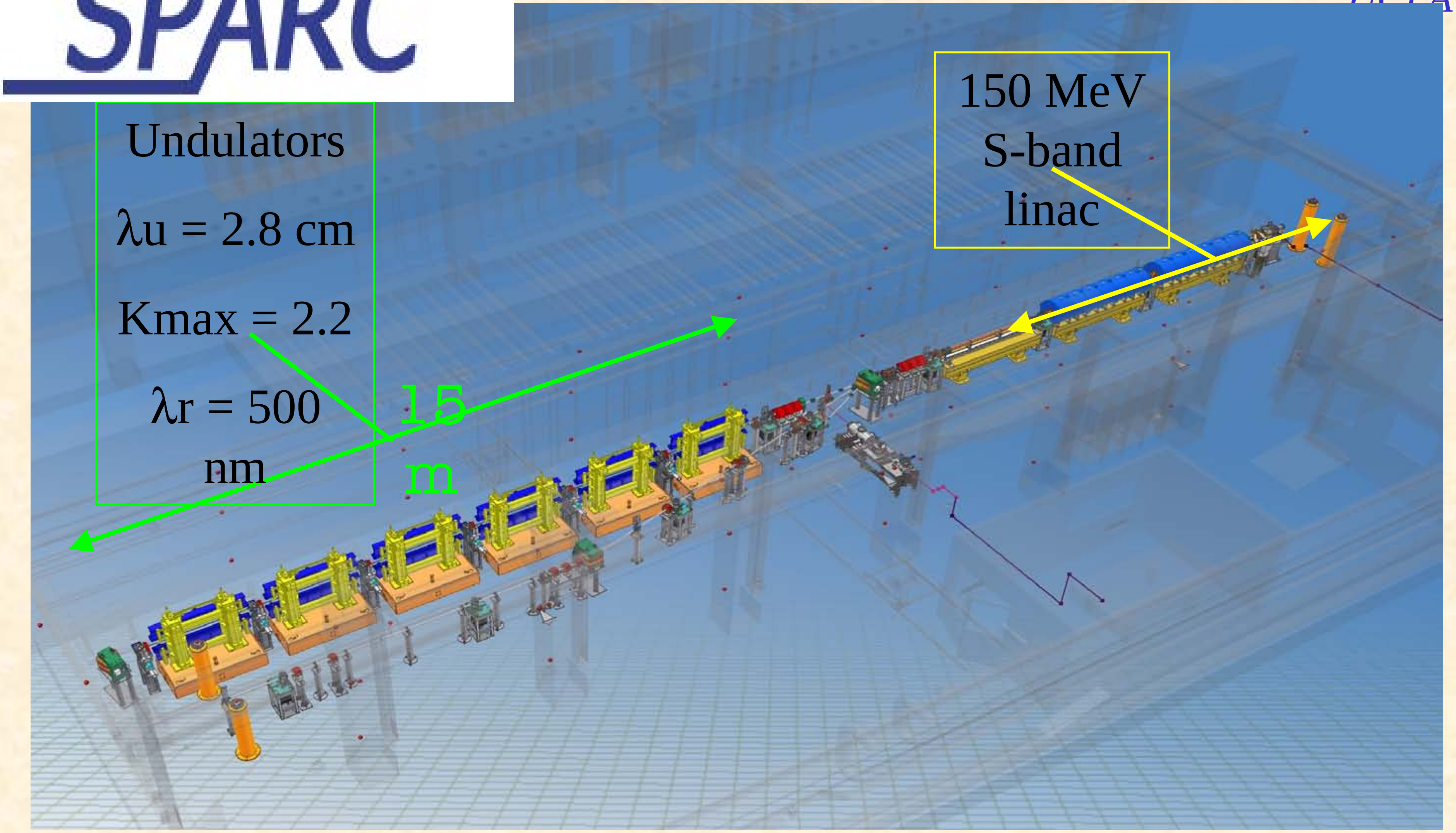
UV to X-ray FEL next developments

Flash, LCLS, and the next FELs, like XFEL, SCSS, Fermi, are only the beginning of the road. The parameters of present and next generation FEL capabilities can be extended to higher average brightness, shorter pulses, higher repetition rates, variable polarization.

Next developments

>Very short radiation pulses, femtosecond to attosecond, from about a few to 0.1 nm or less

>High energy photon FELs, E>10keV



Undulators

λu = 2.8 cm

Kmax = 2.2

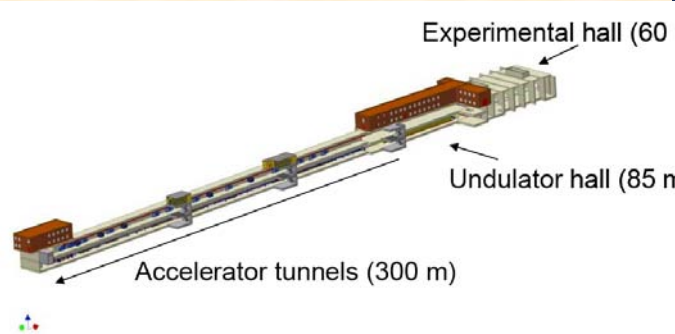
λr = 500 nm

15 m

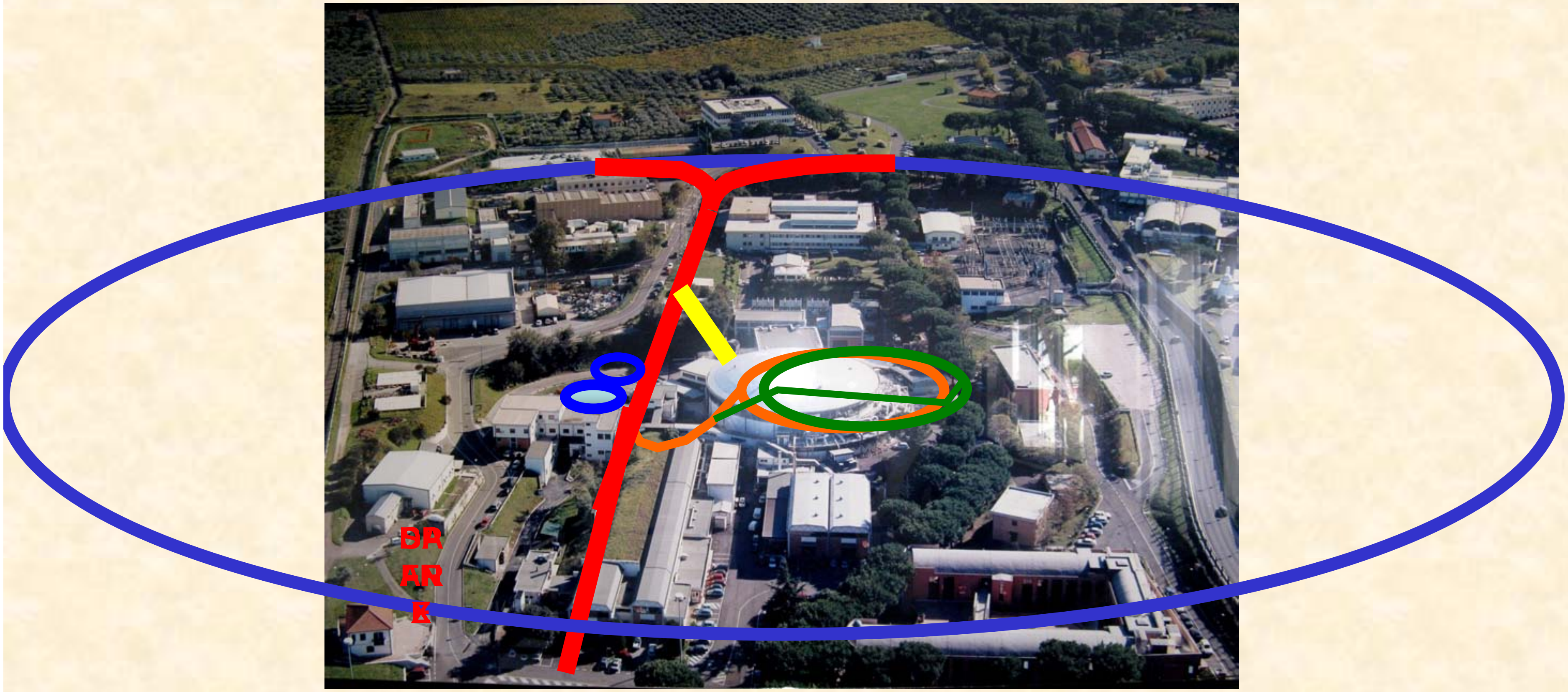
150 MeV S-band linac

FELs Initiatives in Italy

Fermi@Elettra



Super B: the highest luminosity collider



Conclusions

- ✓ The collective properties of particle beams offers interesting examples of self organization of an ensemble of particles
- ✓ These properties can be used to our advantage, as in the FEL case.
- ✓ Much of this work started here in Frascati in the 1960s with the leadership and vision of Touschek and others.

For we should not do physics by following groundless postulates and stipulations, but in the manner called for by the phenomena; for our life does not now need irrationality and groundless opinions, but rather for us to live without fear and with peace of mind.

...Epicurus (circa 350 BCE) , letter to Pythocles

Example of developments: from 100fs to ultra-short X-ray pulses

Many methods have been proposed to reduce the pulse length to the fs range: slotted spoiler; ESASE; two stage undulator with energy chirped pulse.

All these methods select and use part of the electron bunch to lase. Pulse length can be as short as 1fs or less. The number of photons in the pulse is reduced by the number of electron lasing to the total number of electrons. There is a spontaneous radiation pedestal.

Reducing the X-ray FELs Pulse Duration

FEL characteristics that can be used to reduce the pulse length:

1. The large gain bandwidth;
2. The dependence of the wavelength on the electron energy;
3. The dependence of the pulse length on the electron bunch length (they are about equal);
4. Chirping the electron beam energy and the radiation pulse wavelength;
5. Local increase of the electron bunch emittance and/or energy spread.

From 100 fs to ultra-short X-ray pulses

Another possibility studied recently is to operate the FEL at low electron bunch charge[1,2]. The scaling laws of the beam phase-space density with charge, studied in these papers, show the convenience of operating at low charge to obtain short gain length and short pulses. For charges as low as 1-20 pC the electron bunch length can be reduced to a few femtosecond or less, and be made shorter than the cooperation length. The corresponding X-ray pulse duration is also a few femtosecond or less, and the radiation can be in a single spike. There is no pedestal for the X-ray pulse.

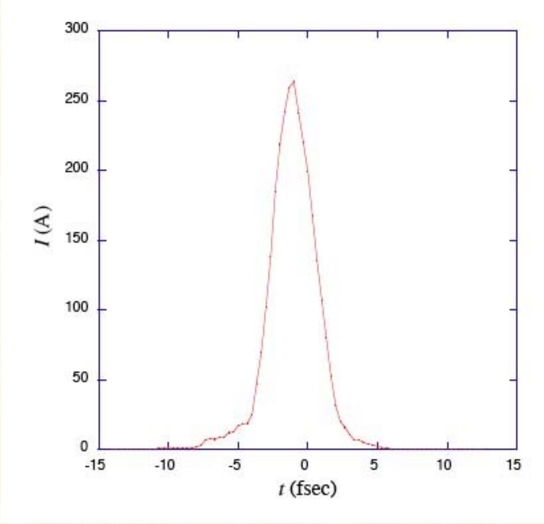
[1] Rosenzweig, C. Pellegrini et al. ", Nuclear Instruments and Methods, A 593, 39-44 (2008).

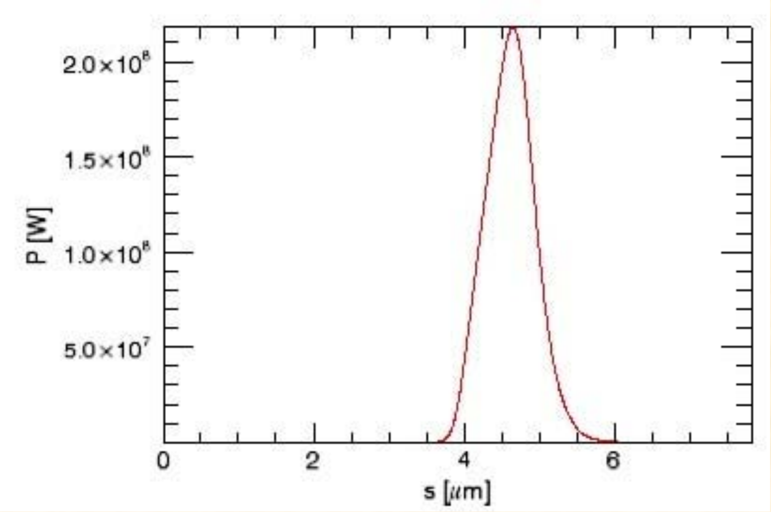
[2] Reiche, Rosenzweig, Musumeci, Pellegrini, Nucl. Instr. And Methods, A 593, 45-48 (2008).

Low charge electron bunches for ultra-short X-ray pulses

UCLA

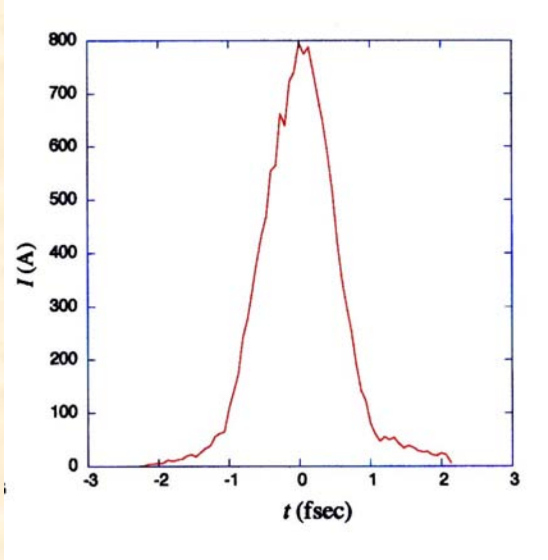
Recent studies show that a smaller emittance (x 0.1), larger electron beam brightness (x 10-100) and very short, ~ 1fs or less, electron bunches can be produced by reducing the bunch charge from about 1nC to few, 1 to 10 pC, and using velocity and magnetic bunching .



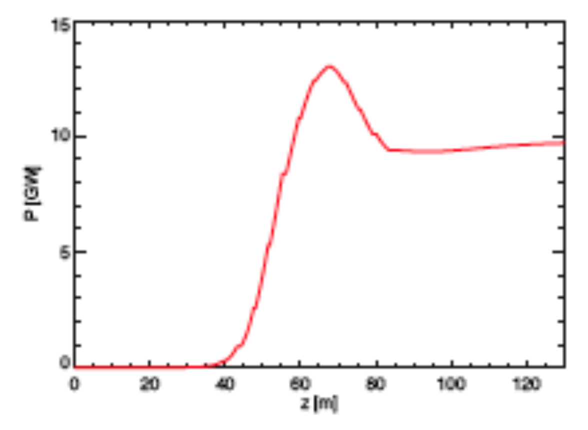


SPARX: E=2 GeV, λ=3 nm, Single spike σ_B=0.48 μm (1.6 fsec), $2\text{x}10^{10}$ photons in the pulse.

LCLS 1pC example: attosecond pulses.



Beam current profile



Peak power vs. z

$$\lambda = 0.15nm,$$
$$\sigma_E = 10^{-4},$$
$$\sigma_L = 160nm(530as).$$

Single spike at saturation, with 10^{10} photons.

Beam brightness~ $4\text{x}10^{17}$ A/m^2 rad^2 compared to $6\text{x}10^{15}$ A/m^2 rad^2 for the 1 nC design case.

60 KeV, short pulse FEL, using low emittance electron bunches

The small emittance at 1pC can be used to obtain high energy photons at low beam energy with a short period undulator.

Beam Parameters

Energy =11.5 GeV

I_P =800 A

ε_N=6.x10^{-8} m

σ_E= 10^{-4}

Undulator

λ_U=0.015 m

K=1

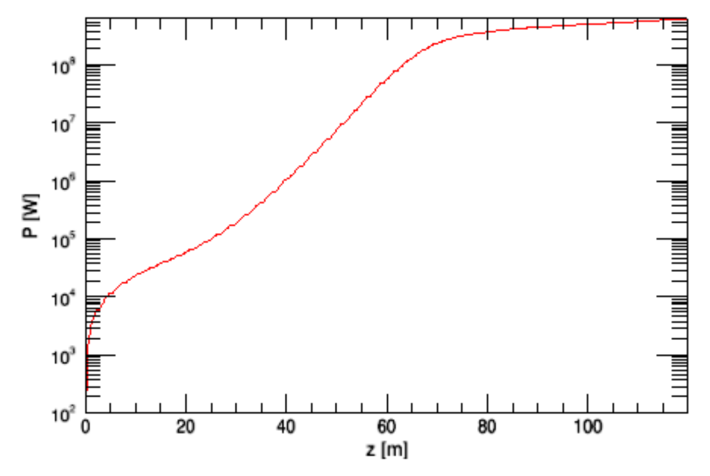
FEL Parameters

Wavelength	*0.02 nm*
FEL parameter	*0.0004*
Gain Length	*2.7 m*
Saturation power	*1 GW*
Coherent Photons	10^8
Pulse length	*0.5 fs*

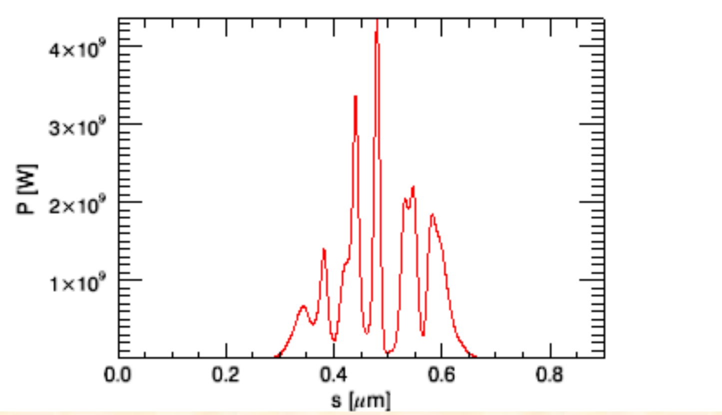
LCLS can do this with a new undulator!

0.02nm, short pulse FEL

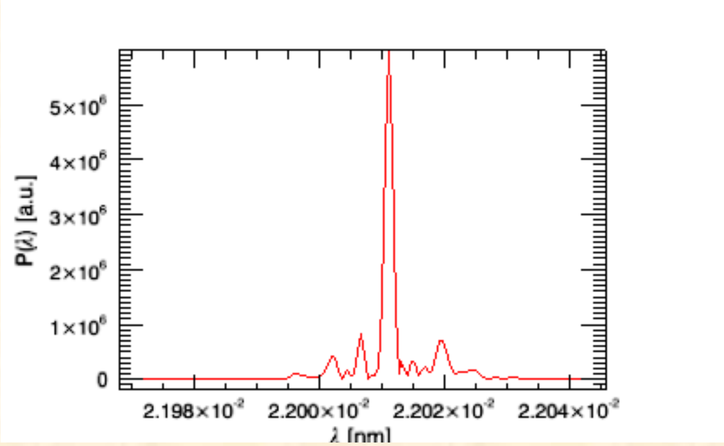
UCLA



Power vs undulator length



Pulse duration~0.5 fs



Spectrum

….. or a Compact soft X-ray FEL

- Beam energy 1.4 GeV, S-band injector X or C-band linac, length <35 m, linac repetition rate, 120 Hz, electron bunches in one linac pulse, 1 to 100
- 1.5 cm period, K=1, undulator, length 15 m
- Bunch charge, 1-20 pC, pulse length, 1 to few fs
- Number of coherent photons/pulse, 10^{10}-10^{12}
- Synchronization to external laser using the signals from the photoinjector laser and the coherent radiation in the visible from the electron bunch after compression.

Other future developments

- Plasma laser accelerators, 1 GeV/m or more, greatly decrease the linac length.
- Small period, large gap/period ratio undulators, like microwave undulator or other new ideas, reduce the beam energy for given λ.
- Novel electron sources , using plasmas or ultra-cold gases or .?., reducing the emittance < 0.1 mm mrad, and increasing the beam 6-D phase space density give:
  - Reduced beam energy for same wavelength
  - Larger FEL parameter -> more photons/electron, short pulse duration

FEL Collective Instability: short history


UCLA

The theoretical derivation of the existence of imaginary solutions of the FEL dispersion relation goes back to the late 70, early 80s.

Ref: N.M. Kroll and McMullin,Phys.Rev.A17,300 (1977); A.M. Kondratenko and E.L. Saldin, Dokl. Aka. Nauk SSSR 249, 843 (1979); P. Sprangle and R.A Smith, Phys. Rev. A21, 293 (1980); ..

First proposal to use the instability to produce IR radiation starting from noise published by A.M. Kondratenko and E.L. Saldin, Part. Acc.10, 207 (1980).

First complete 1-D theory of a SASE-FEL including start-up and saturation given in 1984 by R. Bonifacio, C. Pellegrini and L. Narducci, Optics Comm.50, 313 (1984). This theory introduced the universal FEL parameter ρ, which gives all the basic FEL properties.

FEL Collective Instability: short history

First proposal to use the instability for a soft SASE-X-ray FEL was published by J.B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B2, 259 (1985), using a bypass in a storage ring.

First proposal to use the instability for a 1 Å SASE-X-ray FEL using the SLAC linac was published by C. Pellegrini, Proc. of the Workshop on 4th Generation Light Sources, Stanford 1992. Reaching 1 Å was made possible by the development of a novel electron source, the photoinjector, by J.S. Fraser, R.L. Sheffield, and E.R. Gray, Nucl. Instr. and Meth. in Phys. Res., 250, 71, (1986).

FEL Collective Instability: short history


UCLA

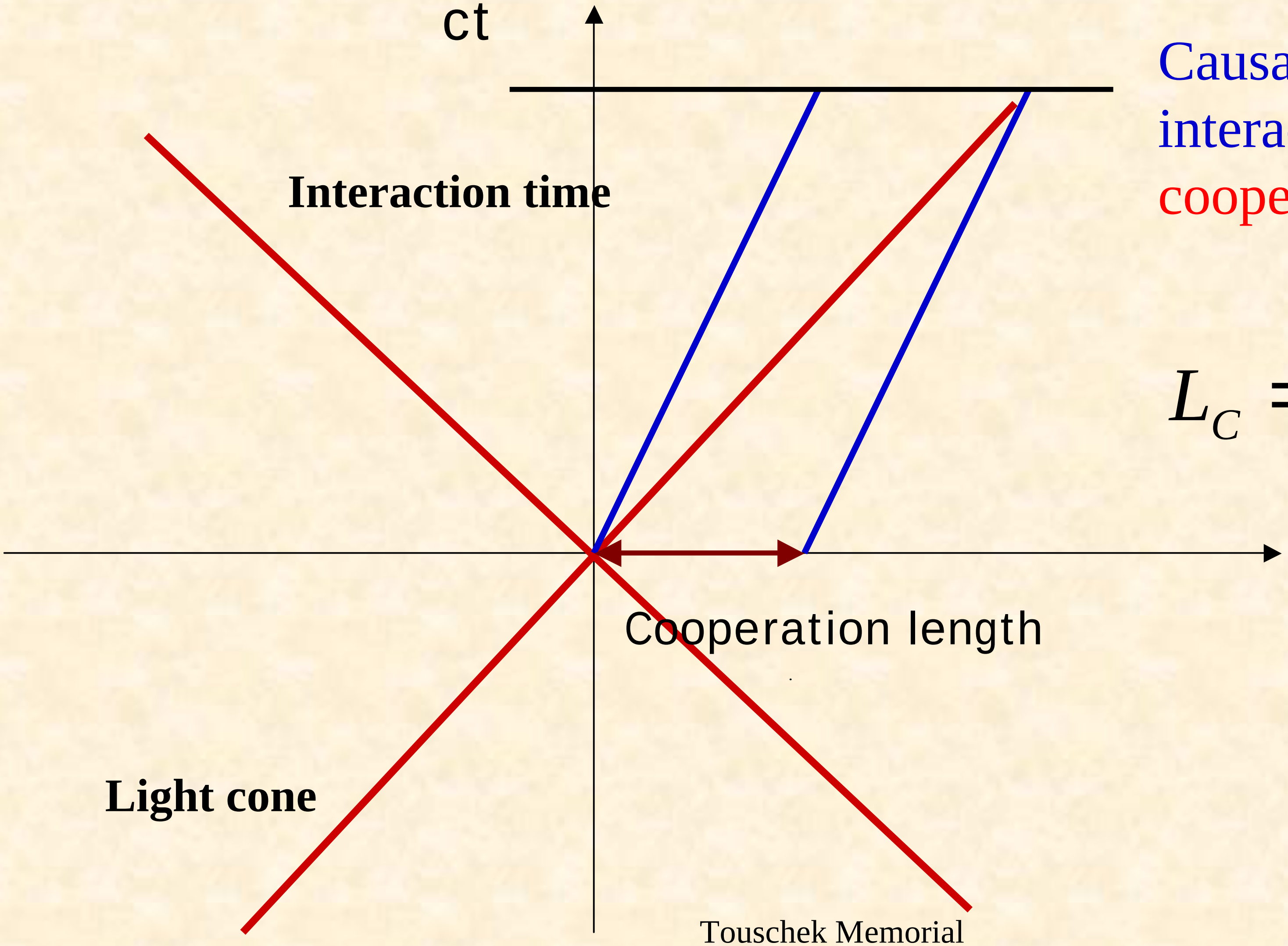
First experimental demonstration of SASE: UCLA/Kurchatov
M. Hogan et al. Phys. Rev. Lett. 80, 289 (1998).
First saturation Milton et al., Science*xpress*, May 17, 2001

Slippage, Cooperation Length, Time Structure

- The radiation propagates faster than the electron (it “slips” by λ per undulator period); thus electrons communicate with the ones in front, but only if their separation is less than the total slippage $S=N_U\lambda$.
- Cooperation length (slippage in one gain length) $L_c=\lambda/4\pi\rho$
- The local intensity in a SASE radiation pulse is proportional to the initial random bunching within a cooperation length, leading to the formation of “spikes”, with independent intensity, if the bunch length>L_C.
- Number of “spikes” in an X-ray pulse: bunch length/$2\pi L_c$.

(R. Bonifacio, C.Pellegrini, et al., Phys. Rev. Lett. 73, 70 (1994)).

FEL Collective Instability: causality

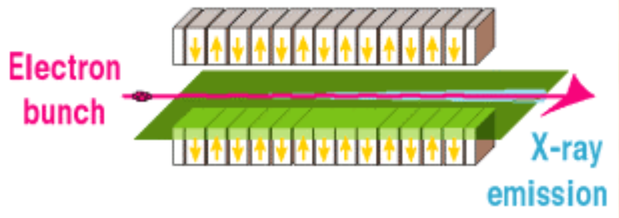


Causality limits the interaction to the cooperation length:

$$L_C = \frac{\lambda}{4\pi\rho}$$

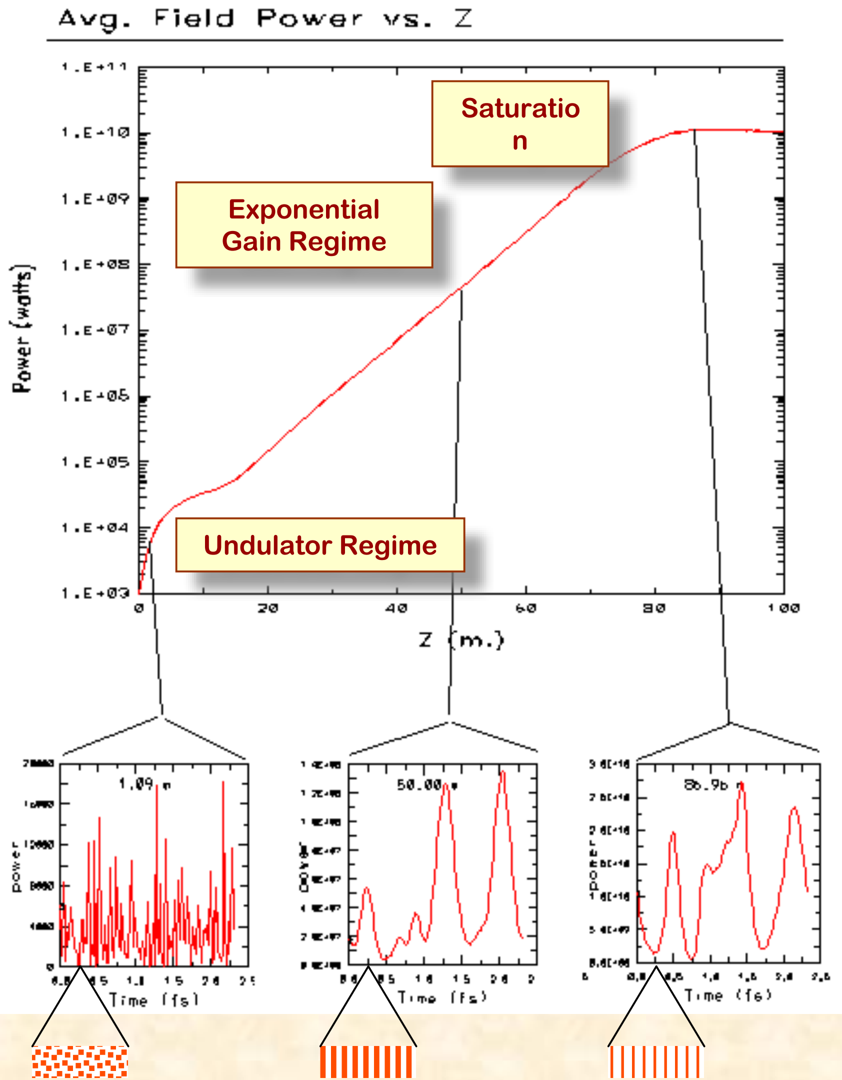
The spiky nature of SASE-FEL

- >*FEL radiation starts from noise in spontaneous radiation*



- >*Transverse radiation electric field modulates the energy and bunches the electrons within an optical wavelength*
- >*Exponential build-up of radiation along undulator length*

LCLS: L_c=0.03 µm, spike length ~ 0.20 µm, 0.8 fs, $\Delta\lambda/\lambda$=3x10^{-4}, number of spikes ~ 100.



Slippage and Cooperation Length, Time Structure, Fluctuations

- Since a SASE-FEL starts from random noise the output intensity fluctuates; the intensity distribution is given by a Γ distribution

  $$P(I)=M^M/\{\Gamma(M)<I>\}\{I/<I>\}^{M-1}\ e^{-MI/<I>}$$

  where M is the number of spikes ; the

  width of distribution is $\sigma_I=M^{-1/2}$.
- For LCLS, $M\sim250$, $\sigma_I\sim7\%$.

FEL Collective Instability: main characteristics


UCLA

All key characteristics are given by one universal FEL parameter:

$\rho=\{(K/4\gamma)(\Omega_p/\omega_w)\}^{2/3}$*

($\omega_w=2\pi c/\lambda_w$, Ω_p=beam plasma frequency).

- Gain Length: $L_G=\lambda_w/4\pi\rho$,
- Saturation power: $P\sim\rho I_{beam} E$
- Saturation length: $L_{sat}\sim 10L_G\sim\lambda_w/\rho$
- Line width: $1/N_w\sim\rho$

Typical values of ρ, 10^{-3}-10^{-4}. Number of photons/electron at saturation: $N_{ph}\sim\rho E/E_{ph}$. For E_{ph}=10keV, E=15 GeV, $\rho=10^{-3}$, $N_{ph}\sim10^3$, a gain of 5 orders of magnitude.

*Bonifacio, Pellegrini, Narducci, Optics Comm, 50, 373, 1984

FEL Collective Instability: electron beam conditions

The exponential growth occurs if

$\sigma_E < \rho$	cold beam
$\varepsilon \sim \lambda / 4\pi$	Phase-space matching
$Z_R / L_G > 1$	Diffraction losses from the beam less than the gain

The beam Rayleigh range is $Z_R = \pi a^2 / \lambda$, where a is the beam transverse radius. These conditions are more difficult to satisfy when the radiation wavelength is smaller.