INTERNATIONAL
YEAR OF LIGHT
2015

Historical survey of Free Electron Lasers

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Synchrotron SOLEIL

Free Electron Laser

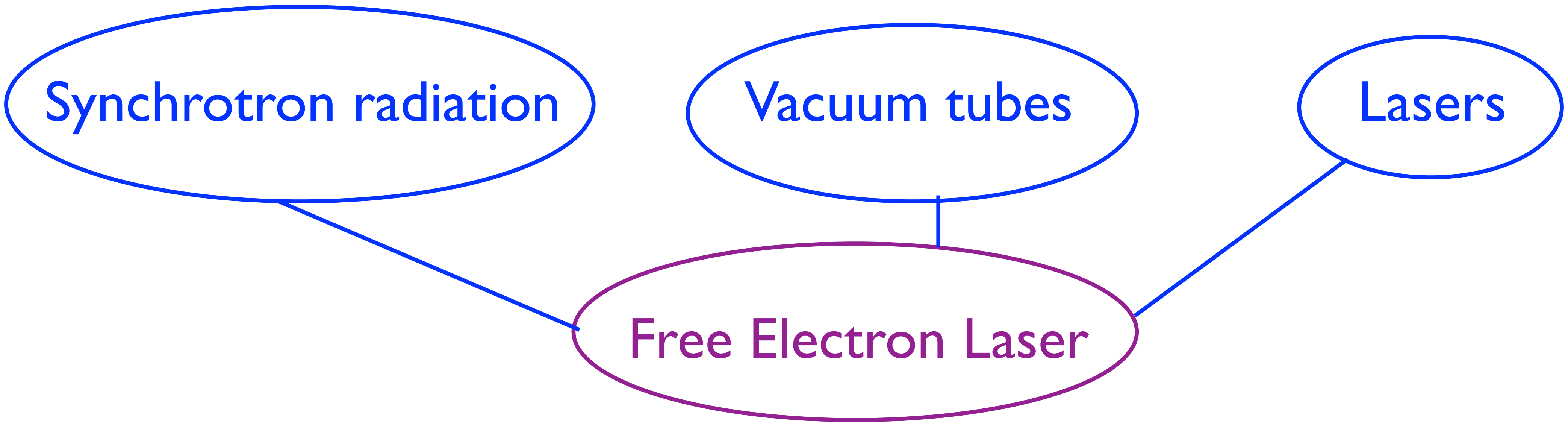
Free Electron Laser:

«simple and elegant gain medium» : an electron beam in a magnetic field

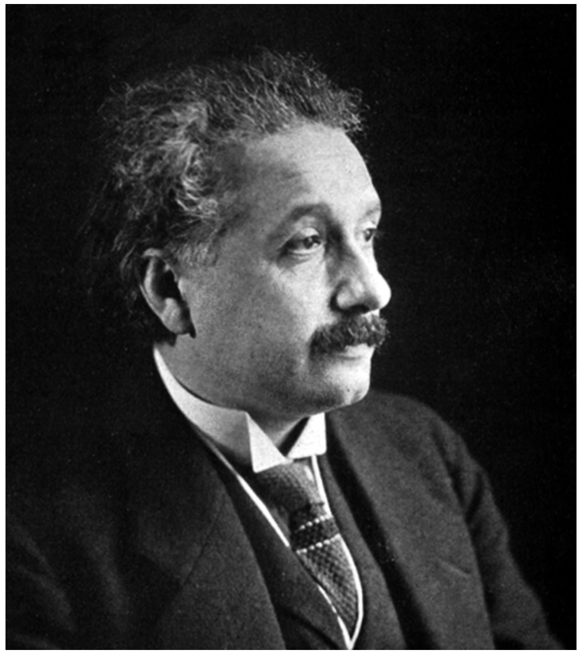
- broad wavelength tunability (vibration frequency can be adjusted by changing the magnetic field or the speed of the electrons)
- excellent optical beam quality
- high power

free electrons

bound electrons in atoms and molecules : vibrate at specific frequencies



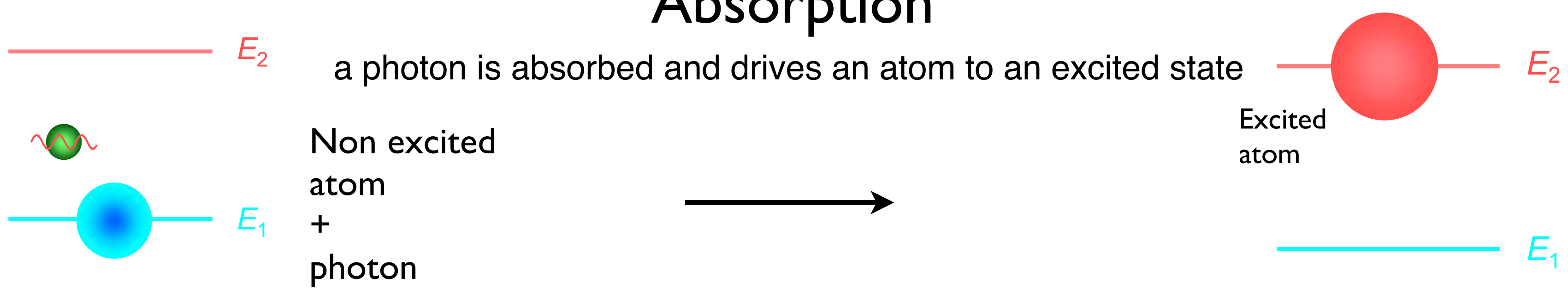
1.1 : The photon-matter interaction processes



1917: black-body analysis
prediction of the stimulated emission

Absorption

a photon is absorbed and drives an atom to an excited state

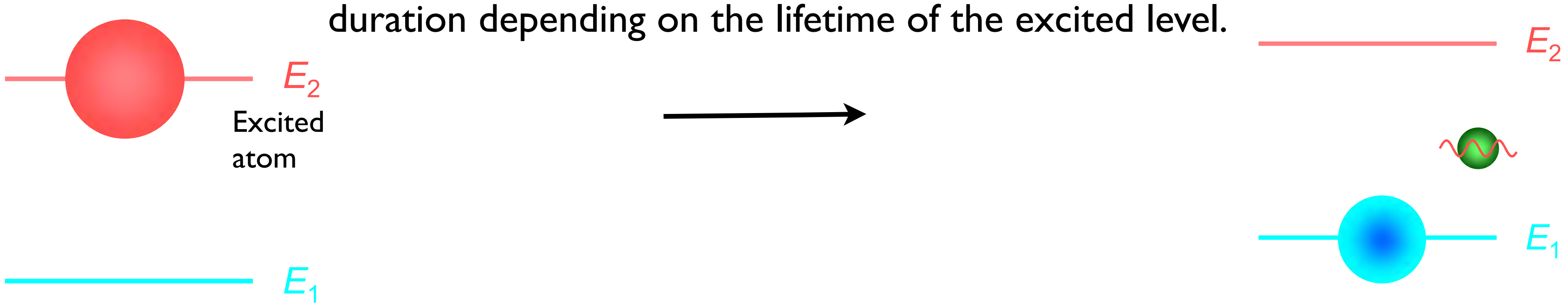


Non excited atom
+
photon

Excited atom

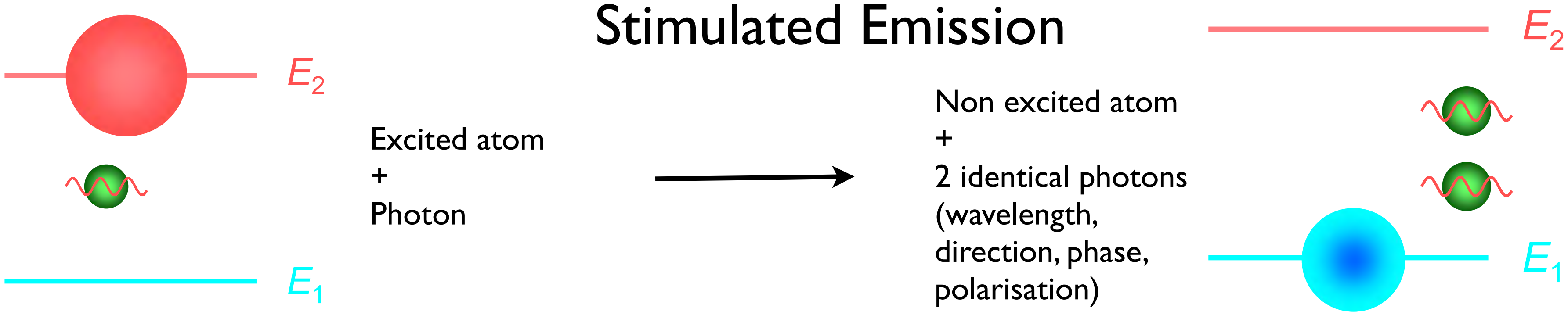
Spontaneous Emission

The excited atom being unstable, it emits a spontaneous photon after a duration depending on the lifetime of the excited level.



Excited atom

Stimulated Emission



Excited atom
+
Photon

Non excited atom
+
2 identical photons (wavelength, direction, phase, polarisation)

A photon is absorbed by an excited atom, which results in the emission of two photons with identical wavelength, direction, phase, polarisation, while the atom returns to its fundamental state.

Stimulated emission was seen as addition of photons to already existing photons, and not as the amplification of a monochromatic wave with conservation of its phase. The notion of light coherence, related to its undulatory properties, was not considered at that time.

I. The origins of the Free Electron Laser

I.3 The early times of synchrotron radiation

Josepf Larmor (1857-1942)

J. Larmor, On the Theory of the Magnetic Influence on Spectra ; And On the Radiation from Moving Ions, Phil. Mag. 44, 503-512 (1897)

first specific prediction of time dilation : "... individual electrons describe corresponding parts of their orbits in times shorter for the [rest] system in the ratio $(1 – v^2/c^2)^{1/2}$".

Alfred-Marie Liénard (1869-1958)

First correct calculation of the emitted power by an accelerated charged particule $(E/mc^2)^4/R^2$

A. Liénard, L ' Eclairage électrique, 16, 5 (1898)

George Adolphus Schott(1868-1937)

G. A. Schott

G. A. Schott, Ann. Phys. 24, 635 (1907), G. A. Schott, Electromagnetic Radiation, : And the mechanical reactions arising from it, Cambridge University Press (1912)

angular and spectral distribution and polarization properties

Dmitri Ivanenko (Дми́трий Дми́триевич Ивані́нко) (1904-1994)

Isaak Yakovlevich Pomeranchuk (Исаа́к Яковлевич Померанчу́к (1913-1966)

D. Ivanenko and I. Pomeranchuk, Phys. Rev. 65, 343 (1944)

energy losses due to radiating electrons would set a limit on the energy obtainable in a betatron (around 0.5 GeV).

Julian Seymour Schwinger (1918 –1994)

Physics, 1965

J. Schwinger, Phys. Rev. 70, 798 (1946)

peaked spectrum

Edwin Mattison McMillan (1907-1991)

Chemistry, 1951

E. M. McMillan, PRL 68, 1434 (1945)

Synchronism and phase stability

Vladimir Iossifovitch Veksler (Владимир Иосифович Векслер) (1907-1966)

V. Veksler J. Phys. USSR 9, 153 (1946)

peaked spectrum

1.3 The early times of synchrotron radiation

1946 : first energy loss measurement

J. P. Blewett, Phys. Rev. 69, 87 (1946)
F. K. Gloward et al., Nature 158, 413 (1946)

1947 : first observation of synchrotron radiation

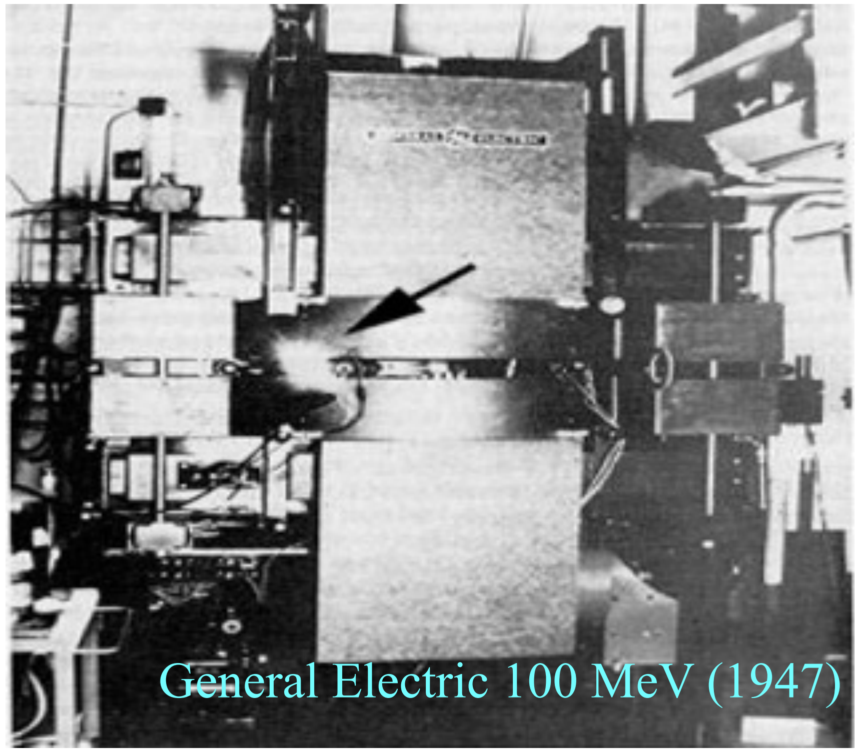
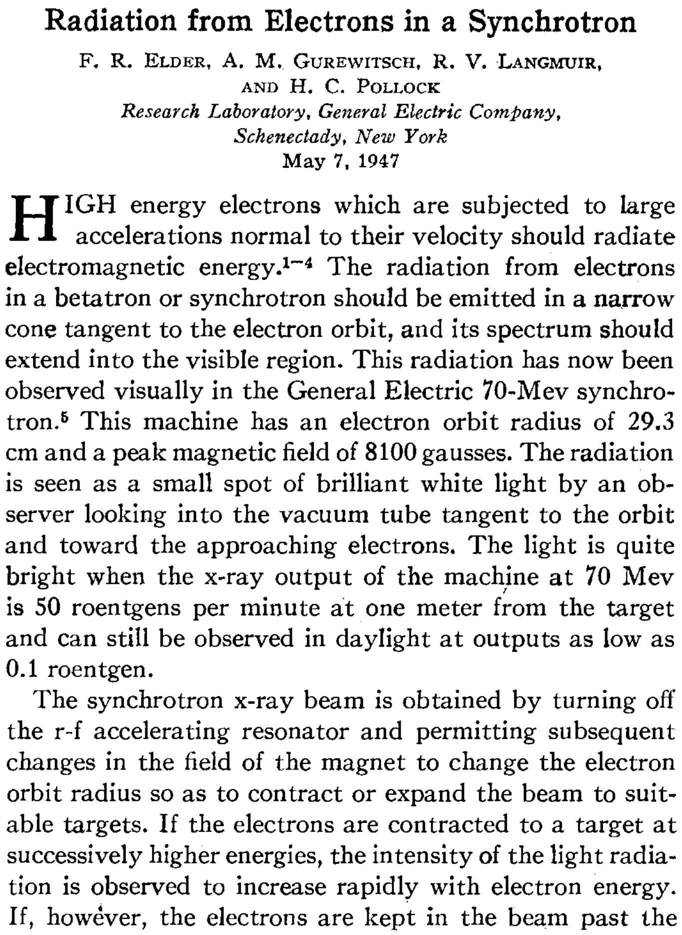


Figure 5
The General Electric team (from left to right, Langmuir, Elde
Gurewitsch, Charlton and Pollock) looking at the vacuu
chamber of the 70 MeV synchrotron – the world's second
synchrotron.



Radiation from Electrons in a Synchrotron

F. R. Elder, A. M. Gurewitsch, R. V. Langmuir,
and H. C. Pollock
Research Laboratory, General Electric Company,
Schenectady, New York
May 7, 1947

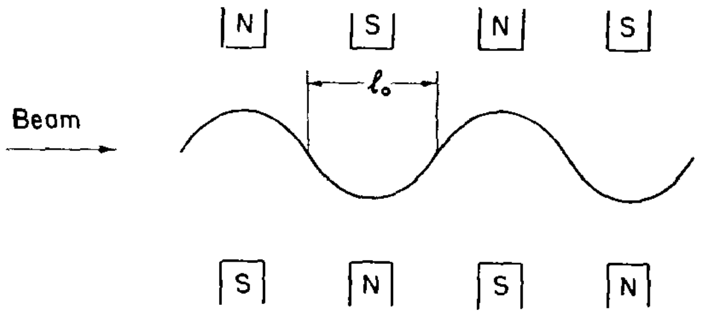
HIGH energy electrons which are subjected to large accelerations normal to their velocity should radiate electromagnetic energy.[1–4] The radiation from electrons in a betatron or synchrotron should be emitted in a narrow cone tangent to the electron orbit, and its spectrum should extend into the visible region. This radiation has now been observed visually in the General Electric 70-Mev synchrotron.[5] This machine has an electron orbit radius of 29.3 cm and a peak magnetic field of 8100 gausses. The radiation is seen as a small spot of brilliant white light by an observer looking into the vacuum tube tangent to the orbit and toward the approaching electrons. The light is quite bright when the x-ray output of the machine at 70 Mev is 50 roentgens per minute at one meter from the target and can still be observed in daylight at outputs as low as 0.1 roentgen.

The synchrotron x-ray beam is obtained by turning off the r-f accelerating resonator and permitting subsequent changes in the field of the magnet to change the electron orbit radius so as to contract or expand the beam to suitable targets. If the electrons are contracted to a target at successively higher energies, the intensity of the light radiation is observed to increase rapidly with electron energy. If, however, the electrons are kept in the beam past the

F. R. Elder et al., Physical Review, 71, 11, (1947), 829-830
J. P. Blewett, 50 years of synchrotron radiation, J. Synchrotron Rad., 5, 135-139 (1998)

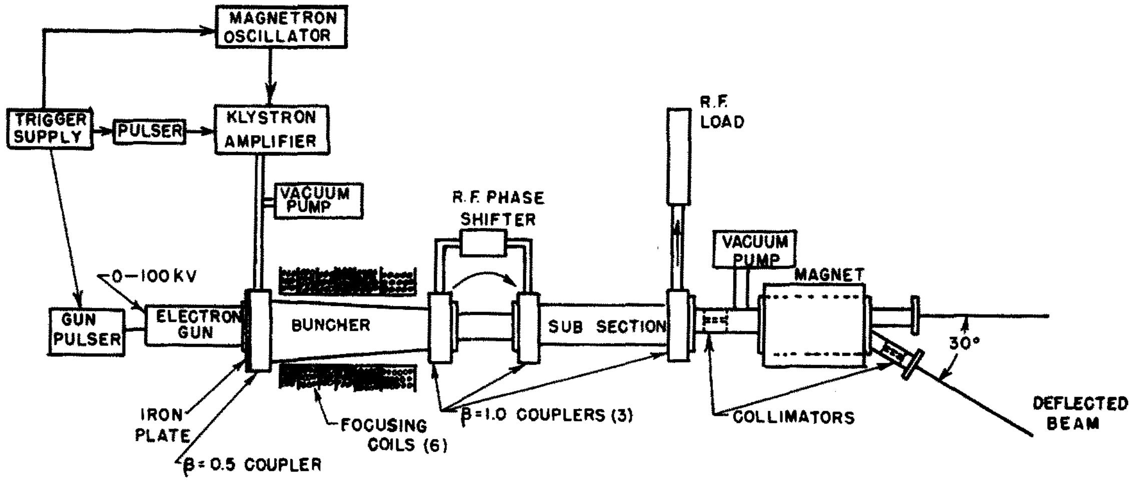
I. The origins of the Free Electron Laser

1.3 The early times of synchrotron radiation
The undulator



- Calculation of the field created by a relativistic particle in the magnetic sinusoidal field (i.e. such as produced by undulators)

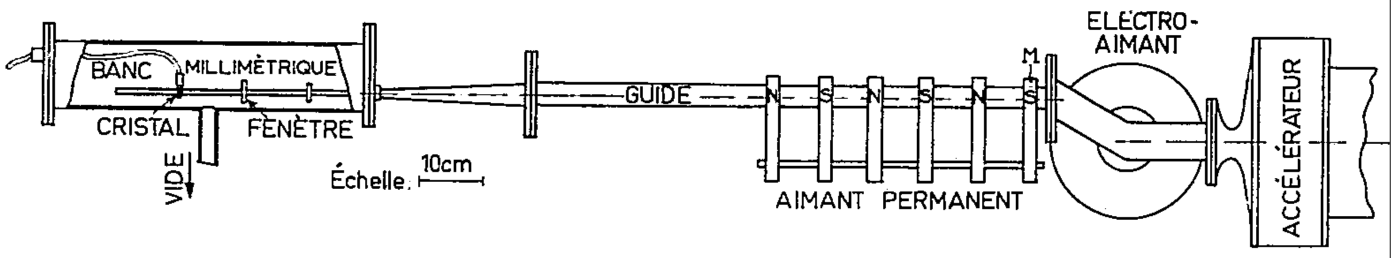
Motz H.: Applications of the radiation from fast electron beams, Journ. Appl. Phys. 22, 527–535 (1951)



- Influence of the bunching of the electrons on the coherence of the produced radiation
- observation of the polarized visible radiation from an undulator installed on the 100 MeV Stanford accelerator.

A buncher set-up after a 3.5 MeV accelerator enables to achieve 1 W peak power at 1,9 mm thanks the the bunching of the electrons.

Motz H., Thon W., Whitehurst R. N.: Experiments on Radiation by Fast Electron Beams, Journ. Appl. Phys. 24, 826–833 (1953)



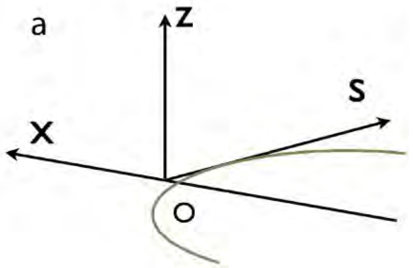
ONDULATEUR

- Emission of the radiation spectrum (6 mm) produced from an undulator installed on a 2.3 MeV accelerator

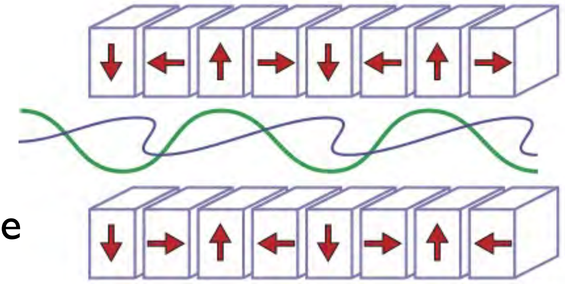
Combes R., Frelot T., présenté par L. de Broglie, Production d'ondes millimétriques par un ondulateur magnétique. Comptes-Rendus Hebd. Scéance Acad. Sci. Paris, 241, 1559 (1955)

I.3 The early times of synchrotron radiation

electron movement in the undulator



s : longitudinal coordinate
x : horizontal direction
z : vertical direction



e. beam $\gamma = \frac{E}{m_o c^2}$ $\beta = \frac{v}{c}$ $\boxed{\gamma = \frac{1}{\sqrt{1-\beta^2}}}$ $\boxed{\beta^2 = 1 - \frac{1}{\gamma^2}}$

Approximation of ultra-relativistic beams $1/\gamma << 1$ $\beta \approx 1 - \frac{1}{2\gamma^2}$

Case of a planar undulator of N$_u$ periods

$$\boxed{\overrightarrow{B_{uz}} = B_{uz}\cos\left(\frac{2\pi}{\lambda_u}s\right)\vec{z} = B_{uz}\cos(k_u s)\vec{z}} \quad \boxed{K_u = \frac{eB_u\lambda_u}{2\pi m_o c}}$$

$$K_u = 0.934 B_u(T)\lambda_u(cm)$$

undulator wavenumber k_u $k_u = \frac{2\pi}{\lambda_u}$

$$\vec{\beta}\begin{pmatrix} \frac{K_u}{\gamma}\sin(k_u s) \\ 0 \\ 1 - \frac{1}{2\gamma^2} - \frac{K_u^2}{2\gamma^2}\sin^2(k_u s) \end{pmatrix} \quad \overrightarrow{<\beta>}\begin{pmatrix} 0 \\ 0 \\ 1 - \frac{1}{2\gamma^2}(1 + \frac{K_u^2}{2}) \end{pmatrix}$$

$$\begin{cases} x = \frac{K_u c}{\gamma}\int \sin(\omega_u t)dt = \frac{K_u c}{\gamma\omega_u}\cos(\omega_u t) \\ y = 0 \\ s = c(1 - \frac{1}{2\gamma^2} - \frac{K_u^2}{4\gamma^2})t + \frac{K_u^2\lambda_u}{16\pi\gamma^2}\sin(2\omega_u t) = <v> ct + \frac{K_u^2\lambda_u}{16\pi\gamma^2}\sin(2\omega_u t) \end{cases}$$

Case of a helical undulator of N$_u$ periods

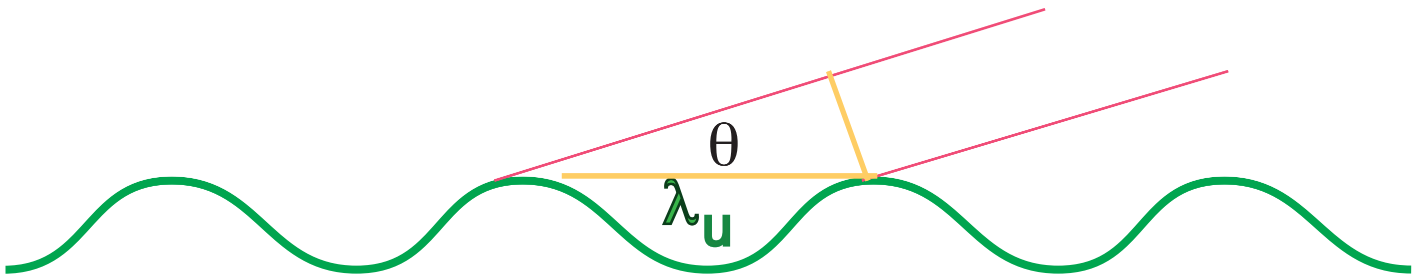
$$\boxed{\begin{cases} \overrightarrow{B_{ux}} = B_{ux}\sin(\frac{2\pi}{\lambda_u}s)\vec{x} = B_u\sin(k_u s)\vec{x} \\ \overrightarrow{B_{uz}} = B_u\cos\left(\frac{2\pi}{\lambda_u}s\right)\vec{z} = B_u\cos(k_u s)\vec{z} \\ \overrightarrow{B_{us}} = 0 \end{cases}}$$

$$\vec{\beta}\begin{pmatrix} \frac{K_u}{\gamma}\sin(k_u s) \\ -\frac{K_u}{\gamma}\cos(k_u s) \\ 1 - \frac{1}{2\gamma^2} - \frac{K_u^2}{2\gamma^2} \end{pmatrix}$$

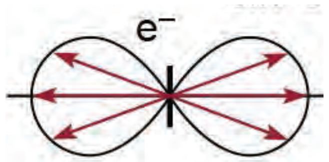
$$\begin{cases} x = \frac{K_u c}{\gamma}\int \sin(\omega_u t)dt = -\frac{K_u c}{\gamma\omega_u}\cos(\omega_u t) \\ y = \frac{K_u c}{\gamma}\int \cos(\omega_u t)dt = \frac{K_u c}{\gamma\omega_u}\sin(\omega_u t) \\ s = c(1 - \frac{1}{2\gamma^2} - \frac{K_u^2}{4\gamma^2})t = <v> ct \end{cases}$$

1.3 The early times of synchrotron radiation

Recall on Undulator radiation : condition of interference



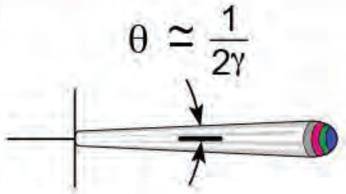
electron frame



$$\lambda' = \frac{\lambda_u}{\gamma}$$

Resonance condition :
wavelengths for which one electron radiation interfers constructively

observer frame



$\lambda = \lambda' \Upsilon(1-\beta\cos\theta)$
$= \lambda_u (1-\beta\cos\theta)$

Path difference between the two rays : $n\lambda_n$
$c\lambda_u/v_s - \lambda_u\cos\theta/c = n\,\lambda_n \quad \Rightarrow \quad n\,\lambda_r = \lambda_u\,(1 - \beta_s\cos\theta)/\,\beta_s$

Synchrotron radiation emitted ahead (small angle) => $\cos\theta \approx 1 - \theta^2/2$
$\beta_s \approx \langle\beta_s\rangle = 1 - 1/2\Upsilon^2 - K_u^2/2\Upsilon^2$

$$\boxed{n\lambda_n = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K_u^2}{2}+\gamma^2\theta^2\right)} \qquad K_u = \frac{eB_u\lambda_u}{2\pi m_o c}$$

$\cos\theta = 1 - \theta^2/2$
$\beta_z = 1 - 1/2\Upsilon^2 - K^2/4\Upsilon^2 = 1 - 1/2\Upsilon^2\,(1+K^2/2)$
$1-\beta_z\cos\theta = 1/2\Upsilon^2\,(1+K^2/2+\Upsilon^2\,\theta^2)$

$\theta = 0 \quad \lambda = \lambda' \Upsilon(1-\beta)$
$\theta = \pi \quad \lambda = \lambda' \Upsilon(1+\beta)$

Wavelength tuneability by change of magnetic field or electron beam energy

I.3 The early times of synchrotron radiation

Recall of undulator radiation : linewidth

- Homogeneous linewidth

interference from trains N_u periods :

$$\boxed{\frac{\Delta\lambda}{\lambda_n} = \frac{1}{nN_u}}$$

Intensity α N_u^2

Nu= 300 => 0.3 % on H1, 0.07 % on H5
Nu = 100 => 1 % on H1, 0.2 % on H5, 0.07 % on H15

- Inhomogeneous linewidth

- energy spread :

$$\boxed{\frac{\Delta\lambda}{\lambda_n} = \frac{2\sigma_\gamma}{\gamma}}$$

Storage ring : SOLEIL = 0.1%
Conventional linac : 0.01 %

- divergence and size (emittance)

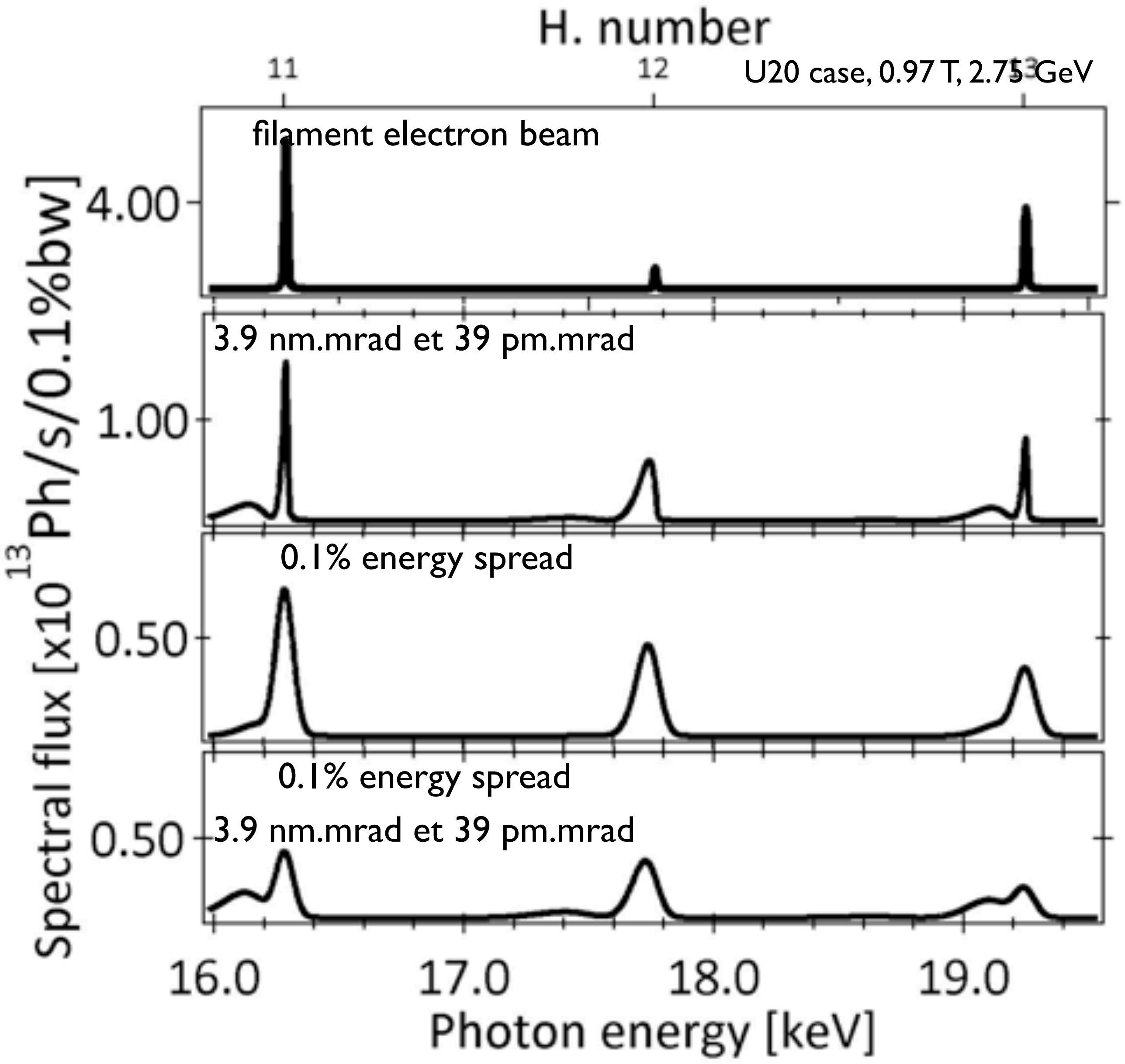
100 µrad SOLEIL U20: 10%
100 µrad LUNEX5, U15, 0.01%

$$\boxed{\frac{\Delta\lambda_i}{\lambda_n} = \frac{\gamma^2\theta^2}{1+\frac{K_u^2}{2}}}$$

-observation angle

- beam size

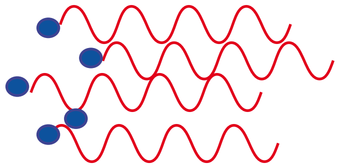
$$\boxed{\frac{\Delta\lambda}{\lambda_n} = \frac{2\pi^2 K_u^2}{1+K_u^2}\,\frac{\sigma^2\gamma}{\lambda_u^2}}$$



=> When inhomogenous bandwidth becomes dominant, then Intensity α N_u

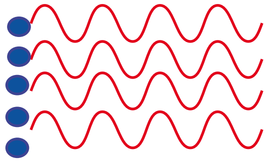
1.3 The early times of synchrotron radiation

Coherent emission



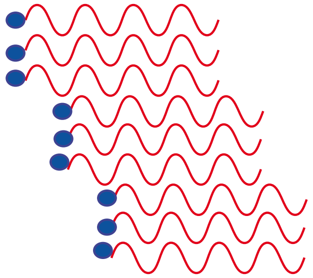
$$n(s) = N_e S(s) \qquad E(\omega) = E_o(\omega) N_e f(\omega) \qquad f(\omega) = \int_{-\infty}^{\infty} S(s) exp(i\frac{\omega s)}{c} ds$$

$$I(\omega) = I_o(\omega)[\underbrace{N_e(N_e-1)f(\omega)^2}_{\text{Coherent}} + \underbrace{N_e}_{\text{Incoherent}}]$$



Short bunch

Ex : Gaussian beam
10 orders of magnitude for $\lambda >> \sigma_l$
8 for $\lambda = 2\sigma_l$
5 for $\lambda = \sigma_l$



Bunched beam

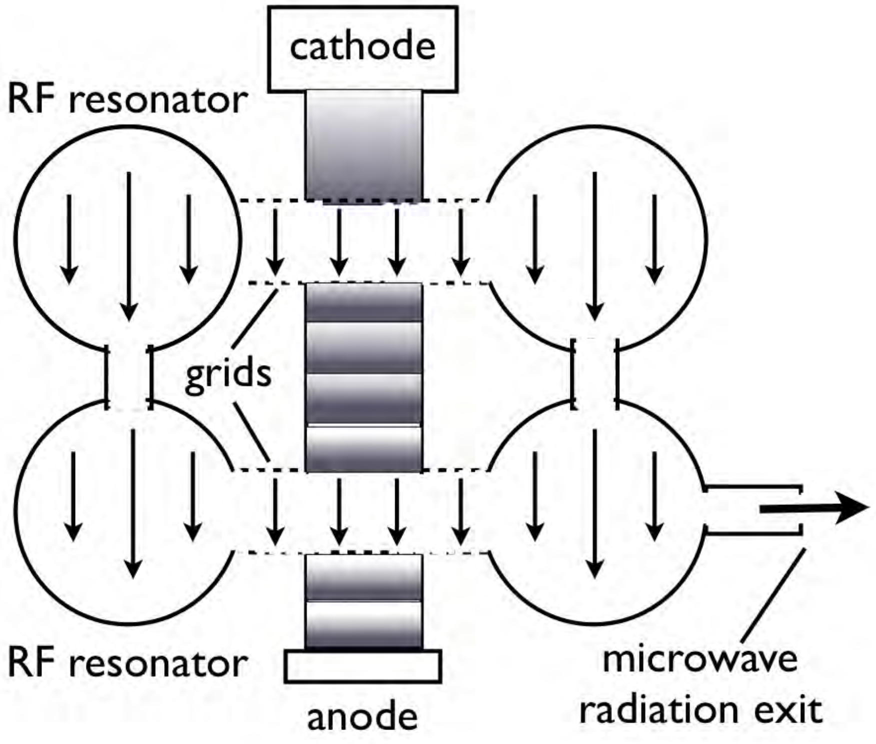
$$S(s) = \sum_{m=1}^{M} S(s - m\lambda_r)$$

Coherent emission for $\lambda = \lambda_r/n$ with the form factor, corresponding the bunching efficency (equivalent to the form factor in Bragg diffraction)

I.4 : The development of vacuum tubes

Begining of the twentieth century : rapid and spectacular development of electron beams in vacuum tubes
Applications : radiodiffusion, radar detection for iceberg or military use (high frequency oscillations needed).

Example : the klystron



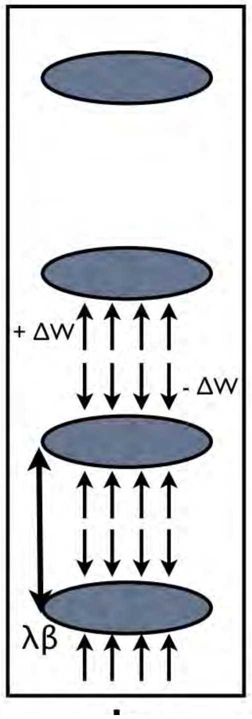
Cavity 1

an electric field oscillates on a length Δs at a frequency ν=2 π f (1-10 GHz, i.e. 30-3 cm). The electrons, generated at the cathode, enter in the first cavity where the input RF signal is applied.

energy gain

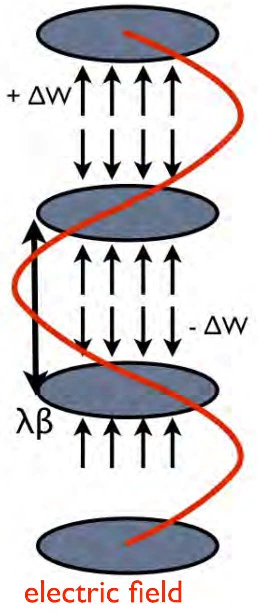
$$\Delta W_1 = \int_0^{\Delta s} \vec{\beta}\,.\,\vec{E}\,dt \alpha E.\beta \cos\omega t.\frac{\Delta s}{\beta} = E.\Delta s.\cos\omega t \qquad \frac{d\gamma}{dt} = \frac{e\,\vec{\beta}\,.\,\vec{E}}{mc}$$

The sign of ΔW depends on the moment t when the electron arrives inside the cavity.
ΔW is modulated in time at a temporal period T = 2π/ω or spatial period λβ.
In average over the electrons, ΔW =0 since the electrons have different phases.



Drift section

Then, the electrons enter into the drift space),
The electrons accumulate in bunches.
The drift space length is adjusted to enable an optimal electron bunching.



Cavity 2

the electrons have the same phase with respect to the electromagnetic wave in the cavity, since they are bunched.
Second energy exchange :

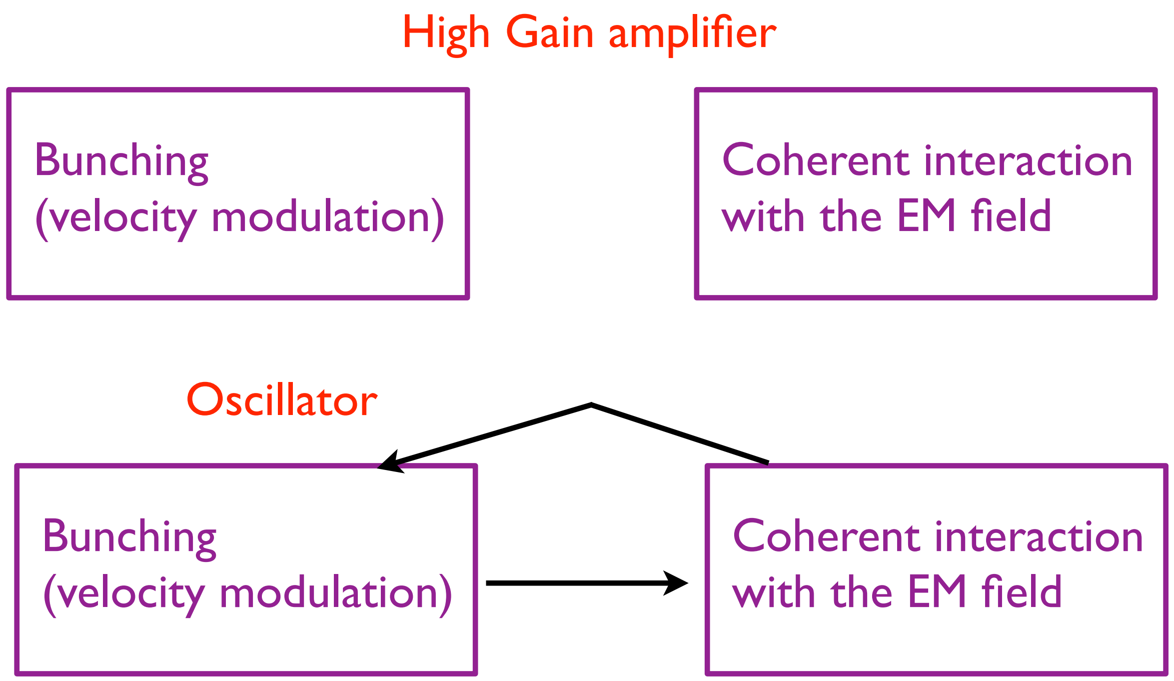
$$\Delta W_2 = \sum_{electrons} \int_0^{l_2} \vec{\beta}\,.\,\vec{E}\,dt = N_e E L_2 \cos\omega t$$

with N_e the number of electrons, L_2 the interaction region in the second cavity, E the electric field. The phase of the electrons in the second cavity is ruled by the electrons themselves.
The gain in electric field can be very high (10^3-10^6) .

R. H. Varian, S. F. Varian : A high frequency oscillator and amplifier. J. Appl. Phys. 10(5), 321–327 (1939)

I.4 : The development of vacuum tubes

Block diagram of the klystron



High Gain amplifier

Bunching (velocity modulation)

Coherent interaction with the EM field

Oscillator

Bunching (velocity modulation)

Coherent interaction with the EM field

- a block for the bunching,
- a block for the phased interaction with the field : a high intensity electron beam excites the RF wave in the second cavity.

The klystron can be operated in the oscillator mode with a feedback loop on the radiation.

In a klystron, the cavity and the waveguides should be of the order of the wavelength.
While looking for larger values of the frequency or for short wavelengths, the cavities and waveguides manufacturing thus limit the operation of the klystron to the microwave region.
=> Another system should be realised for the micrometer and submicrometer spectral ranges.

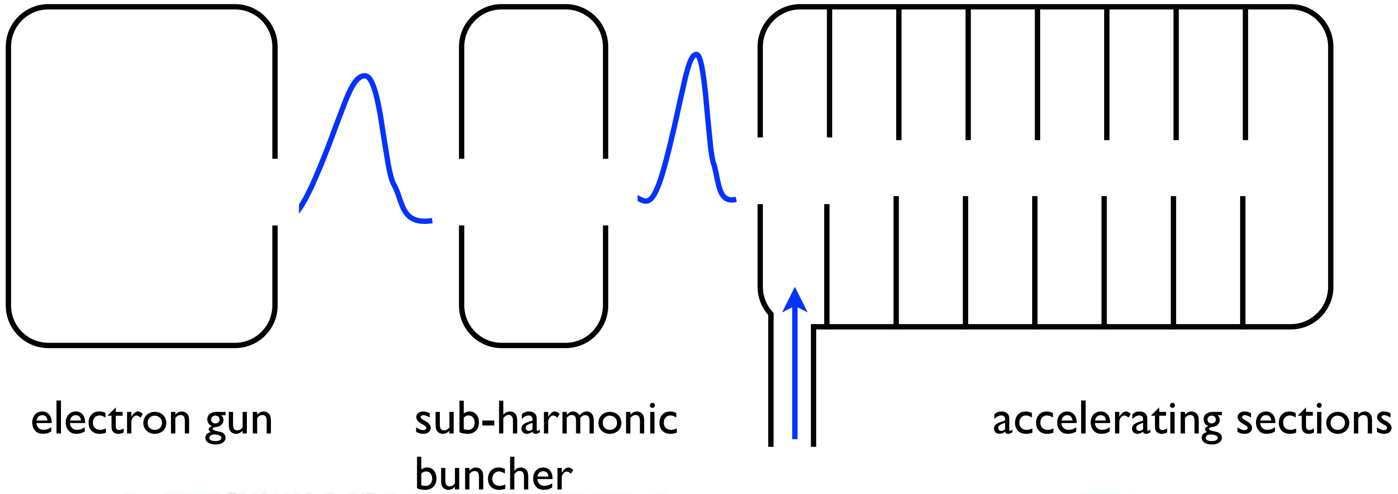
I.4 : The development of vacuum tubes

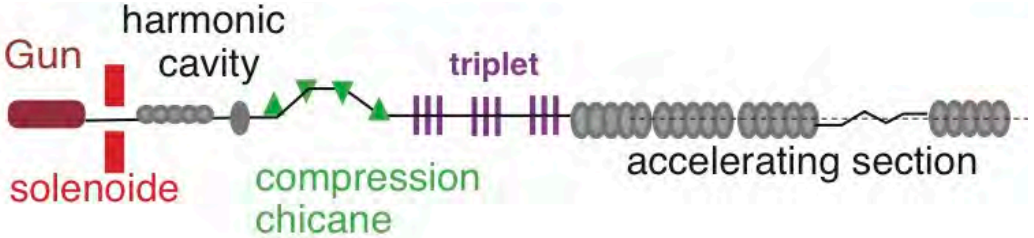
Example : the accelerator

More generally, an electron bunch can be accelerated or decelerated by an wave which period is longer than the electron bunch's one => principle of the linear accelerator

The electrons are produced in an electron gun : a thermo-ionic gun or with a photo-injector where the electrons are then generated in trains. With the conventional thermo-ionic gun, the electrons travel into the so-called buncher (a sub-harmonic or harmonic cavity) where the electrons travel on the edge of the RF wave, for acquiring energy spread and being bunched by the velocity modulation, as in the klystron case.

Then, the electron beam is accelerated by an intense RF wave produced by a klystron and sent in the cavities of the accelerating sections. The accelerating section can be considered as a series of coupled cavities or as a waveguide where irises slow down the phase of the RF wave so that it becomes equal to that of the electrons. In the accelerating sections, the electrons should have the same phase with respect to the RF wave. For being so, they are bunched in small bunches. For example, for a RF frequency of 1.3GHz, the period is of 0.77 ns, 1 phase corresponds to 2.1ps.





I.4 : The development of vacuum tubes

Vacuum tubes such as klystrons and magnetrons and more generally electronics, discovered at the end of the thirties, knew a wide development during the second world war with applications such as radiodiffusion, radar detection, where oscillators with high frequencies are needed.

The sources generally use electron beams submitted to electric or magnetic fields, where the ''bunching'' is the key concept for the wave amplification.

The use of resonant cavities at the frequency of the emitted wavelength can efficiently insure the retroaction needed for the production of a coherent wavelength.

=> This field of electronics enables to understand that in setting a loop on a wide band amplifier (in connecting one part of its output to its entry), on can transform it into a very monochromatic oscillator.

=> This concept will be used later for the maser and laser inventions.

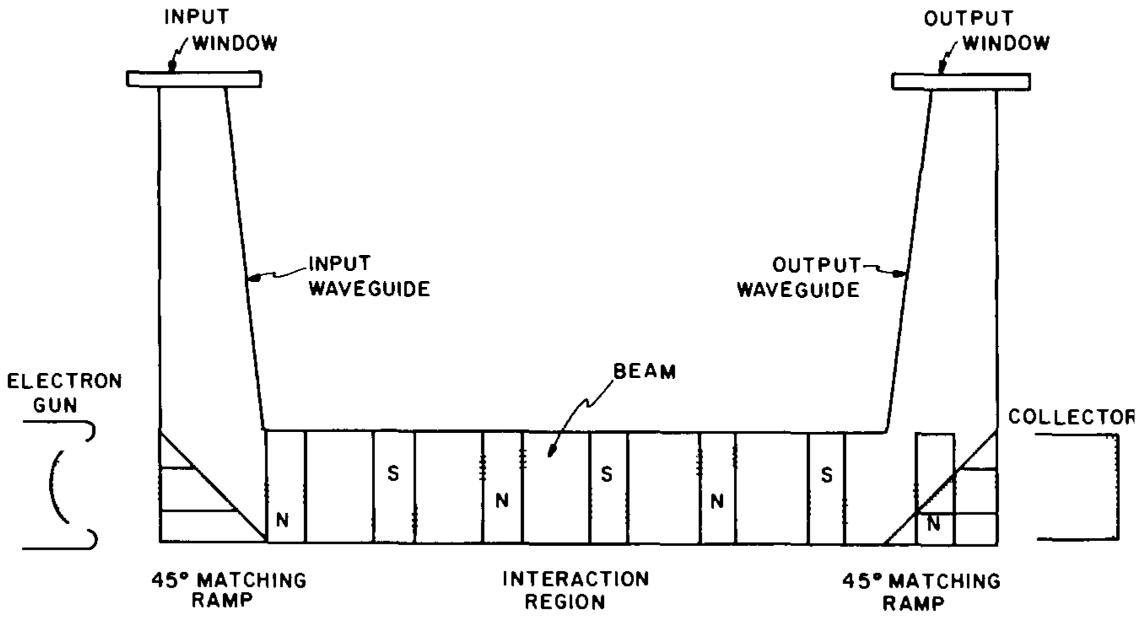
K. Landecker, Possibility of frequency multiplication and wave amplification by means of some relaticistic effects, Phys. Rev. 36 (6) (1952) 852-855J. Schneider, Stimulated emission of radiation by relativistic electrons in a magnetic field, Phys. Rev. Lett. 2(12) (1959) 504-505
R. H. Pantell, G. Soncini, H. E. Puthoff, Stimulated Photon-Electron Scattering, IEEE Jounral of Quantum Electronics 4 (11) 906-908 (1968)
R. B. Palmer, Interaction of relativistic particles and Free Electromagnetic waves in the presence of a static helical magnet, J. Appl. Phys. 43(7) (1972) 3014-3023
K.W. Robinson , Nucl. Instr. Meth. A239 (1985)
Csonka (1976)

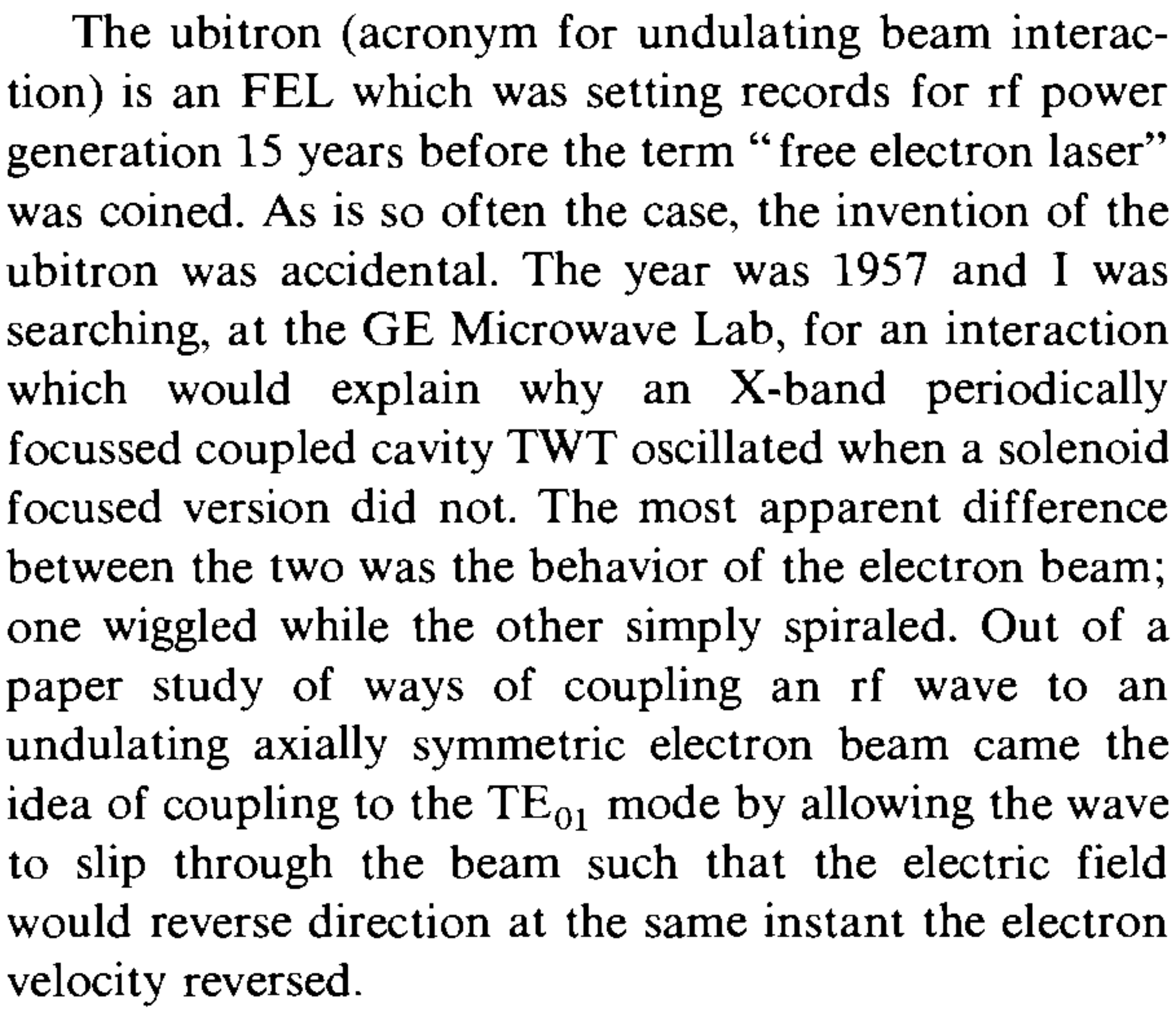
1.5 The ubitron : Undulating Beam Interaction

1960 : Combining Travelling Wave Tubes and undulators

The Ubitron :

high-power traveling-wave tube which makes use of the interaction between a magnetically undulated periodic electron beam and the TE01mode in unloaded waveguide.





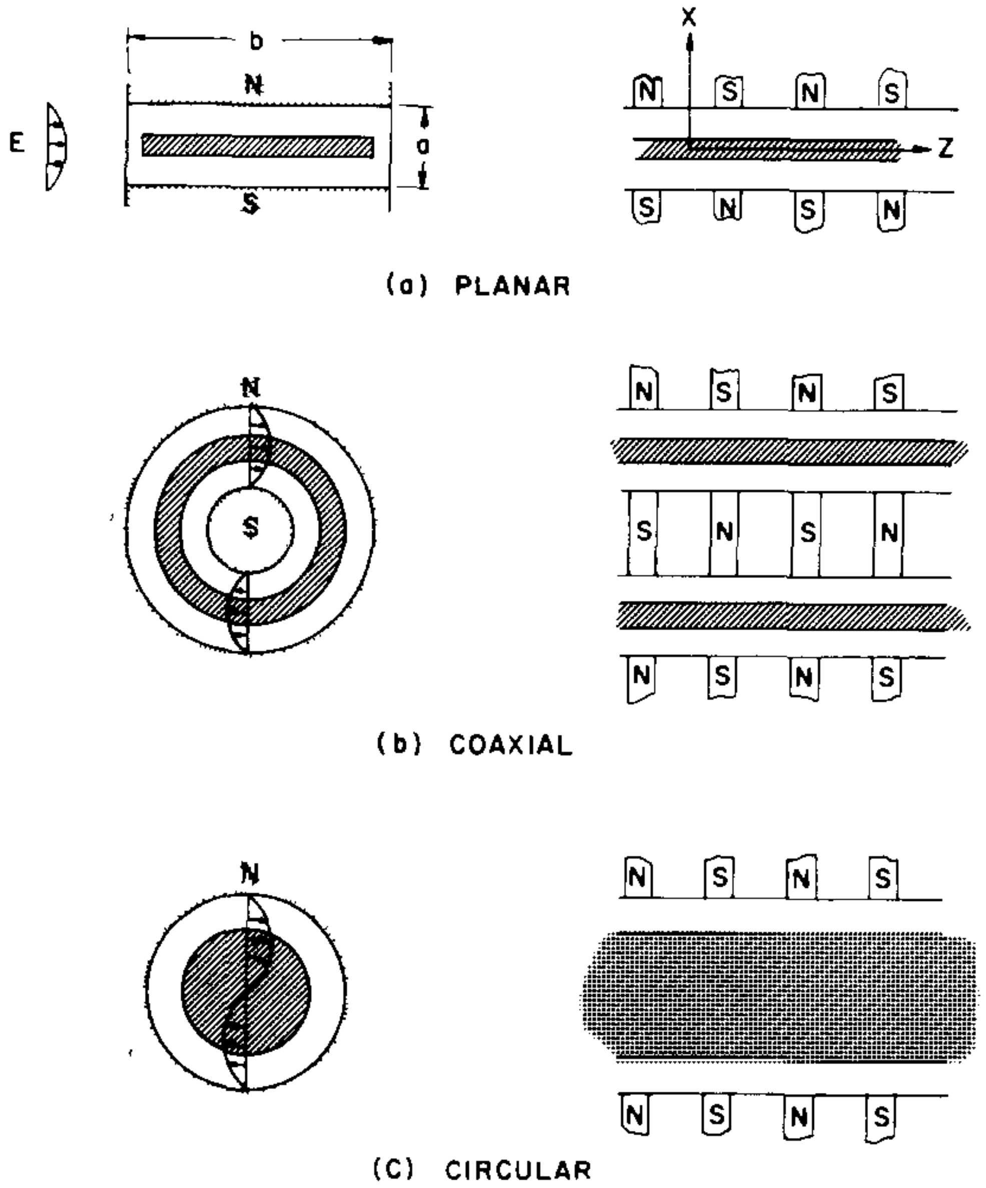
The ubitron (acronym for undulating beam interaction) is an FEL which was setting records for rf power generation 15 years before the term "free electron laser" was coined. As is so often the case, the invention of the ubitron was accidental. The year was 1957 and I was searching, at the GE Microwave Lab, for an interaction which would explain why an X-band periodically focussed coupled cavity TWT oscillated when a solenoid focused version did not. The most apparent difference between the two was the behavior of the electron beam; one wiggled while the other simply spiraled. Out of a paper study of ways of coupling an rf wave to an undulating axially symmetric electron beam came the idea of coupling to the TE_{01} mode by allowing the wave to slip through the beam such that the electric field would reverse direction at the same instant the electron velocity reversed.

R. M. Phillips, The Ubitron, a high-power traveling-wave tube based on a periodic beam interaction in unloaded waveguide, IRE Transactions on Electron Devices (Volume:7 , Issue: 4), 231 - 241 (1960)
R. M. Phillips, History of the ubitron, Nuclear Instruments and Methods in Physics Research A272 (1988) 1-9

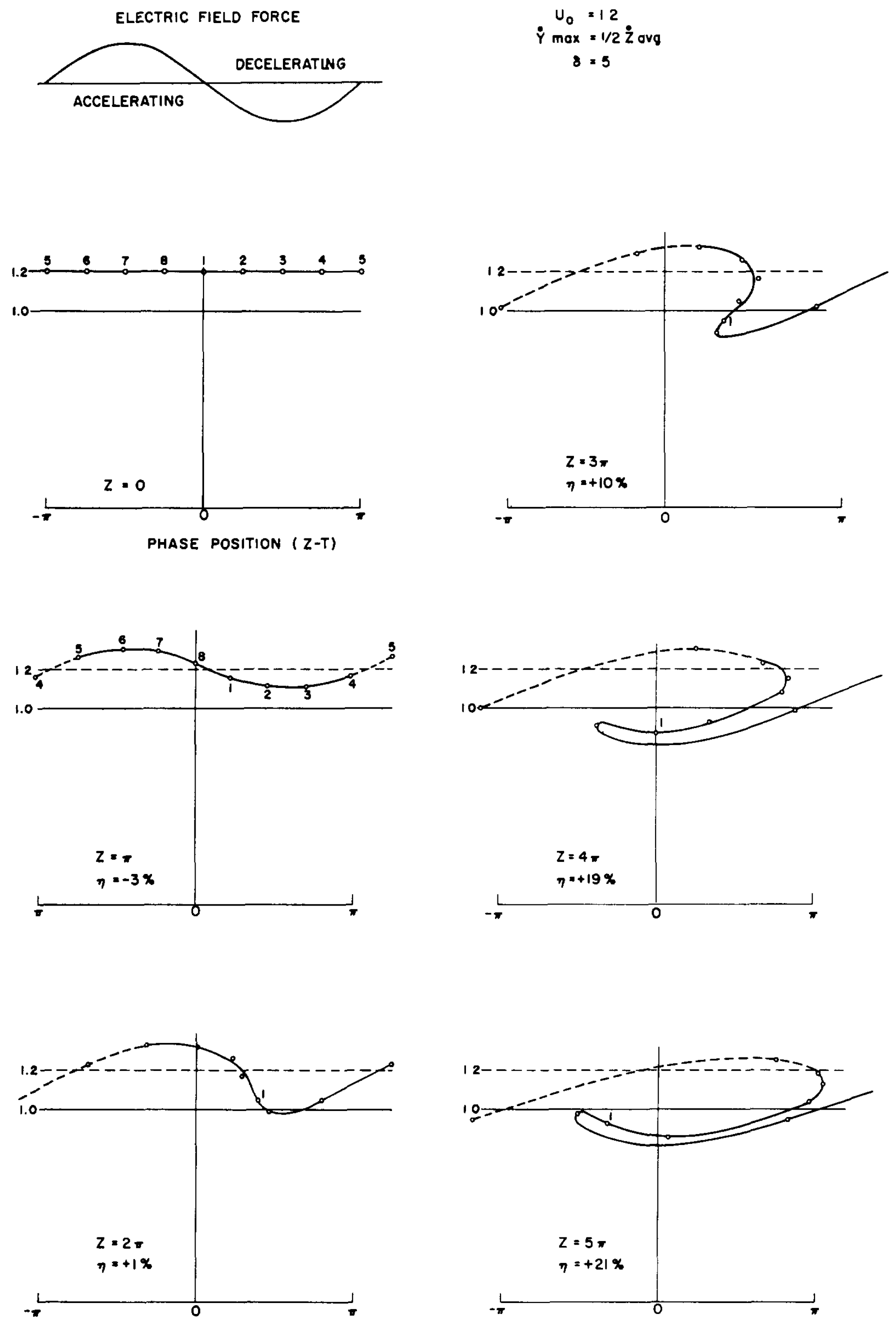
GE Microwave Lab

1.5 The ubitron : Undulating Beam Interaction

Idea :coupling to the TE01 mode by allowing the wave to slip through the beam such that the electric field would reverse direction at the same instant the electron velocity reversed.

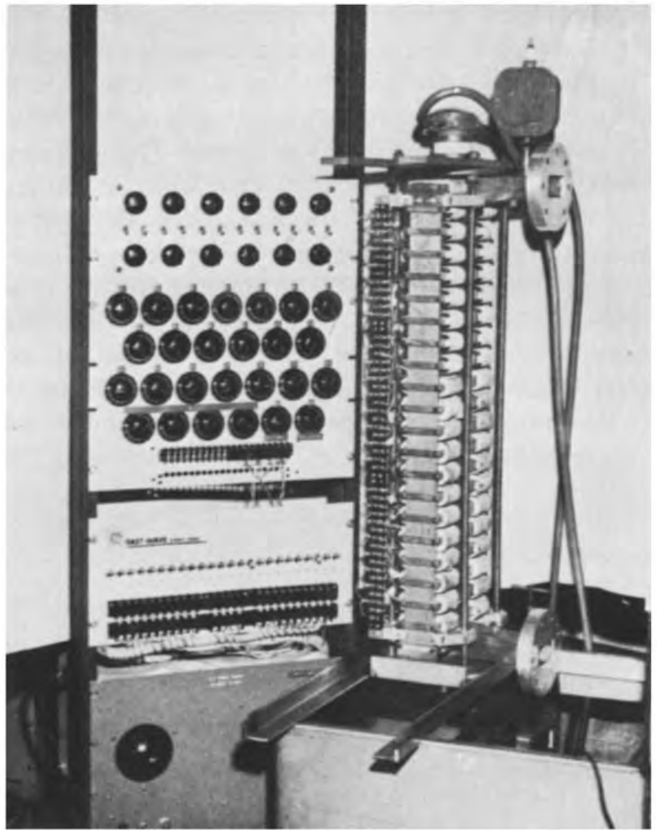


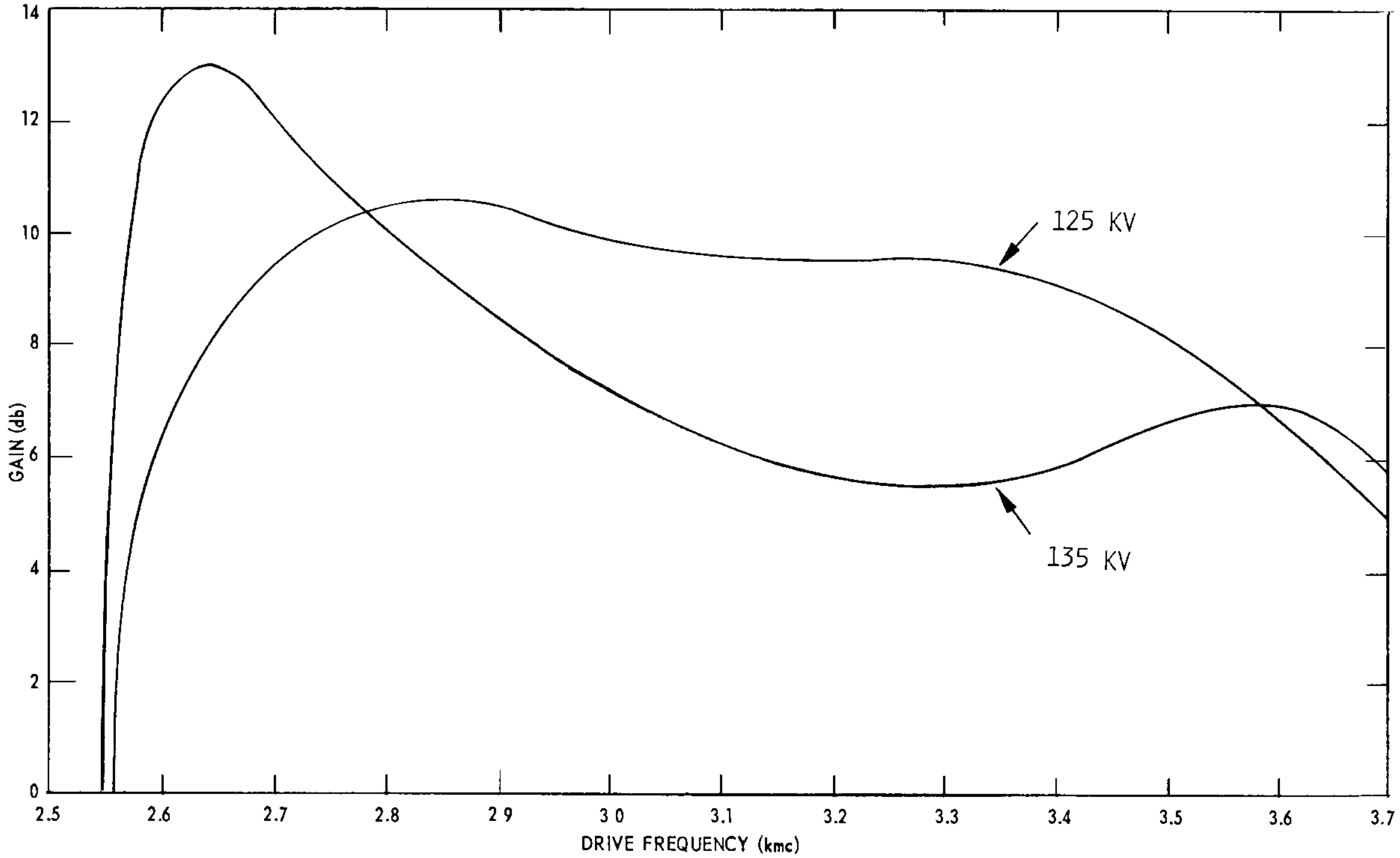
Examples of beam-guide ubitron configurations which provide100 times the interaction area of a TWT.



The electron-wave interaction exhibits the same type of first-order axial beam bunching characteristic of the conventional slow-wave traveling-wave tube
=> it can be used in extended interaction klystrons and electron accelerators, as well as traveling-wave tubes.

I.5 The ubitron : Undulating Beam Interaction





Experiments : an undulated pencil beam in a rectangular waveguide.

unique features :
- very broad interaction bandwidth which results from the absence of a dispersive slow-wave circuit,
- variable interaction phase velocity--hence, variable saturation power level.

Among the physical embodiments of the Ubitron are a number of higher-order mode waveguide and beam configurations.
=>interesting prospect for high-power millimeter wave amplification.

R. M. Phillips, The Ubitron, a high-power traveling-wave tube based on a periodic beam interaction in unloaded waveguide, IRE Transactions on Electron Devices (Volume:7 , Issue: 4), 231 - 241 (1960)
R. M. Phillips, History of the ubitron, Nuclear Instruments and Methods in Physics Research A272 (1988) 1-9

1.6 The maser discovery

Goal : create a «quantum» microwave sources in replacing the amplification by an electron beam by stimulated emission in molecules.
In order to do a "quantum" microwave oscillator, an excited molecules is introduced in a microwave cavity which is resonant for the frequency of the molecule transition.

Charles
Townes
(1905-2015)
Nobel 1964)

Nicolay
Gennadiyevich Basov
(1922-2001)
Nobel 1964

Aleksandr
Mikhailovich
Prokhorov
(1916-2002)
Nobel 1964

Population inversion:

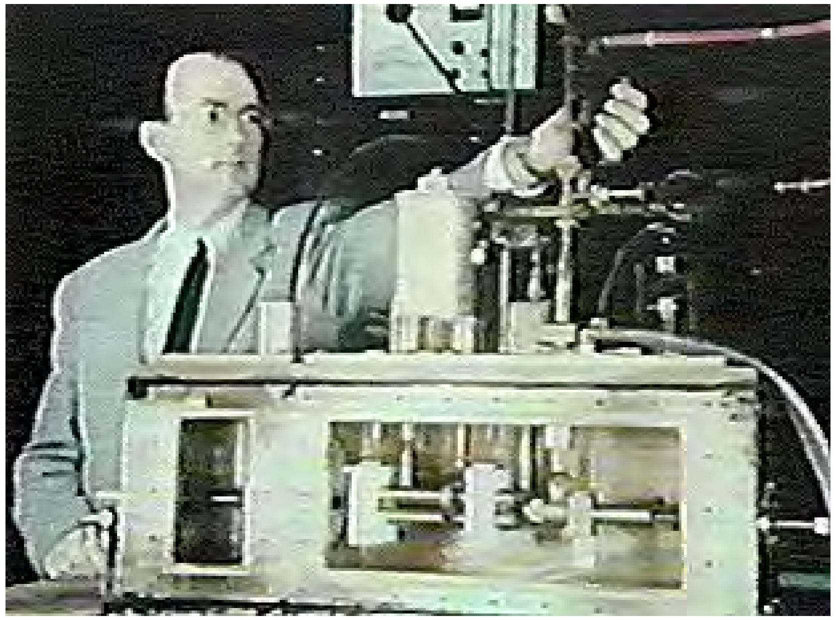
- Townes, Basov et Prokhorov : spatial separation of excited molecules (Stern-Gerlach type), efficient but not very practical.
- proper exciting radiation of the atoms and molecules.

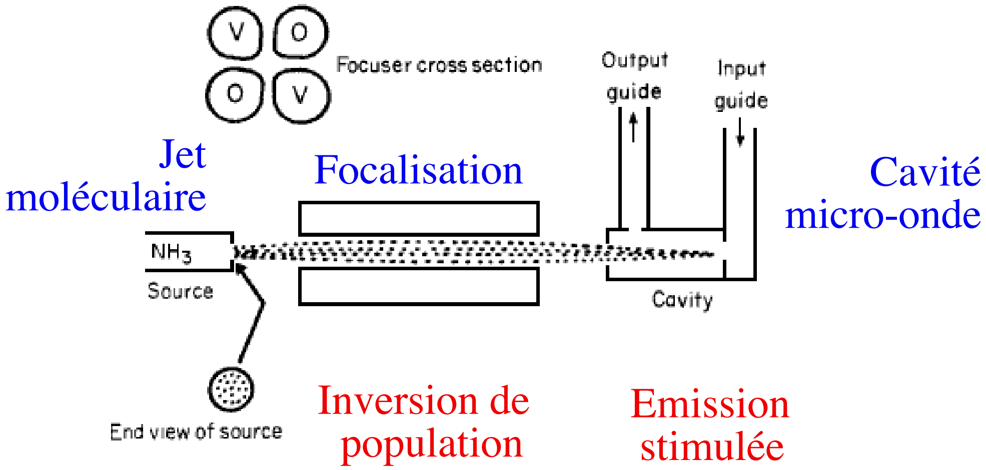
1949 : "optical pumping", with circularly polarised light for selectively filling some Zeeman sub-levels of atoms (Alfred Kastler (1902-1984, Nobel 1966) and Jean Brossel).

-1951, population inversion by RF radiation enabling to create samples of "negative temperature", (E. Purcell and R. Pound, working on Nuclear Magnetic Resonance)

A. Kastler
(1902-1984,
Nobel 1966)

1954 : first MASER in the micro-waves (NH_3 molecule).





Jet moléculaire

Focalisation

Cavité micro-onde

Inversion de population

Emission stimulée

Columbia University
J.P. Gordon, H. J. Zeiger and C.H. Townes, Phys. Rev., 95 (1954) 282.
J. P. Gordon, H. J. Zeiger and C. H. Townes, Phys. Rev., 99 (1955) 1264.

I. The origins of the Free Electron Laser

1.7 The laser discovery

1958 : principle of realisation of the laser by Charles Townes and Arthur Schawlow (1921-1999, Nobel 1981)

Charles Townes (1905-2015 Nobel 1964)

Arthur Leonard Schawlow (1905-1999 Nobel 1981)

Bell Tel. I.aboratories,

«The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light. For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical. Although use of a multimode cavity is suggested, a single mode may be selected by making only the end walls highly reflecting, and defining a suitably small angular aperture. Then extremely monochromatic and coherent light is produced. The design principles are illustrated by reference to a system using potassium vapor.»

A. L. Schawlow C. H. Townes, Infra-red and optical masers, Phys. Rev. Lett. 1940-1948 (1958)

Patent, Optical Masers and Communication, by Bell Labs.

I.7 The laser discovery

To shorten the wavelength, use a Fabry Perot type optical resonator

In order to achieve an optical maser, the maser cavity resonant on its fundamental mode would become extremely small (of the order of 1 micrometer) and becomes not doable at that time.

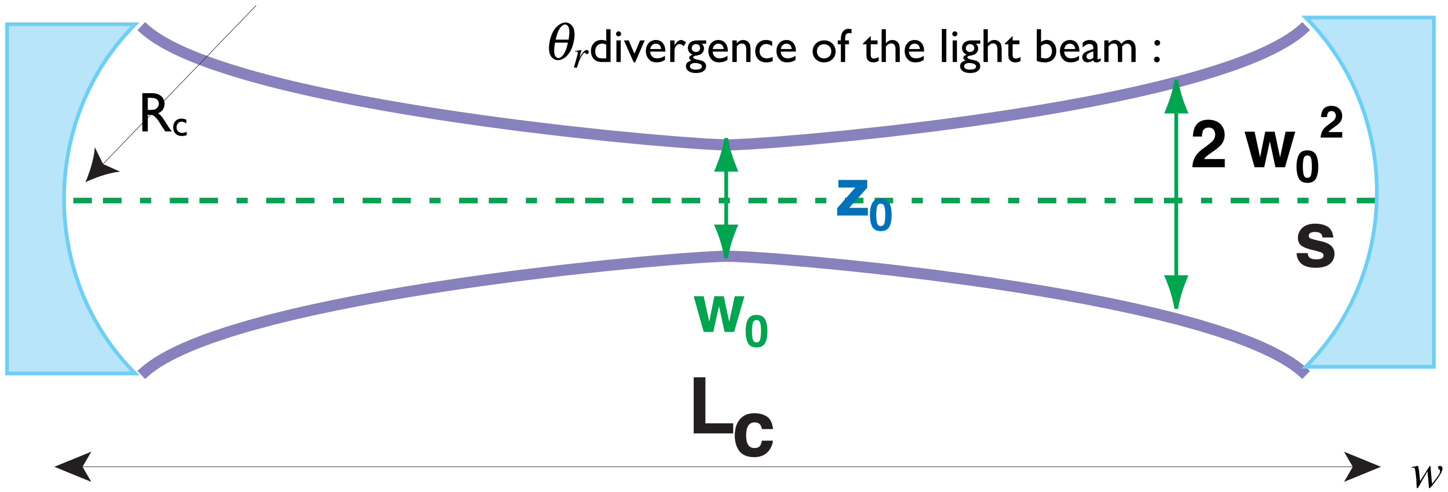
Condition for the light to interact at each pass with the amplifier medium:
the light should be in phase with the one from the previous pass :
the optical path for one round trip should be equal to an integer number p of wavelength λ

$$2L_c = p.\lambda$$

For a fixed cavity length L_c, only the wavelengths verifying $L_c = \frac{p.\lambda}{2}$ can be present in the "optical maser" light. The longitudinal modes associated to different values of p verifying this equation are called the longitudinal modes of the cavity.

The shift in frequency between two modes is given by :

$$\nu = \frac{c}{\lambda} = \frac{c}{2L_c}$$



$$w_0 = (\lambda/2\pi)^{1/2}\,[L_c(L_c-2R_c)]^{1/4}$$

$$w_0^2 \propto \lambda \qquad z_0 = \pi\, w_0^2/\lambda$$

$$w(s) = w_0\sqrt{1+\frac{s^2}{Z_R^2}} \qquad Z_R = \frac{\pi w_0^2}{\lambda} \qquad \theta_r = \frac{\lambda}{\pi w_0}$$

Case of a HeNe laser at 633nm, waist of 600 µm, Rayleigh length of the order of 2m. Over 2m propagation length, the light beam diameter remains practically constant. => The beam is very directional.

1.7 The laser discovery

1960 : First Ruby laser (Ion CR3+ in ruby)

Hughes Research Laboratories

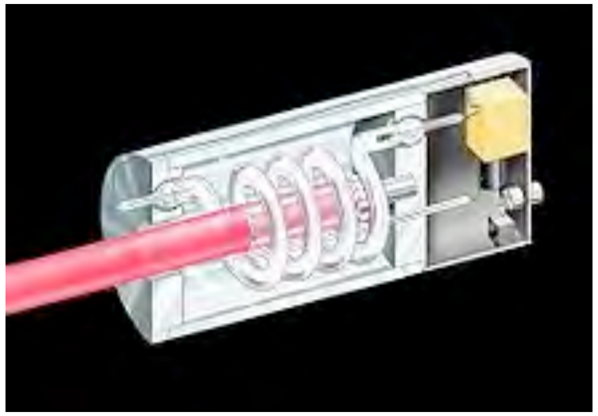
T.H. Maiman, Nature, 187 (1960) 493T. Maiman, Stimulated Optical radiation in Ruby, Nature 187, 493-494 (1960).
T. H. Maiman, Hoskins, D'Haenens, Asawa and Evtuhov, Phys. Rev., 123 (1961) 1151.

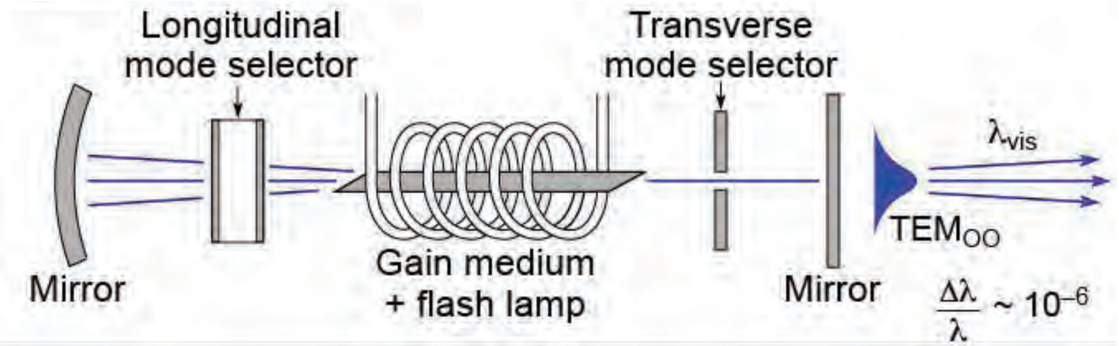
In 1954, N. Bloembergen, Basov and Prokhorov propose the 3-level MASER concept : with a proper illumination of a solid such as a Ruby crystal, population inversion takes place.

first working laser by generating pulses of coherent light from a fingertip-sized lump of ruby illuminated by a flash lamp

Easier to operate than the equivalent gas based maser. It has been used in particular as a very low noise amplifier.

Theodore Harold Maiman
(1927-2007)





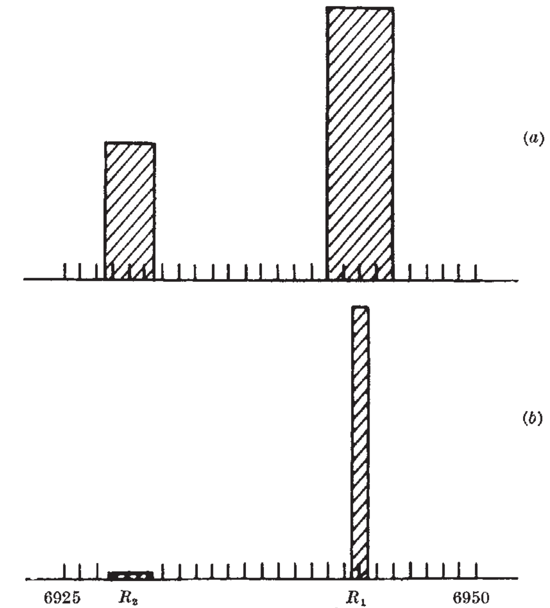


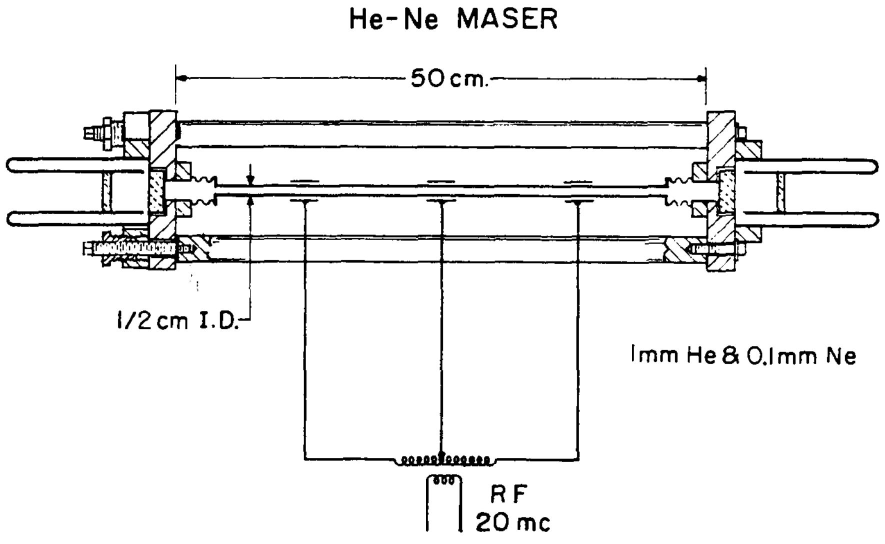
Fig. 2. Emission spectrum of ruby : *a*, low-power excitation ; *b*, high-power excitation

1.7 The laser discovery

1960: Ali Javan

first gas laser (He-Ne)

Gaseous discharge
CW source of infra red, 1 mW

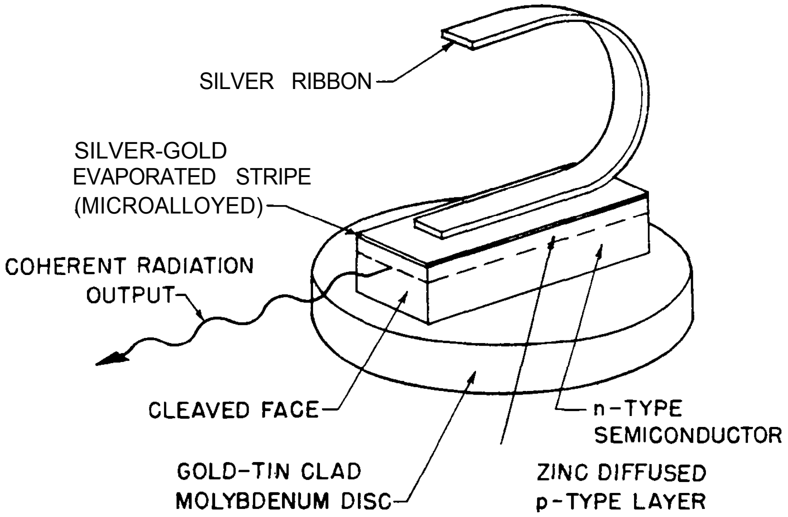


Javan, Bennett and Herriott, Phys. Rev. Letters, 6 (1961) 106.

1962 : R. Hall

first semi-conductor
AsGa laser (diode laser)

p-n junction of the semiconductor gallium arsenide through which a current is passed can emit near-infrared light from recombination processes with very high efficiency.



R. J. Keyes and T.M. Quist, Proc. IEEE (Inst. Electron. Elec. Engrs.), 50 (1962) 1822.
Hall, Fenner, Kingsley, Soltys and Carlson, Phys. Rev. Letters, 9 (1962) 366.

1966: Mirek Stevenson and Peter Sorokin at General Electric
first dye laser
tuneable yellow to red

....

1971: Concept of the Free Electron Laser
1977 : First FEL in the IR (Stanford, USA)
1983 : First FEL in the visible (Orsay, France)

I.7 The laser discovery

The limitations of the «optical maser»

«As one attempts to extend maser operation towards very short wavelengths, a number of new aspects and problems arise, which require a quantitative reorientation of theoretical discussions and considerable modification of the experimental techniques used.»

...

«These figures show that maser systems can be expected to operate successfully in the infrared, optical, and perhaps in the ultraviolet regions, but that, unless some radically new approach is found, they cannot be pushed to wavelengths much shorter than those in the ultraviolet region.»

A. L. Schawlow and C. Townes, Infra-red and Optical masers», Phys. Rev. 112 1940 (1958)

II. The invention of the Free Electron Laser concept

II.1 The FEL concept emergence : Motivations for an exotic laser

«Schawlow and Townes' descriptions of masers and lasers coupled with the new understanding of the Gaussian eigenmodes of free space offered a new approach to high frequency operation that was not constrained by the established limits to the capabilities of electron tubes»

- Was there a Free Electron Radiation Mechanism that Could Fulfill these Conditions?

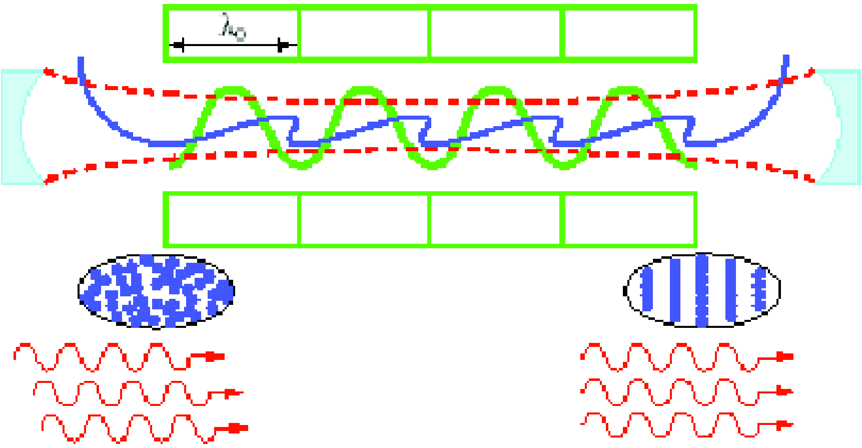
Compton Scattering Appeared as the Most Promising Candidate

Benefit of using relativistic electrons beams:

=> Strong periodic field
 Undulator
- tuneability

$$E_{CBS} = \frac{4\gamma^2 E_{ph}}{1+(\gamma\theta)^2}$$

$$n\lambda_n = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K_u^2}{2}+\gamma^2\theta^2\right)$$



Need of high peak current = > electron beam sources

=> FEL concept

Can gain be achieved with such a system?

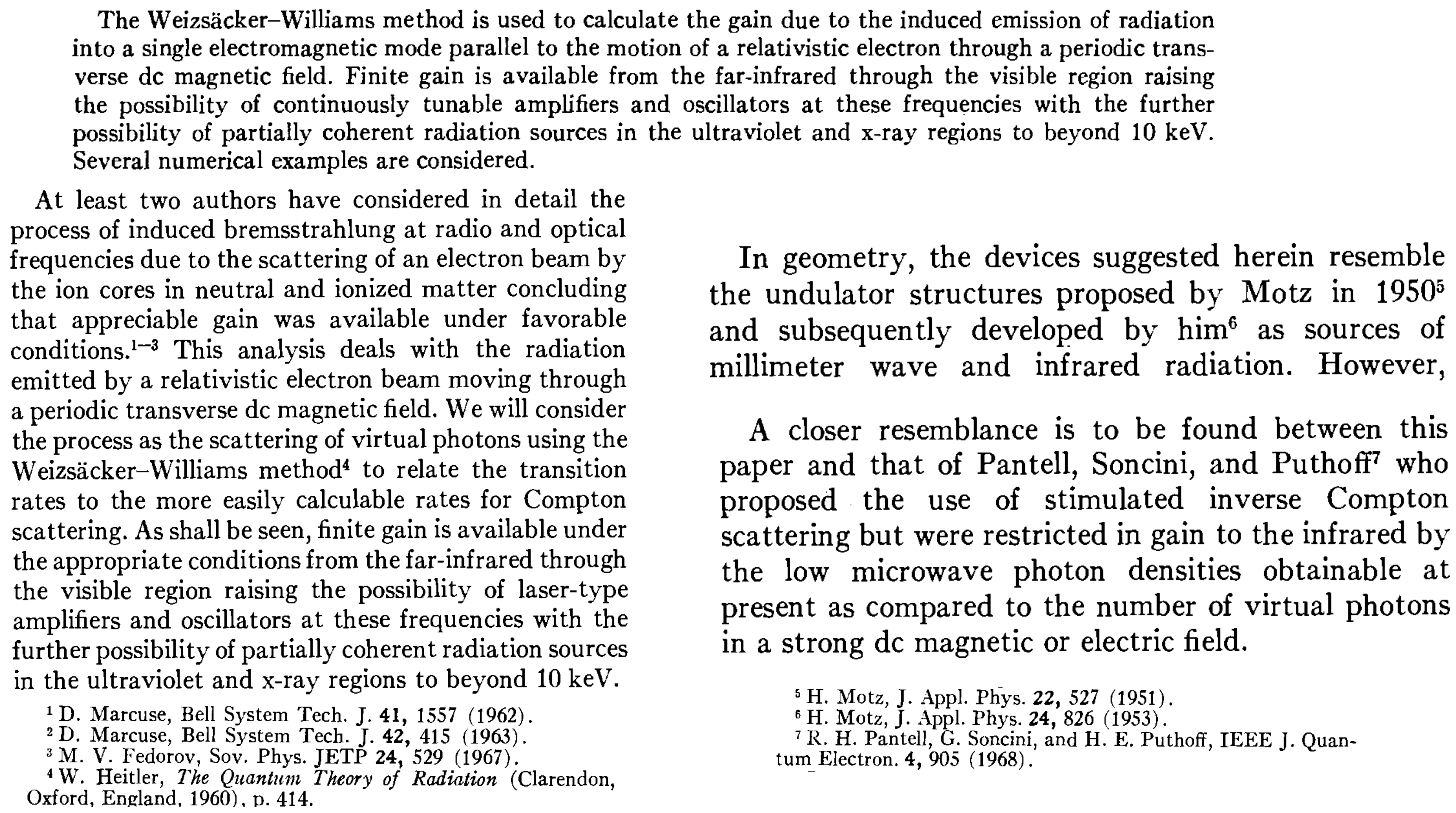
J. M. J. Madey, Nobel Symposium, Sigtuna, Sweden, June 2015
J. M. J. Madey, Wilson Prize article: From vacuum tubes to lasers and back again, Phys. Rev. ST Accel. Beams 17, 074901 (2014)

II. The invention of the Free Electron Laser concept

II.2 The FEL quantum approach

J. M. J. Madey.: Stimulated emission of Bremmstrahlung in a periodic magnetic field; J. Appl. Phys., 42, 1906–1913 (1971)

Stimulated emission of Bremmstrahlung :



The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

At least two authors have considered in detail the process of induced bremsstrahlung at radio and optical frequencies due to the scattering of an electron beam by the ion cores in neutral and ionized matter concluding that appreciable gain was available under favorable conditions.[1–3] This analysis deals with the radiation emitted by a relativistic electron beam moving through a periodic transverse dc magnetic field. We will consider the process as the scattering of virtual photons using the Weizsäcker–Williams method[4] to relate the transition rates to the more easily calculable rates for Compton scattering. As shall be seen, finite gain is available under the appropriate conditions from the far-infrared through the visible region raising the possibility of laser-type amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV.

[1] D. Marcuse, Bell System Tech. J. **41,** 1557 (1962).
[2] D. Marcuse, Bell System Tech. J. **42,** 415 (1963).
[3] M. V. Fedorov, Sov. Phys. JETP **24,** 529 (1967).
[4] W. Heitler, *The Quantum Theory of Radiation* (Clarendon, Oxford, England, 1960), p. 414.

In geometry, the devices suggested herein resemble the undulator structures proposed by Motz in 1950[5] and subsequently developed by him[6] as sources of millimeter wave and infrared radiation. However,

A closer resemblance is to be found between this paper and that of Pantell, Soncini, and Puthoff[7] who proposed the use of stimulated inverse Compton scattering but were restricted in gain to the infrared by the low microwave photon densities obtainable at present as compared to the number of virtual photons in a strong dc magnetic or electric field.

[5] H. Motz, J. Appl. Phys. **22,** 527 (1951).
[6] H. Motz, J. Appl. Phys. **24,** 826 (1953).
[7] R. H. Pantell, G. Soncini, and H. E. Puthoff, IEEE J. Quantum Electron. **4,** 905 (1968).

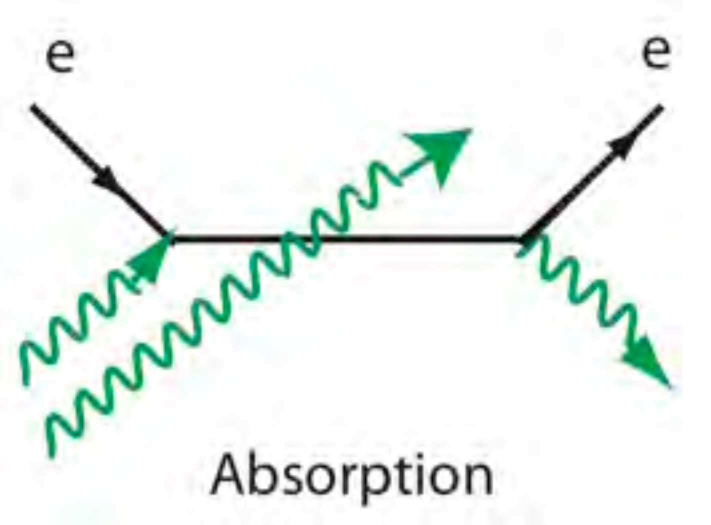
II.2 The FEL quantum approach

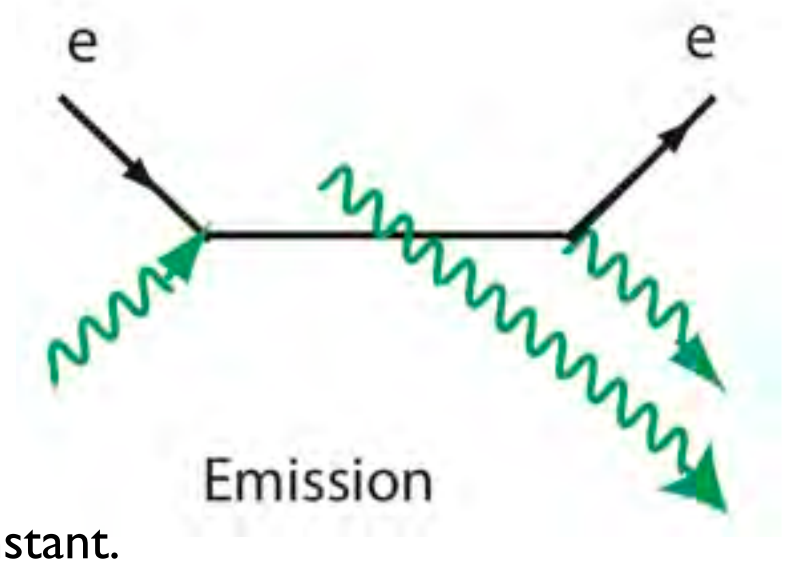
J. M. J. Madey.: Stimulated emission of Bremmstrahlung in a periodic magnetic field; J. Appl. Phys., 42, 1906–1913 (1971)
J. M. J. Madey, H.A. Schwettman, W. M. Fairbank, IEE Trans. Nucl. Sci. NS-20 (1973) 980

Virtual photons : associated to the magnetic field
Weisäcker-Williams approximation:
Undulator : similar to the field of a planar wave of wavelength ; λ_u

Fields in the moving frame of the electrons in the undulator
Undulator wavelength in the electron 's frame : $\lambda_u/\Upsilon_s = \lambda'$
the electrons see the magnetic field as a planar wave

$$\lambda' = \frac{\lambda_u}{\gamma_s}$$





Photon emission / absorption forbidden due to the conservation of energy and momentum
=> for free electrons : two photon process: Compton scattering

emission :
Doppler effect $\lambda = \lambda' / (1 + \beta_s) \Upsilon_s = \lambda_u / 2 \Upsilon_s^2 = \lambda_u / 2 \Upsilon^2$

Stimulated Compton scattering
gain : transition rate(diffusion) - transition rate (absorption)

does not depend on Planck constant.

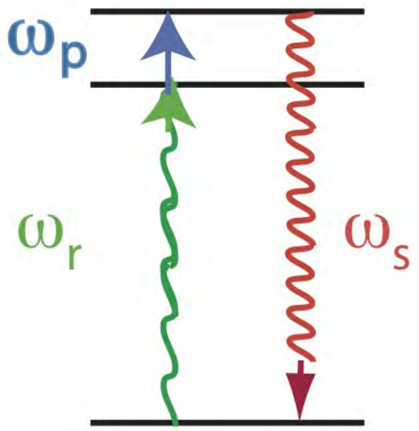
E. Schrödinger, Annalen der Physik IV, Folge 82, 257 (1927)
P. L. Kapitza, P.A. M.ab Dirac, Proc. Cambridge Phys. Soc. 29, 297 (1933)
H. Dreicer, Phys. Fluids 7 (1964) 735
R. H. Pantell, G. Soncini, H. E. Puthoff, Stimulated Photon-Electron Scattering, IEEE Jounral of Quantum Electronics 4 (11) 906-908 (1968)

II.3 The FEL regimes

Compton regime

The scattered wavenumber ks′ equals the incident wavenumber ki′:

$$k_s' = k_i'$$



Raman regime

the scattered wavenumber ks′ is the sum / difference of the incident wavenumber ki′ and of the plasma wavenumber kp, leading to the Stockes and anti-Stockes lines

$$k_s' = k_i' \pm k_p'$$

$$\omega_s = \omega_i \pm \omega_p$$

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_o m_o \gamma^3}} = \sqrt{\frac{J_e e}{\varepsilon_o m_o c \gamma^3}} \qquad J_e = n_e e c\ .$$

Practically, one considers that the FEL is in the plasma regime if the number of plasma oscillation Np done by the electron while it travels into the undulator is at least one.

$$N_p = \frac{N_u \lambda_u}{\lambda_p} = \frac{N_u \lambda_u \omega_p}{2\pi c} = \frac{N_u \lambda_u}{2\pi c}\sqrt{\frac{J_e e}{\varepsilon_o m_o c \gamma^3}}$$

$$N_p > 1 \quad \text{if} \quad J_e < \frac{4\pi^2 \varepsilon_o m_o c^3 \gamma^3}{e N_u^2 \lambda_u^2}$$

M. Kroll, P. L. Morton, M. N. Rosenbluth, Stimulated emission from relativistic electrons passing through a spatially periodic transverse magnetic field., Phys. Rev A 17 (1978) 300

II.3 The FEL classical approach

Weizsäcker-Williams approximation :

for extreme relativistic limit : the static undulator field of period λ_u replaced by a pure electromagnetic field of wavelength

$\lambda_i = (1 + \beta_s)\,\lambda_u \approx 2\lambda_u$

transverse current J_t

electron motion : collisionless relativistic Boltzmann equation, with P the canonical momentum, x the position

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{x}_i \frac{\partial f}{\partial x_i} + \dot{P}_i \frac{\partial f}{\partial P_i} = 0,$$

Case of a pure transverse electromagnetic field
=> Usual classical scattering problem, complicated by the relativistic nature of the particles

Relevant radiation :
back scattered, with a Doppler shift of the wavelength

Maxwell equations

Development of the reduced distribution in perturbations
small-signal theory : incident and scattered modes are kept

reduced distribution in Maxwell eq.
=>small signal gain

New hyp :
- slowly varying amplitude and phase
- depletion of the incident field neglected

=> electron density fluctuations (bunching) responsible for the scattering

$$\Delta\omega = \omega_s - \omega_i,$$

$$K = k_s + k_i,$$

$$\mu = \Delta\omega / v_z - K.$$

$$\alpha \simeq 64\pi^2 r_0^2 \mathfrak{F} \frac{n_e}{m c_2} \frac{k_i^{1/2}}{k_s^{3/2}} L^2 I_i \frac{d}{d\eta} (\sin\eta/\eta)^2$$

$\eta=0$: no net gain
$\eta<0$: $v>v_o$, gain, eq. of Stockes line in Raman scattering
$\eta>0$: $v>v_o$, absorption, eq. of anti- Stockes line

The Gain is produced by a bunching of the electronic density in presence of a field

F.A. Hopf, P. Meystre, M. O. Scully, W. H. Louisell, Classical theory of a Free Electron Laser, Opt. Comm. 18 (4) (1976) 413-416
F.A. Hopf et al., Classical theory of a free-electron laser, Phys. Rev. Lett 57 (18) 1215-1218 (1976);

II.3 The FEL classical approach

Appropriate magnetic field description

Studies on radiation from electrons traveling through a static transverse periodic magnetic field : classical, semiclassical, and quantum field theories.

Stimulated emission rates and laser evolution equations describing exponential gain and saturation.

One-body classical Lorentz force equation in the presence of periodic magnetic field and a plane electromagnetic wave.

Phase space paths for electrons are related to those of a simple pendulum and describe laser gain, saturation, and coherent electron beam modulation.

A single particle classical theory : amplification due to the single electron stimulated Thomson scattering.

necessary tool for the description of the electron dynamics in a storage ring with a free electron laser device.

Saturation : Jacobi elliptical functions

W. B. Colson, Theory of a Free Electron Laser, Phys. Lett. 59A, 187 (1976)

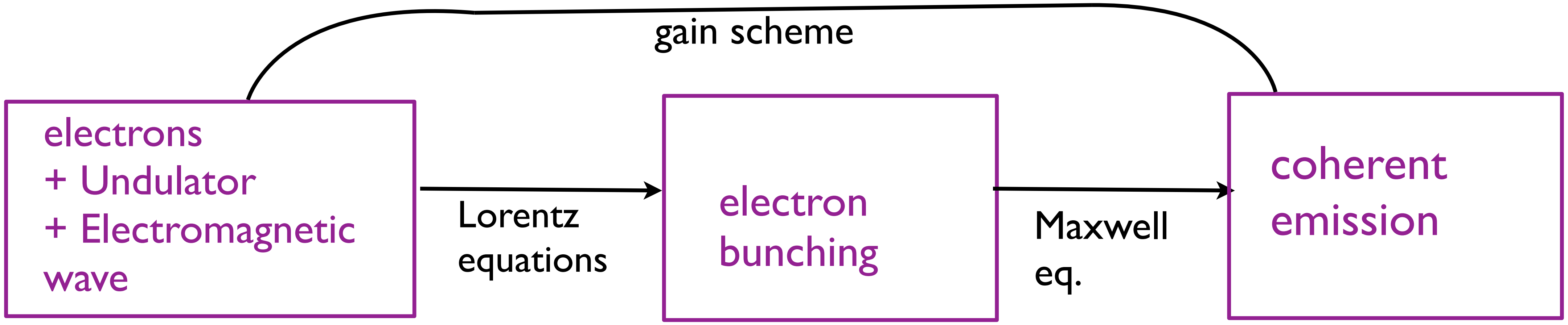
W. B. Colson, One body electron dynamics in a free electron laser, Phys. Lett. 64A (2), 190-192 (1977)

W. H. Louisell, J. F. Lam, D. A. Copeland, W. B. Colson, "Exact" classical electron dynamic approach for a free-electron laser amplifier, Phys. Rev. A 19 (1) (1979) 288-300

W. B. Colson, C. Pellegrini, and A. Renieri, editors for the "Free Electron Laser Handbook", North-Holland Physics, Elsevier Science Publishing Co. Inc., The Netherlands (1990).

A. Bambini, A. Renieri , The free electron laser : A single particle classical model, Lett. Nuovo Cimento 21, 399-404 (1978)

A. Bambini, A. Renieri , S. Stenholm, Classical theory of a free electron laser in a moving frame, Phys. Rev. A 19, 2013-2025 (1979)



gain scheme

electrons
+ Undulator
+ Electromagnetic wave

Lorentz equations

electron bunching

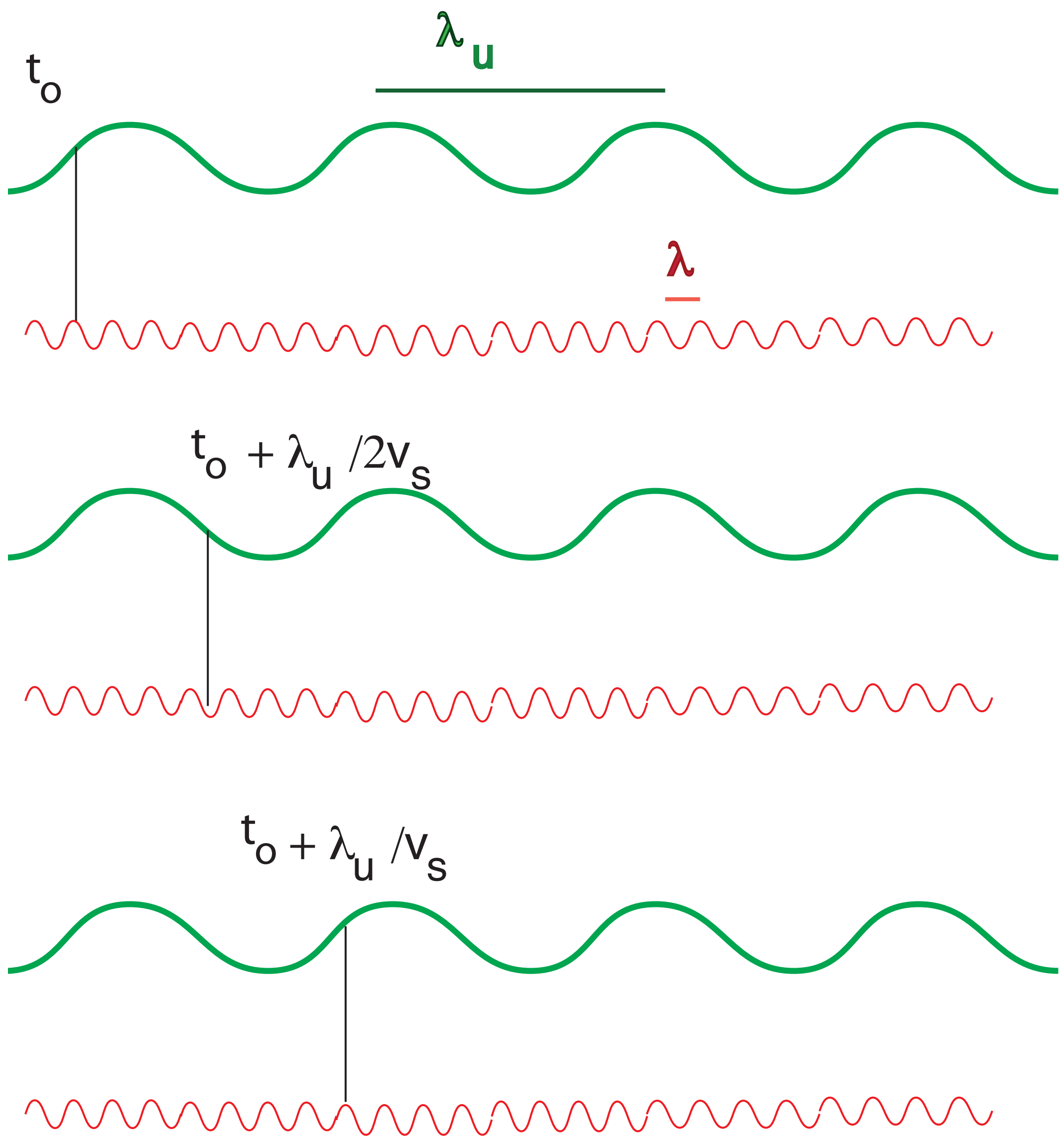
Maxwell eq.

coherent emission

II.3 The FEL classical approach

The resonance

Consider a plane wave travelling in the same direction as the electron, with its electric field in the trajectory plane.
The electron is resonant with the wave if :
while the electron progresses by λ_u, the wave has travelled by $\lambda_u + \lambda$, $(\lambda_u + n\lambda)$



$$\frac{\lambda_u}{v_s} = \frac{\lambda_u + n\lambda_r}{c}$$

$$n\lambda_n = c(1-\beta_s)t$$

$$\lambda_r = \frac{\lambda_u}{n}(\frac{1}{\beta_s} - 1) = \frac{\lambda_u}{n}\frac{1-\beta_s}{\beta_s}) = \frac{\lambda_u}{n}(\frac{(1-\beta_s)(1+\beta_s)}{\beta_s(1+\beta_s)} = \lambda_u\frac{1-\beta_s^2}{\beta_s(1+\beta_s)}$$

Planar

$$\boxed{n\lambda_n = \frac{\lambda_u}{2\gamma^2}(1+\frac{K_u^2}{2})}$$

$$\boxed{\delta W = \overrightarrow{E}\,\overrightarrow{v}\,dt}$$

velocity // E

Helical

$$\boxed{\lambda_r = \frac{\lambda_u}{2n\gamma^2}(1+K_u^2)}$$

II.3 The FEL classical approach

Energy exchange => bunching => amplification

Light wave-electron interaction

The amplitude of the interaction only depends on the longitudinal position of the electron in the electron bunch with the periodicity λ_r.
The electron tend to bunch along given positions, separated by λ_r.

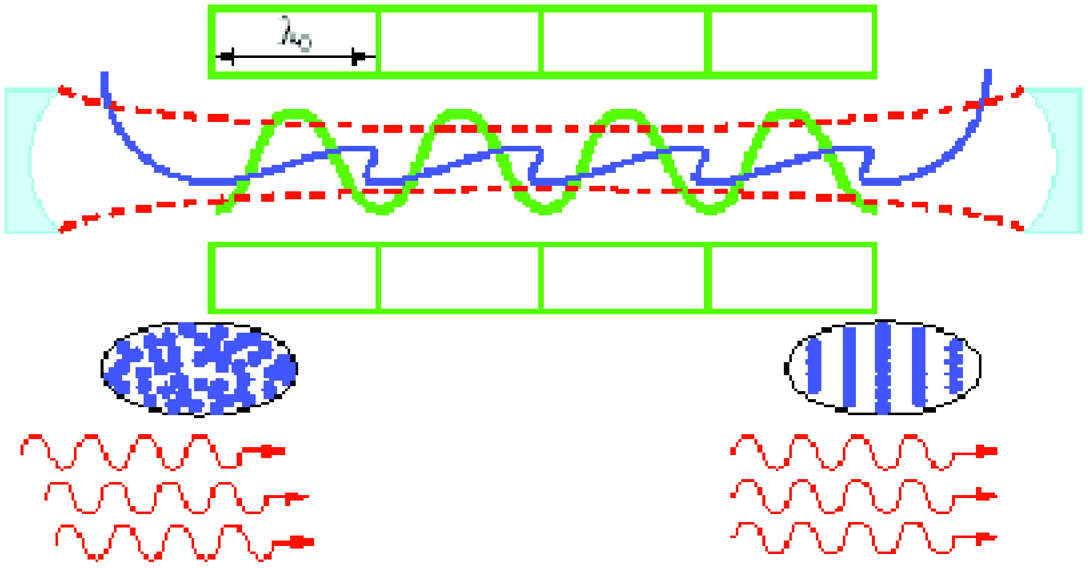
Bunching (λ_r separation) takes place by velocity modulation (electrons set in phase).

$\vec{E}\,\vec{v}$=0 for $\lambda = \lambda_r$, there is no average energy exchange at first order: half of the electron gain energy, half of them loose energy

For the interation to occur, λ should be slightly different from λ_r :
one finds that for $\lambda > \lambda_r$ amplification (gain and beam deceleration)
for $\lambda < \lambda_r$ absorption (beam acceleration)

Optical feedback with an optical cavity

The FEL oscillator :
the historical configuration
optical multi-pass, low gain regime



$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad K = 0.94\,\lambda_0\,(\mathrm{cm})\,B_0\,(\mathrm{T})$$

$G \alpha L_{ond}^2/\Upsilon^3$

M. E. Couprie, CAS School Free Electron Lasers and Energy Recovery Linacs (FELs and ERLs), Hamburg, Germany, 31 May –10 June, 2016

II. The invention of the Free Electron Laser concept

II.3 The FEL classical approach

Gain expression

Small signal gain :

$$\boxed{G = n\frac{2\pi e^2}{\varepsilon_o m_o c^2}\rho_e \frac{K_u^2}{\lambda_u}\left(\frac{L_u}{\gamma}\right)^3 \left[J_{\frac{n-1}{2}}(\xi) - J_{\frac{n+1}{2}}(\xi)\right]^2 \frac{\partial}{\partial\gamma}\mathrm{sinc}^2(\pi N_u \eta)}$$

Depending on the sign of ($\lambda - \lambda_r$), the optical wave is either absorbed to the benefit of a gain of kinetic energy of the electrons, or is amplified to the detriment of the kinetic energy of the electrons.

G varies as the inverse of the cube of the energy. The higher the energy, the lower the gain. But, according to the resonance condition, short wavelength operation requires the use of high electron beam energies. In consequence, for a same undulator length, the gain is smaller at short wavelengths than at longer ones.

The gain is proportional to the electronic density. The more electrons interact, the larger the gain. For short wavelength FELs where the gain is naturally small, one should employ beams with high electronic densities.

The gain is proportional to the beam current.

The gain is proportional to the third power of the undulator length, it seems that the longer the undulator, the higher the gain. As the undulator length, the gain width also decreases by $1/nN_u$, because of the interference nature of the interaction. Temporally, the light pulse should remain in the longitudinal bunch distribution, for the interaction to occur. Similarly, both the optical light and electron bunch should overlap properly all long the undulator propagation.

To account for these effects, let's introduce some correction factors in the gain.

II.3 The FEL classical approach
Gain correction terms

- Transverse filling factor : Non perfect transverse overlap between the laser transverse modes (TEM00 mode of waist w_o) and the transverse dimensions of the electron beam σ_x and σ_z.

$$F_f = \frac{1}{\sqrt{1+(\frac{w_o}{2\sigma_x})^2}\sqrt{1+(\frac{w_o}{2\sigma_z})^2}}$$

- «Inhomogeneous reduction» : According the the Madey's theorem, spontaneous emission broadening due to energy spread and emittance affect directly the gain.

Homogeneous linewidth

$$(\frac{\Delta\lambda}{\lambda_n})_{hom} = \frac{1}{nN_u}$$

Inhomogeneous contributions

- Electron beam emittance

$$(\frac{\Delta\lambda}{\lambda_n})_{div} = \frac{\gamma^2\theta^2}{1+\frac{K_u^2}{2}} \qquad (\frac{\Delta\lambda}{\lambda_n})_{\sigma} = \frac{2\pi^2 K_u^2}{1+K_u^2}\frac{\sigma^2}{\lambda_u^2}$$

- Electron energy spread

$$(\frac{\Delta\lambda}{\lambda_n})_{\sigma_\gamma} = \frac{2\sigma_\gamma}{\gamma}$$

$$F_{inh} = \left[1+\frac{(\frac{\Delta\lambda}{\lambda_n})^2_{\sigma_\gamma}}{(\frac{\Delta\lambda}{\lambda_n})^2_{hom}}\right]^{-1} \cdot \left[1+\frac{(\frac{\Delta\lambda}{\lambda_n})^2_{div}}{(\frac{\Delta\lambda}{\lambda_n})^2_{hom}}\right]^{-1} \cdot \left[1+\frac{(\frac{\Delta\lambda}{\lambda_n})^2_{\sigma}}{(\frac{\Delta\lambda}{\lambda_n})^2_{hom}}\right]^{-1}$$

- Longitudinal overlap : between the electron bunch of RMS length σ_l and the optical wave should be be maintained. The light wave in in advance by $N_u\lambda_u$ with respect to the electrons, and for short electron bunch distributions, it could escape.

$$F_g = \left[1+\frac{N_u\lambda_u}{\sigma_l}\right]^{-1}$$

$$G = n\frac{\pi^2 r_o \lambda_u^2 N_u^3 K_u^2}{\gamma^3} F_f F_{inh} F_g \rho_e \left[J_{\frac{n-1}{2}}(\xi) - J_{\frac{n+1}{2}}(\xi)\right]^2 \frac{\partial}{\partial\gamma}\mathrm{sinc}^2(\pi N_u \eta)$$

II.3 The FEL classical approach

Saturation

- Electron beam energy loss (unsatisfied resonant condition)

- energy exchange
- (spontaneous emission)

- Increase of energy spread

intuitively, the gain bandwidth gets larger because of the inhomogeneous contribution and the gain distribution flattens

- Slippage

- The slippage can stop the interaction : the electrons travel slightly slower than the photons, and one at the exit of the undulator, the time difference becomes typically $N_u\lambda/c$. For not the radiation to escape from an electron bunch of duration σ_l , one can consider that the radiation advance should remain in the peak of the distribution :

$$\frac{N_u\lambda}{c} < \frac{\sigma_l}{10} \qquad N_u < \frac{\sigma_l c}{10\lambda}$$

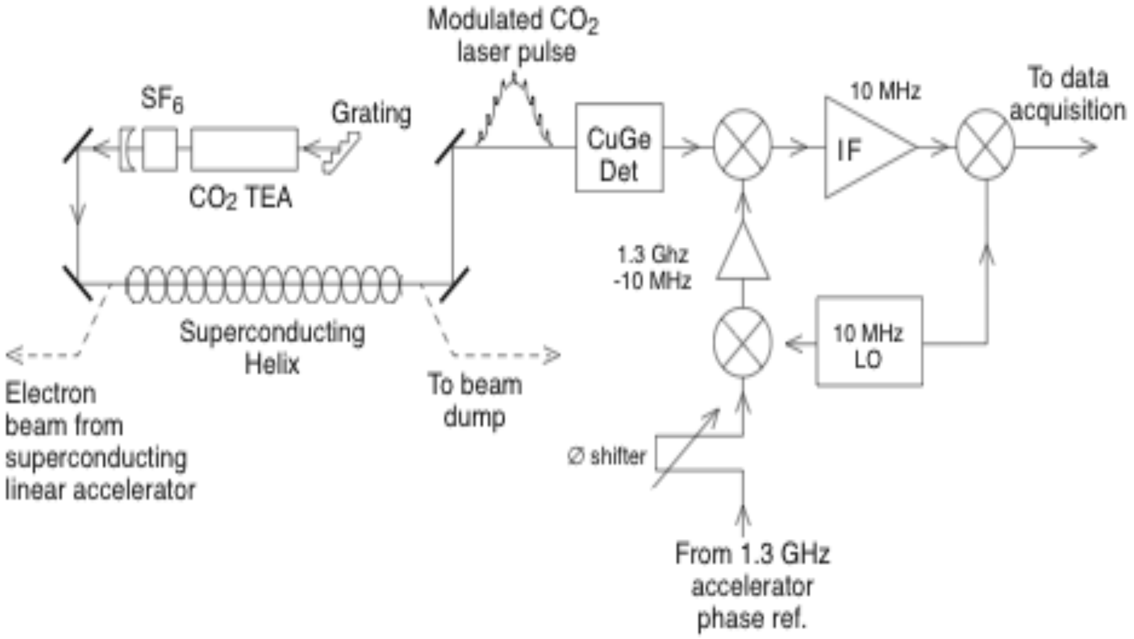
Z. Huang, K. J. Kim, Review of the free-electron laser theory, Physical Review Special Topics-Accelerators and Beams, 10(3), 034801.

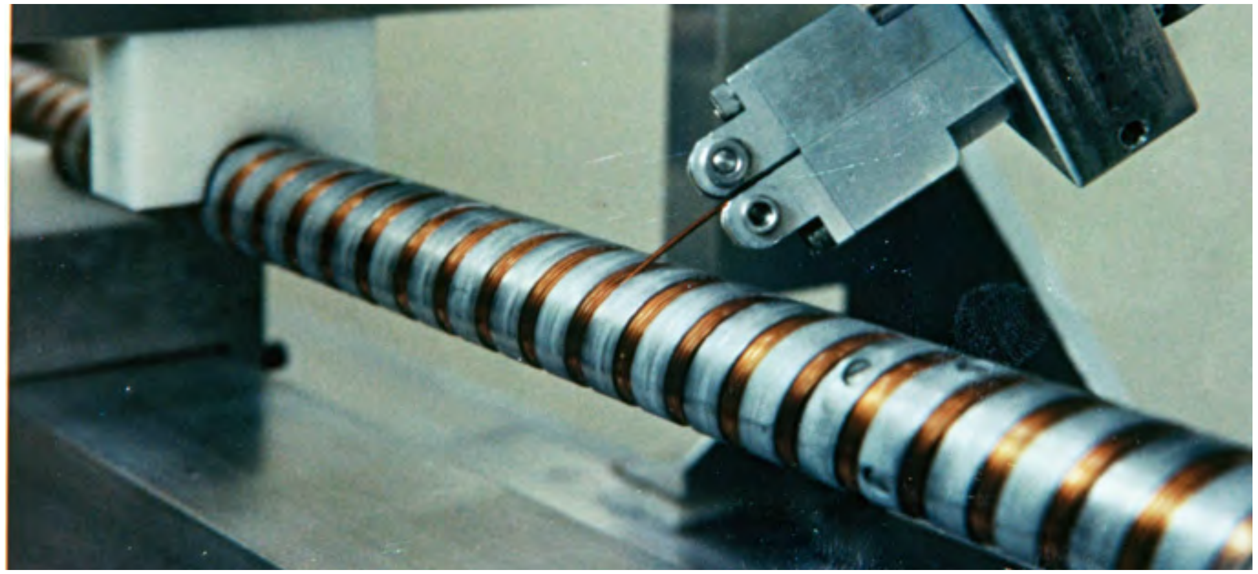
III. The first Free Electron Laser experimental results

The first FEL amplification

24 MeV beam, amplification of a CO2 laser at 10.6 μm

Undulator period : 3.2 cm, length 5.2 m
single pass gain : 7 %





L. Elias et al., *Observation of the stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, Phys. Rev. Lett. 36, 717-720 (1976)*

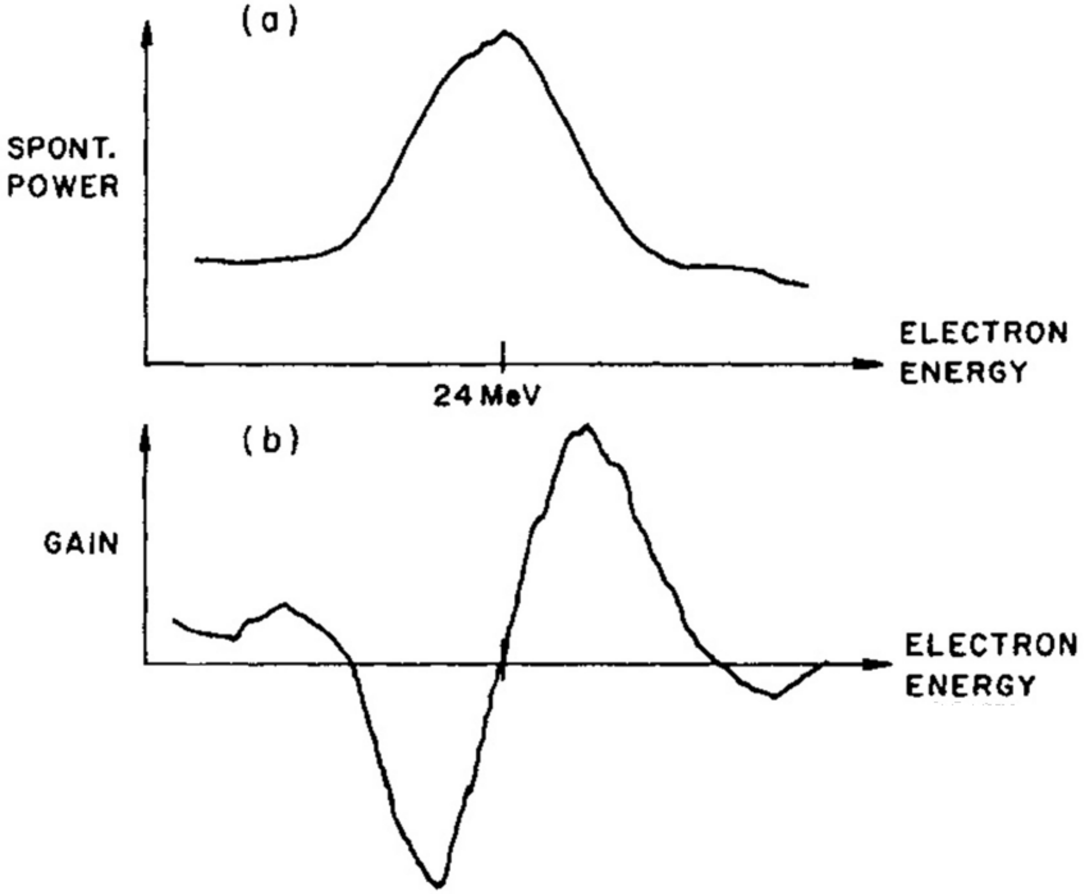
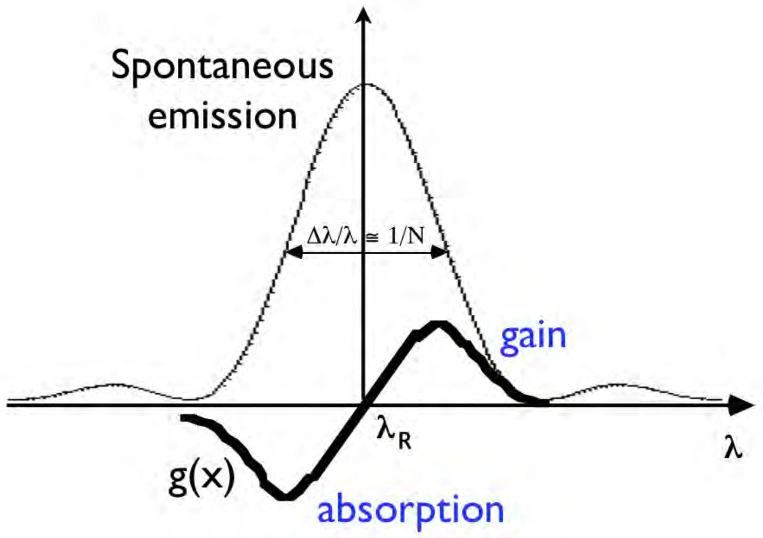


FIG. 2. (a) The spontaneous power at 10.6 μm as a function of the electron energy. (b) The amplitude and phase of the modulation imposed on the 10.6-μm optical radiation from the CO_2 laser. Amplification corresponds to a positive signal. The instantaneous peak gain attained a value of 7% per pass. The helix field amplitude was 2.4 kG and the instantaneous peak electron current was 70 mA. The electron energy was swept through a small range in the vicinity of 24 MeV. The full width in energy (half-width in wavelength) at the $1/e$ points in (a) is 0.4%. The power density of the 10.6-μm radiation in (b) was 1.4×10^5 W/cm^2.

Madey's theorems

The gain can be expressed as the derivative of the undulator spontaneous emission expression.
It is a remarkable result which corresponds to the Madey's theorem.



$$\frac{d\Phi}{d\Omega}(\theta=0)=\frac{2\alpha m_o^2c^4I<\Delta\gamma^2>}{e^2\lambda^2<E_l^2>}$$

$$<\Delta\gamma_2>=\frac{1}{2}\frac{\partial<\Delta\gamma^2>}{\partial\gamma}$$

with α the fine structure constant, I the beam current, $\frac{d\Phi}{d\Omega}(\theta=0)$ the angular spectral flux on-axis of the undulator spontaneous emission.

The first theorem relates the the energy spread $<E_l^2>$ introduced by the optical wave to the spontaneous emission of the undulator.

According to the second theorem, the second order energy exchange $<\Delta\gamma_2>$ is proportional to the derivative of the spontaneous emission of the undulator.

Due to the resonance relationship linking the particles' energy to the emission wavelength, the spectral "gain" distribution is close to the wavelength derivative of the spontaneous emission spectrum versus λ.

Validity : Gain <0.2

J.M.J.Madey,H.A.Schwettman,W.F.Fairbank:,IEEETrans.Nucl.Sci.:20,980–980(1973)
J. M. J. Madey: Relationship between mean radiated energy, mean squared radiated energy and spontaneous power spectrum in apower series expansion of the equations of motion in a free-electron laser, Nuovo Cimento 50B, 64 (1979)

III. The first Free Electron Laser experimental results

The first FEL in 1977

1977 : First Free Electron Laser by J. M. J. Madey in Stanford

D. A. G. Deacon et al, First Operation of a FEL. PRL 38, 16, 1977, 892

J. M. J. Madey

First demo : on linear accelerator, MARK III, Stanford, infra-red

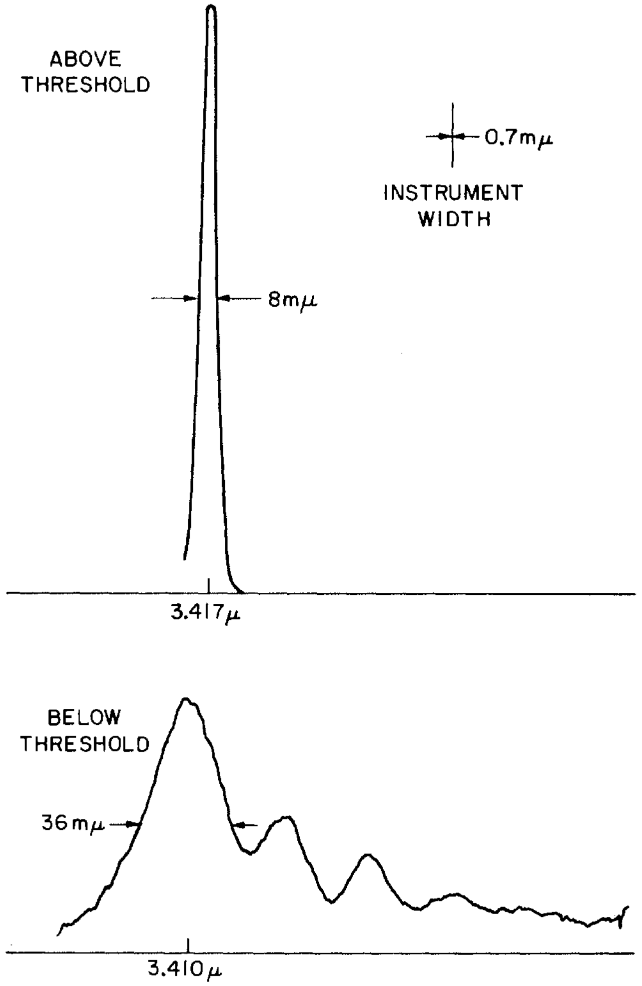
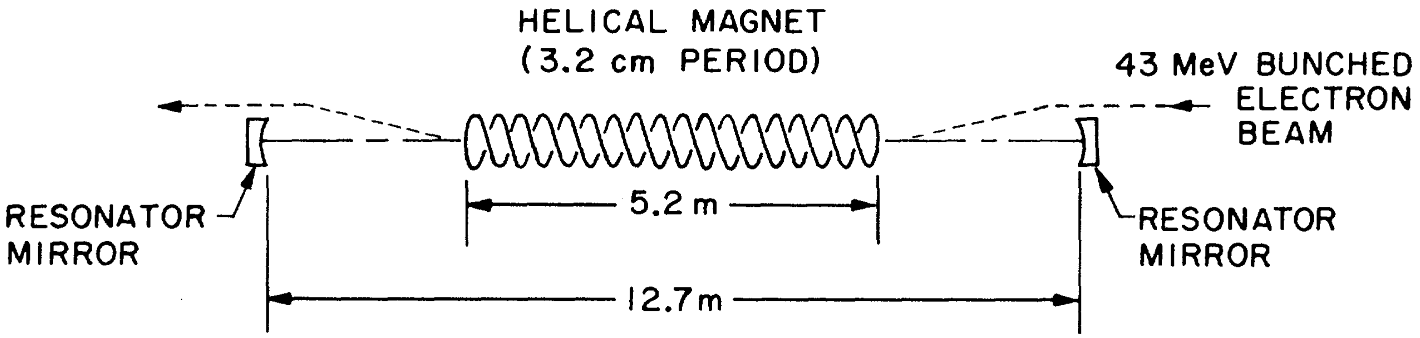
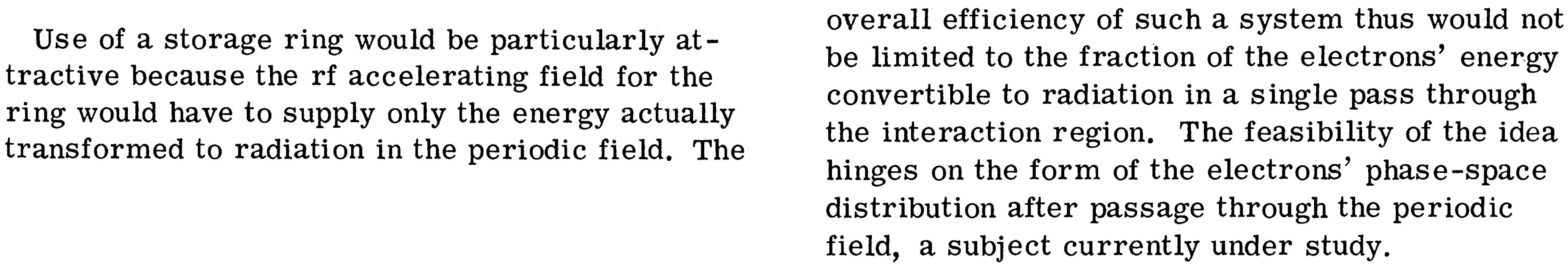


FIG. 2. Emission spectrum of the laser oscillator above threshold (top) and of the spontaneous radiation emitted by the electron beam (bottom).



FEL oscillator at 3.4 µm, 43 MeV, 12.7 m long optical cavity

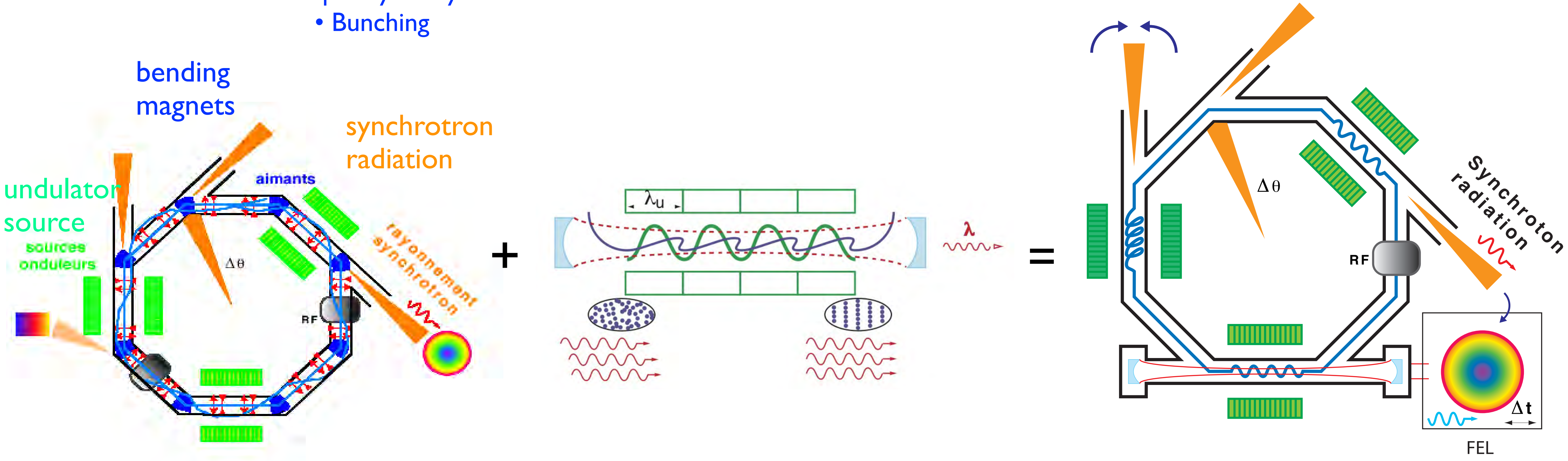
Saturation- Hope in storage ring FELs



Use of a storage ring would be particularly attractive because the rf accelerating field for the ring would have to supply only the energy actually transformed to radiation in the periodic field. The overall efficiency of such a system thus would not be limited to the fraction of the electrons' energy convertible to radiation in a single pass through the interaction region. The feasibility of the idea hinges on the form of the electrons' phase-space distribution after passage through the periodic field, a subject currently under study.

L. Elias et al., Observation of the stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, Phys. Rev. Lett. 36, 717-720 (1976)

- Magnetic elements (dipoles, quadrupoles, sectupoles...)
- Emission of synchrotron radiation (dipoles, undulators)
- Compensation of the energy loss per turn with a radio-frequency cavity
- Bunching



Renieri, A. (1979). Storage ring operation of the free-electron laser: The amplifier. Il Nuovo Cimento B Series 11, 53(1), 160-178.
Dattoli, G., & Renieri, A. (1980). Storage ring operation of the free-electron laser: the oscillator. Il Nuovo Cimento B Series 11, 59 (1), 1-39.

After the first FEL ....

Unfortunately, none of the electron-beam sources available at that time had enough electron-beam current and satisfactory electron-beam quality to make lasing easy. Although gain was measured in several experiments, it was not until six years later, in 1983, that the second free-electron laser was operated in the optical part of the spectrum.
The first was at Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE), in Orsay, France, where the electron beam in the storage ring ACO was used to acheive lasing in the visible.
The second was at Stanford, a team from TRW used the superconducting accelerator previously used by Madey to acheive laseing in the near infra-red.
The third was Los Alamos, where a newly constructed electron accelerator was used to acheive lasing in the mid-infrared.

During the same period, development of ubitron-type devices began at several laboratories. Because the threshold electron-beam current at which space-charge wave can be excited increses as the third power of the electron energy, these devices were limited to low electron energy (no more than a few MeV), and long wavelength. Neverthess, Marshall and his co-workers acheived lasing at 400 µm with electron beam having an energy og 1.2 MeV and a peak current of 25 kA.
sub-mm
collective instabilities involved (space charge waves)

C. Brau, Free Electron Lasers, Advanced in electronics and electron physics, edited by P.W. Hawkes, B. Kazan, supplement 22, Academic press (1990)

M. Billardon et al., First operation of a storage ring free electron laser» Phys. Rev. Lett. 51, 1652,(1983)

J.A. Edighoffer et al., Variable-Wiggler Free-Electron-Laser Oscillation, Phys. Rev. Lett 52, 344 (1984)

R.W. Warren et al, First operation of the Los Alamos Free Electron Laser», DOE_Report (1984)

D. B. McDermott et al., High-Power Free-Electron Laser Based on Stimulated Raman Backscattering, Phys. Rev. Lett. 41, 1368 (1978)

The second Compton FEL : the first visible and first storage ring FEL

M. Billardon et al., Phys. Rev. Lett. 51, 1652,(1983)

Vinokurov et al, Prepint INP,
D.A.G. Deacon, M. Billardon, P. Elleaume et al, Optical klystron experiments for the ACO storage ring FEL, Appl. Phys. B34, 1984, 207-219
P. Elleaume, J. Phys. Colloq 44 C1-333 (1983)

Vsible => 100 MeV
sotorage ring superior in terms of electronic density, energy spread, emittance => higher optical gain

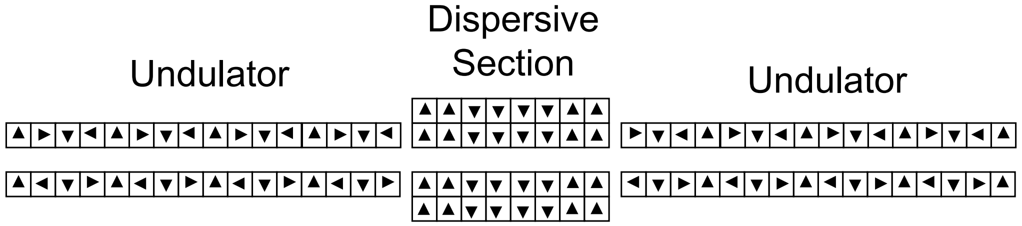
TABLE I. ACO characteristics in the FEL experiment.

Energy	160 – 166 MeV
Circumference	22 m
Bunch to bunch distance	11 m
Electron beam current for oscillation	16 to 100 mA
rms bunch length σ_l	0.5 to 1 ns
rms bunch transverse dimensions σ_x, σ_y	0.3 to 0.5 mm
rms angular spread σ_x', σ_y'	0.1 to 0.2 mrad
rms relative energy spread	$(0.9$ to $1.3) \times 10^{-3}$
Electron beam lifetime	60 to 90 min

TABLE II. Optical cavity characteristics.

Length	5.5 m
Mirror radius of curvature	3 m
Rayleigh range	1 m
Wavelength of maximum Q	620 to 680 nm
Average mirror reflectivity at 6328 Å	99.965%
Round trip cavity losses at 6328 Å	7×10^{-4}
Mirror transmission	3×10^{-5}

Mirror reflectivity degradation observed at 240 MeV



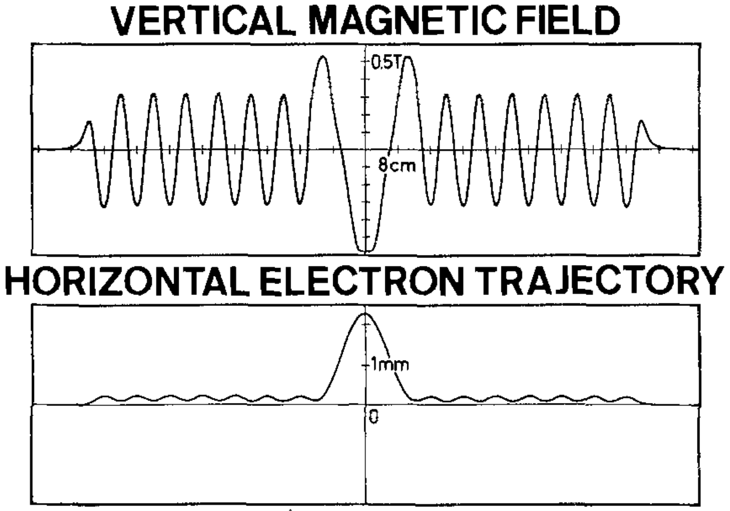


Fig. 1. Vertical magnetic field calculated for the Orsay optical klystron (gap: 33 mm) and the corresponding calculated horizontal electron trajectory at an energy of 240 MeV

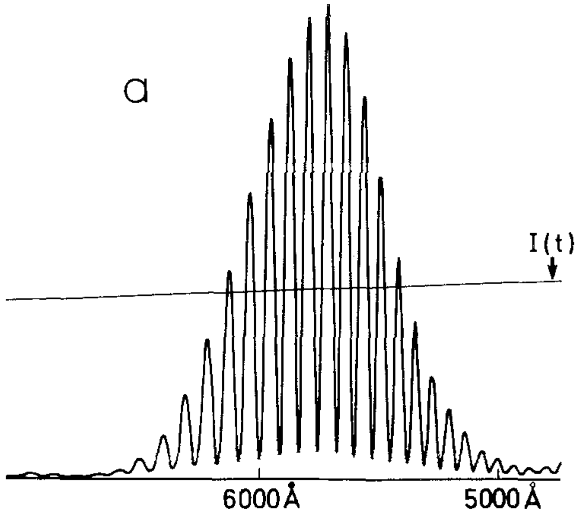
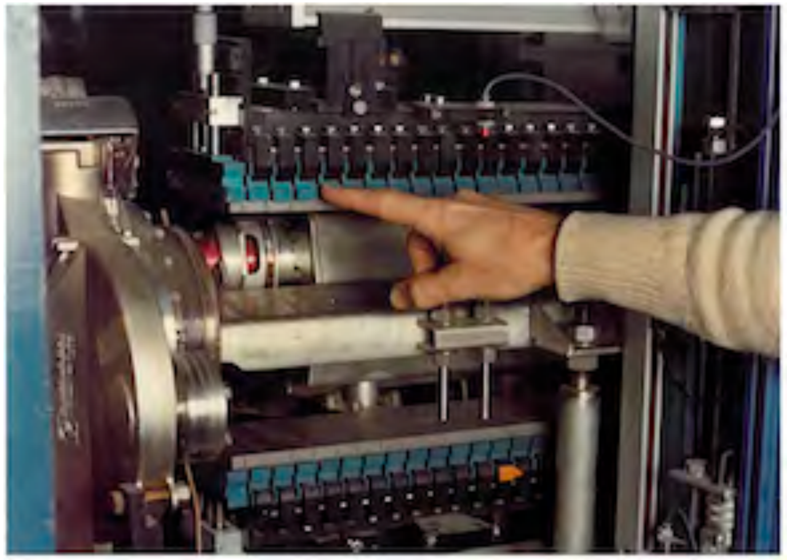


Fig. 3. Spontaneous emission spectrum $dI/d\lambda d\Omega$ measured for an electron energy of 238 MeV and a magnetic field parameter of $K = 2.09$ at low current where the modulation is almost total. The current decay $I(t)$ is superimposed

III. The first Free Electron Laser experimental results

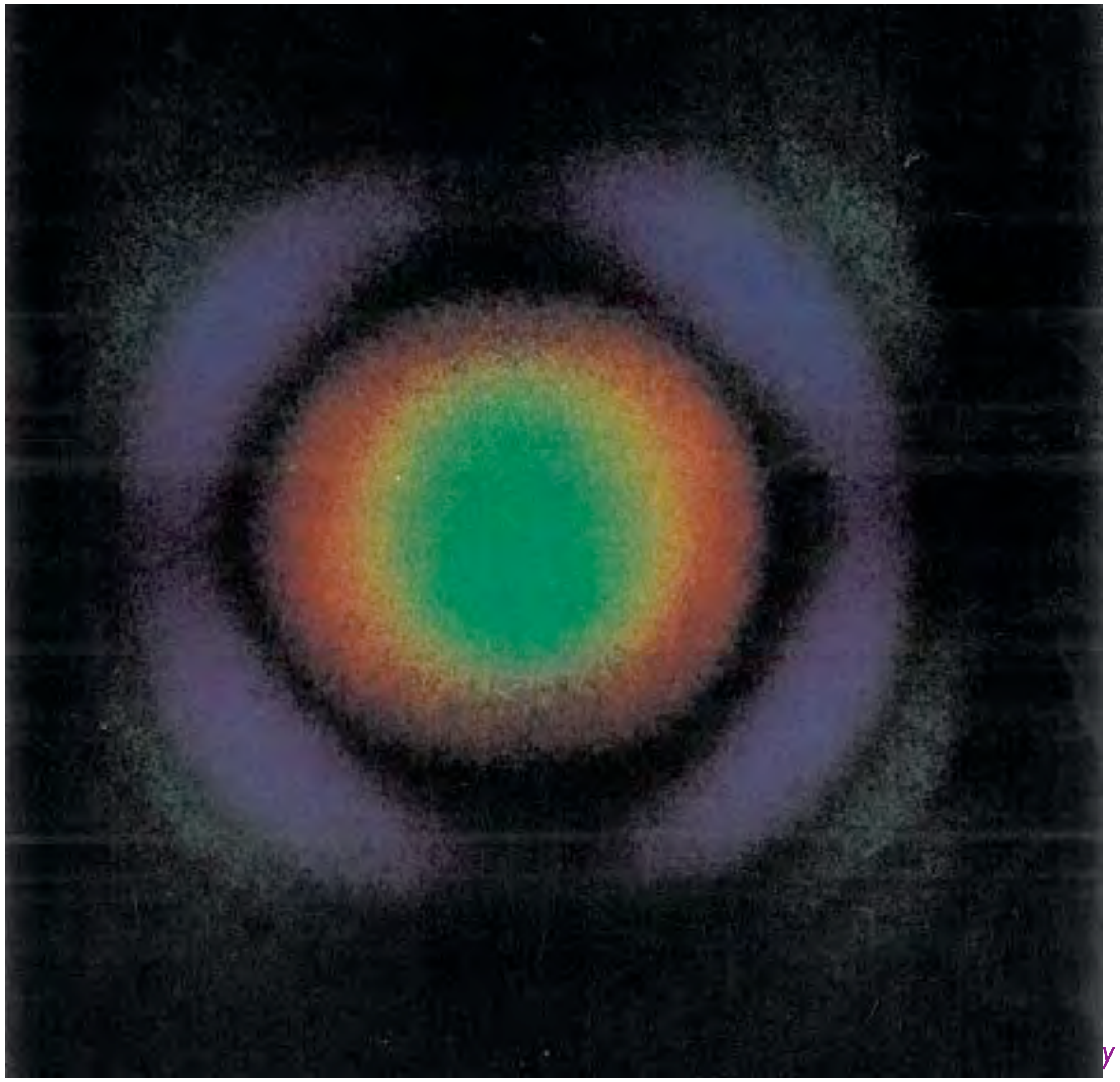
The second Compton FEL : the first visible and first storage ring FEL

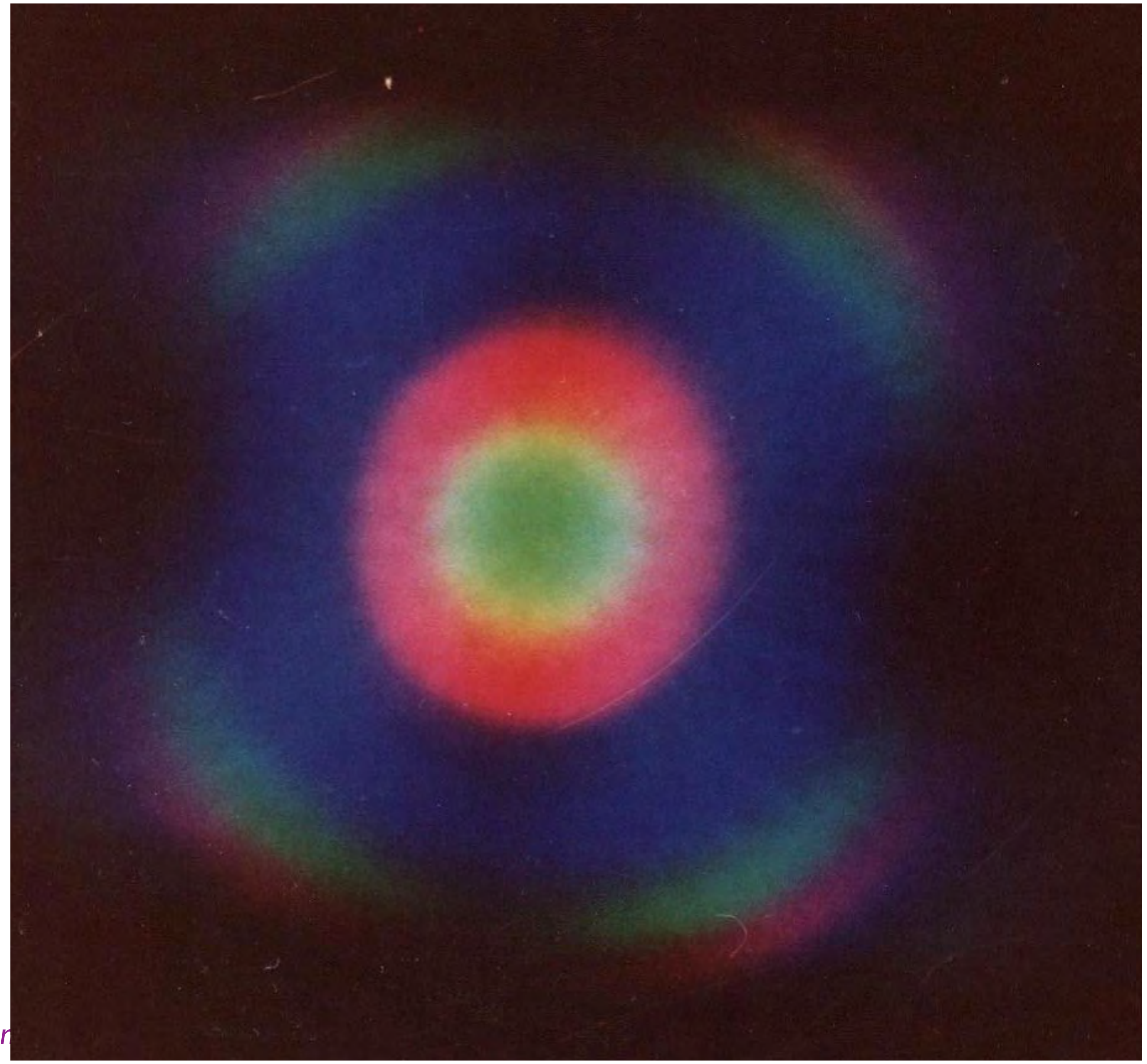


Spontaneous Emission in the visible

ACO

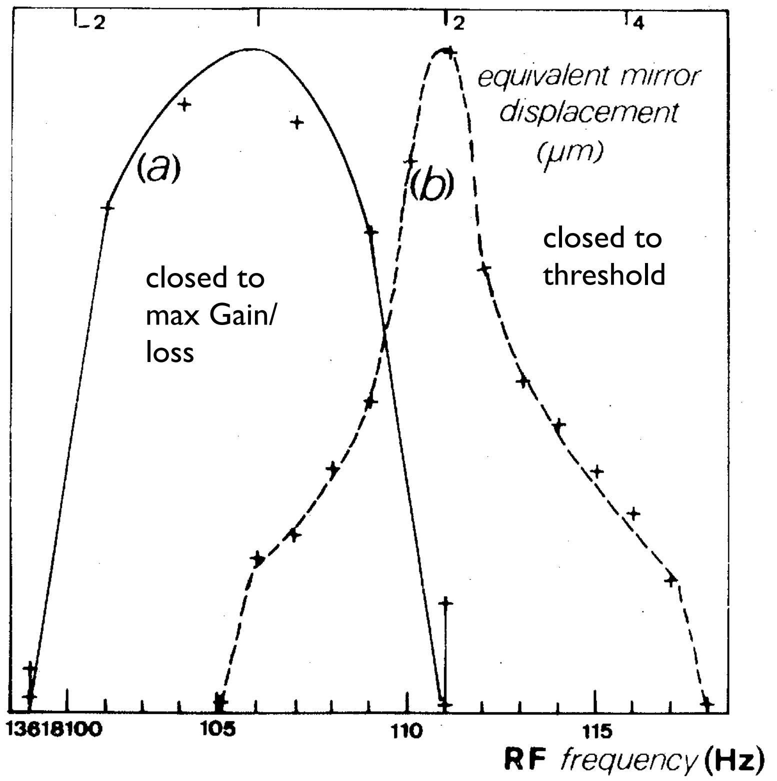
$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K_{ux}^2}{2} + \frac{K_{uz}^2}{2} + \gamma^2\theta_x^2 + \gamma^2\theta_z^2\right)$$





The second Compton FEL : the first visible and first storage ring FEL

M. Billardon et al., Phys. Rev. Lett. 51, 1652,(1983)



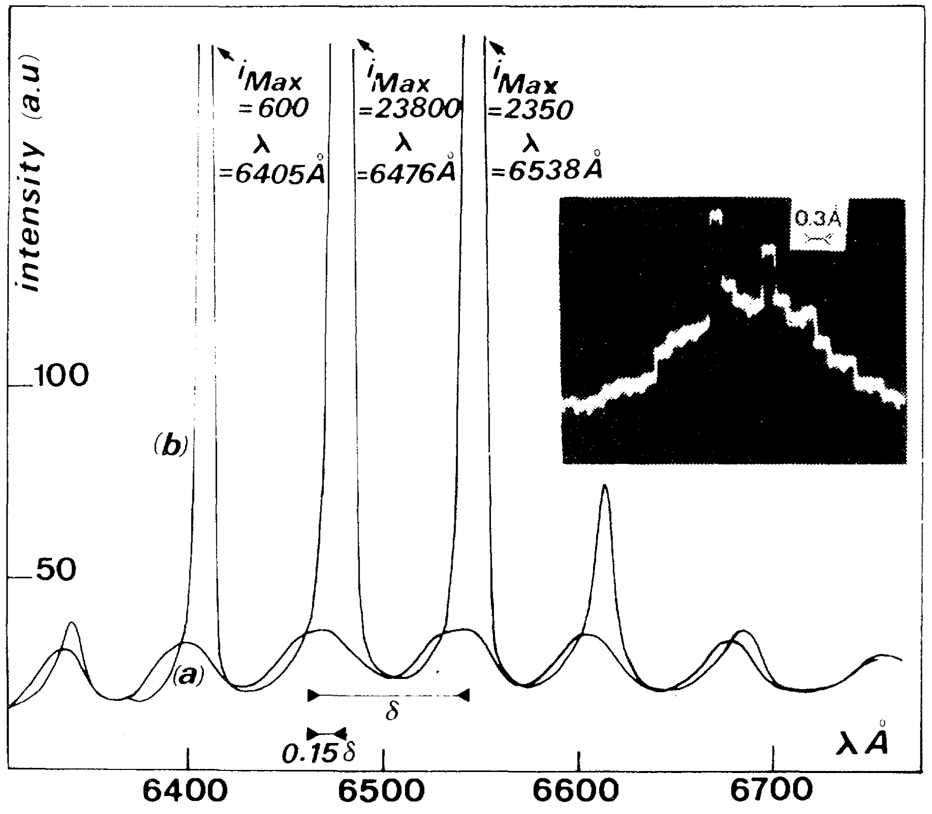
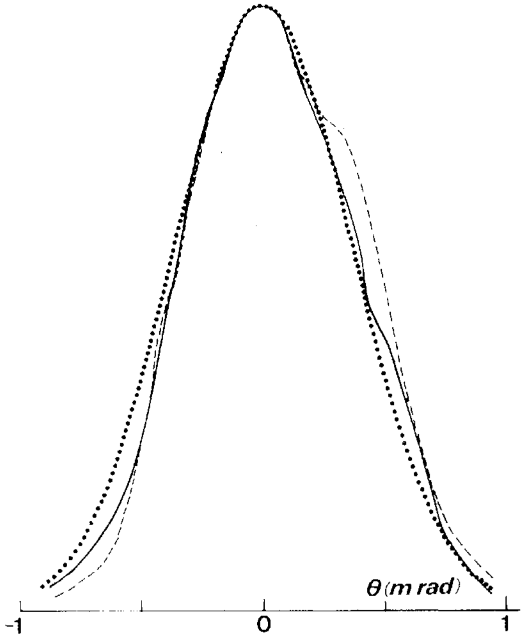
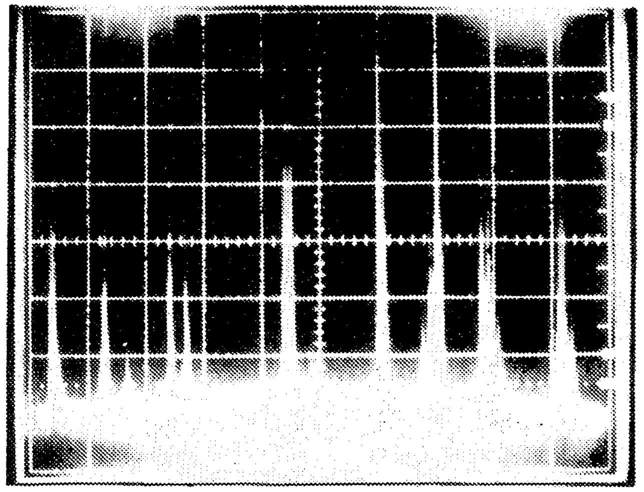


FIG. 4. Spectra of the cavity output radiation under two conditions: curve a, cavity detuned (no amplification) and curve b, cavity tuned (laser on).



Transverse profile

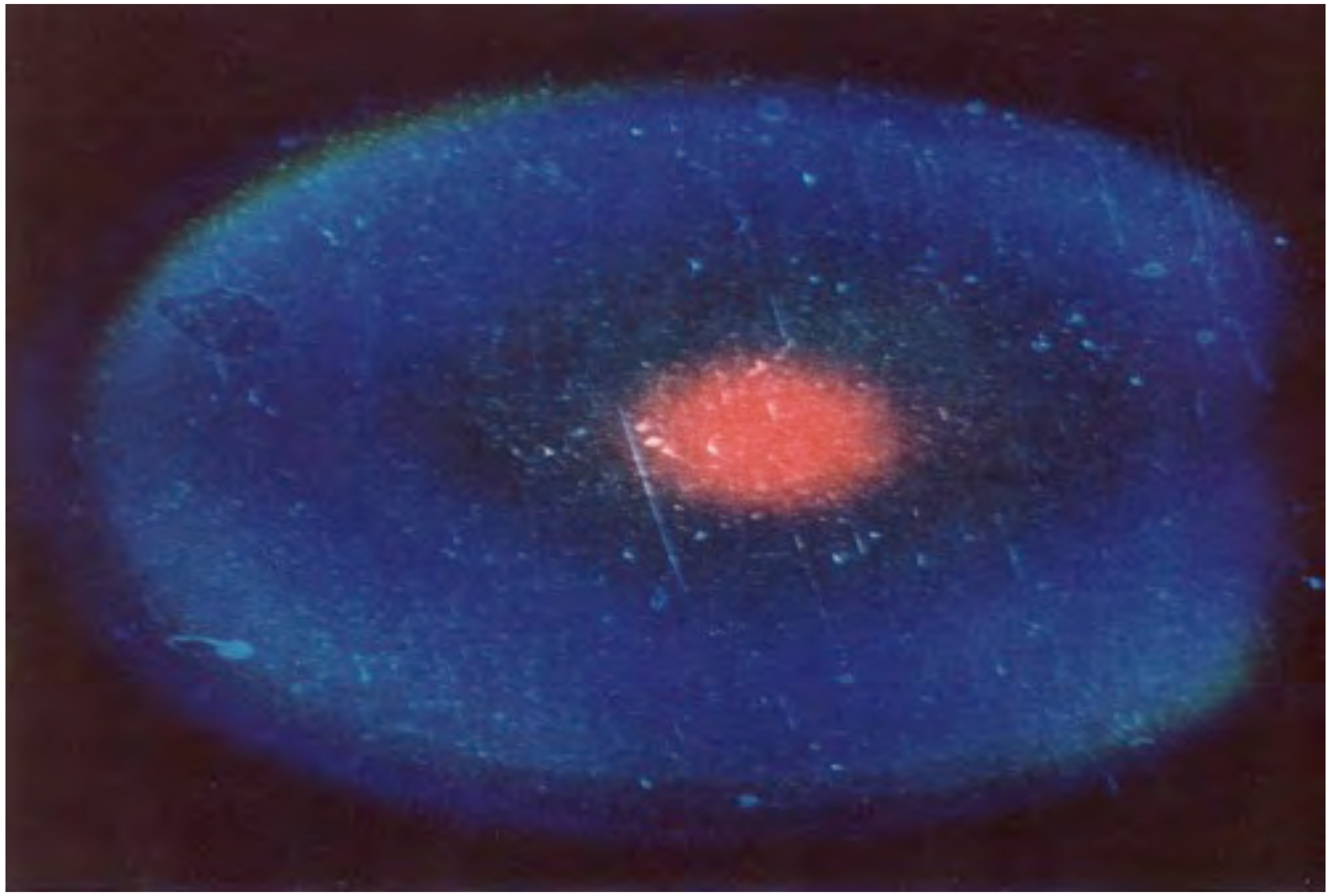
Temporal structure

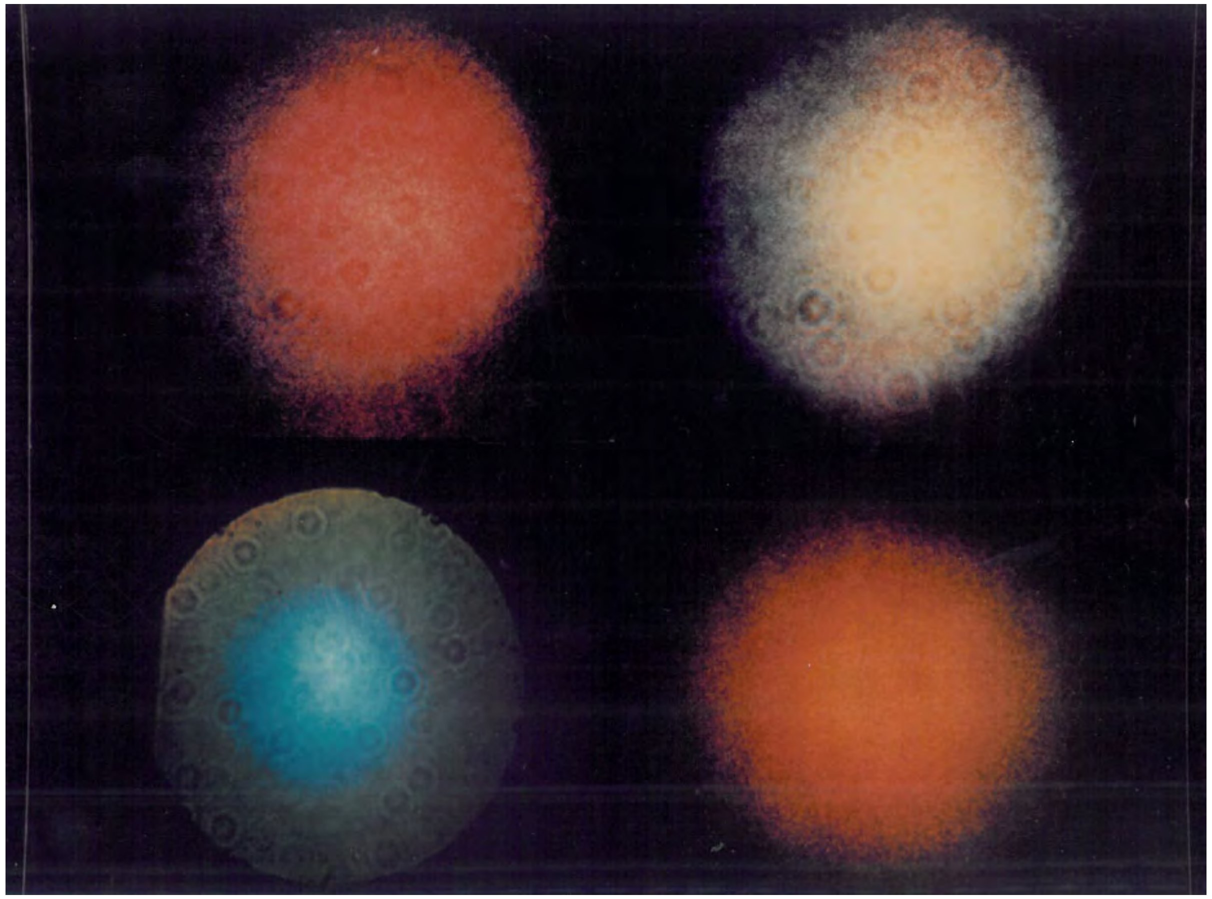


The second Compton FEL : the first visible and first storage ring FEL

Second FEL : on storage ring, ACO, Orsay, visible, 1983

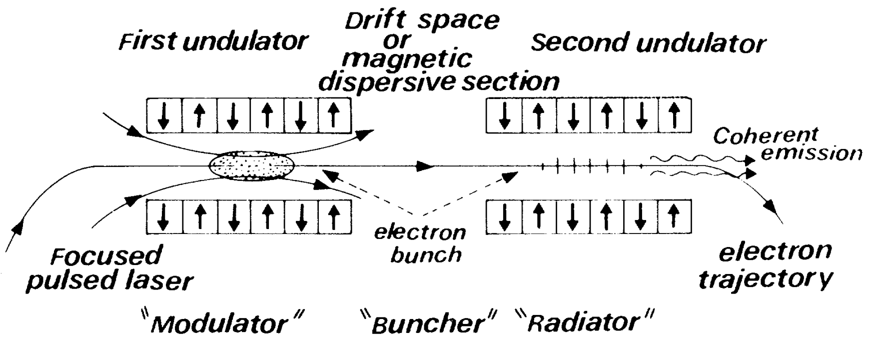
M. Billardon et al., Phys. Rev. Lett. 51, 1652,(1983)



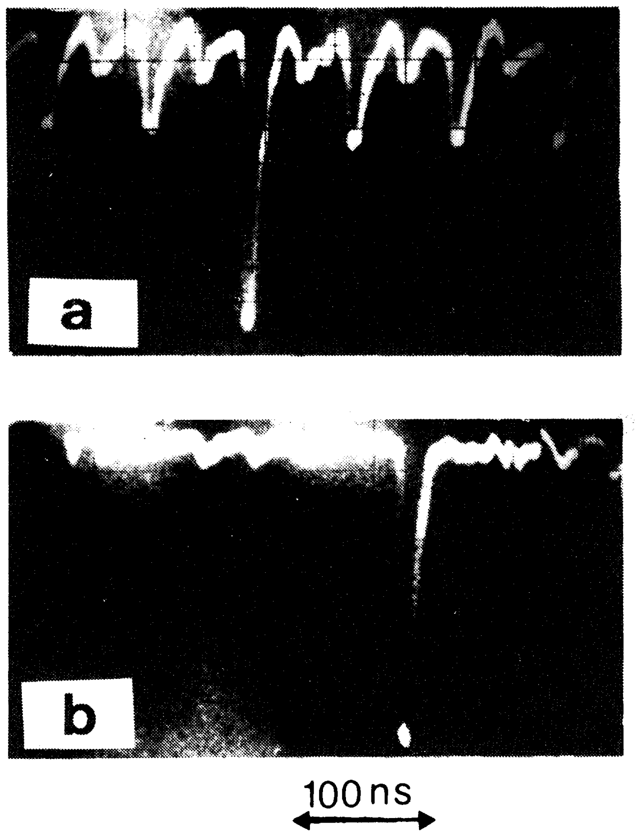


First coherent harmonic generation results

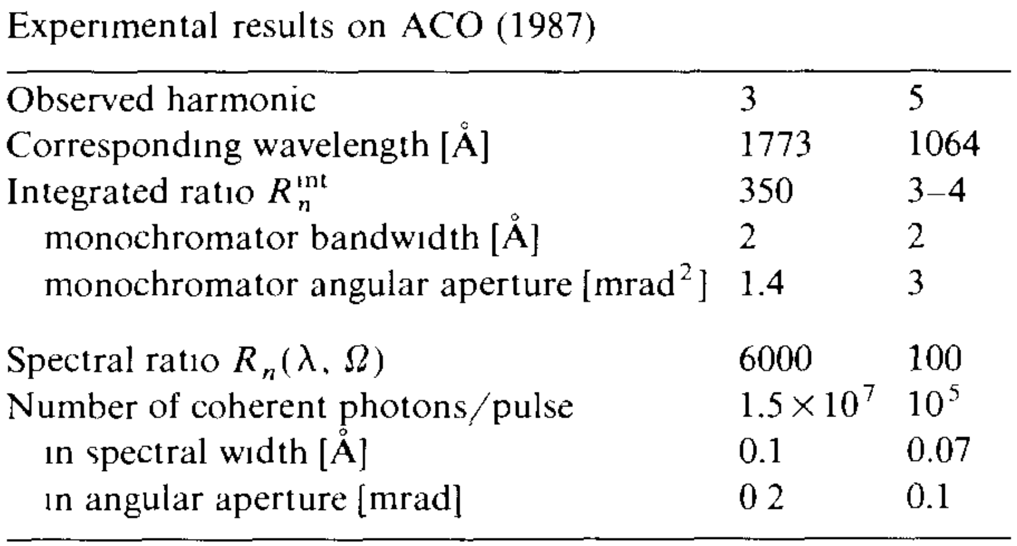
ACO (Orsay, France), 166 MeV
Nd-Yag at 1.06 µm, 20 Hz, 15 MW, 12 ns
=> CHG at 352 nm



B. Girard, Y. Lapierre, J. M. Ortéga, C. Bazin, M. Billardon, P. Elleaume, M. Bergher, M. Velghe, Y. Petroff, Opitcal frequency multiplication by an optical klystron, Phys. Rev. Lett. 53 (25) 2405-2408 (1984)



Linewidth sharpening



Experimental results on ACO (1987)

Observed harmonic	3	5
Corresponding wavelength [Å]	1773	1064
Integrated ratio R_n^{int}	350	3–4
monochromator bandwidth [Å]	2	2
monochromator angular aperture [mrad^2]	1.4	3
Spectral ratio $R_n(\lambda, \Omega)$	6000	100
Number of coherent photons/pulse	1.5×10^7	10^5
in spectral width [Å]	0.1	0.07
in angular aperture [mrad]	0.2	0.1

ACO (Orsay, France), 220 MeV Nd-Yag at 1.06 µm (36 MW) /2 = 532 nm, => CHG at 177 and 106.4 nm

Coherent Harmonic Generation in the Vacuum Ultra Violet Spectral Range on the Storage Ring ACO, R. Prazeres, J.M. Ortéga, M. Billardon, C. Bazin, M. Bergher, M.E. Couprie, H. Fang, M. Velghe Y. Petroff, Nuclear Inst.and Methods in Physics Reasearch A272 (1988), 68-72

III. The first Free Electron Laser experimental results

Efficiency

Small signal gain bandwidth : $1/2N_u$

Resonance condition => $$\frac{\Delta\gamma}{\gamma} = \frac{1}{2}\frac{\Delta\lambda}{\lambda} = \frac{1}{4N_u}$$

When the electron travels on half the width of the gain curve, it can deliver up to $\frac{1}{4N_u}$ of its kinetic energy, the efficiency r comes :

$$\boxed{r = \frac{1}{4N_u}}$$

The maximum efficiency is found in considering the total width of the gain curve, which would lead to $r = \frac{1}{2N_u}$. It is however less realistic because energy spread effect can limit the process.

N.A. 50 periods, r = 0.1 %

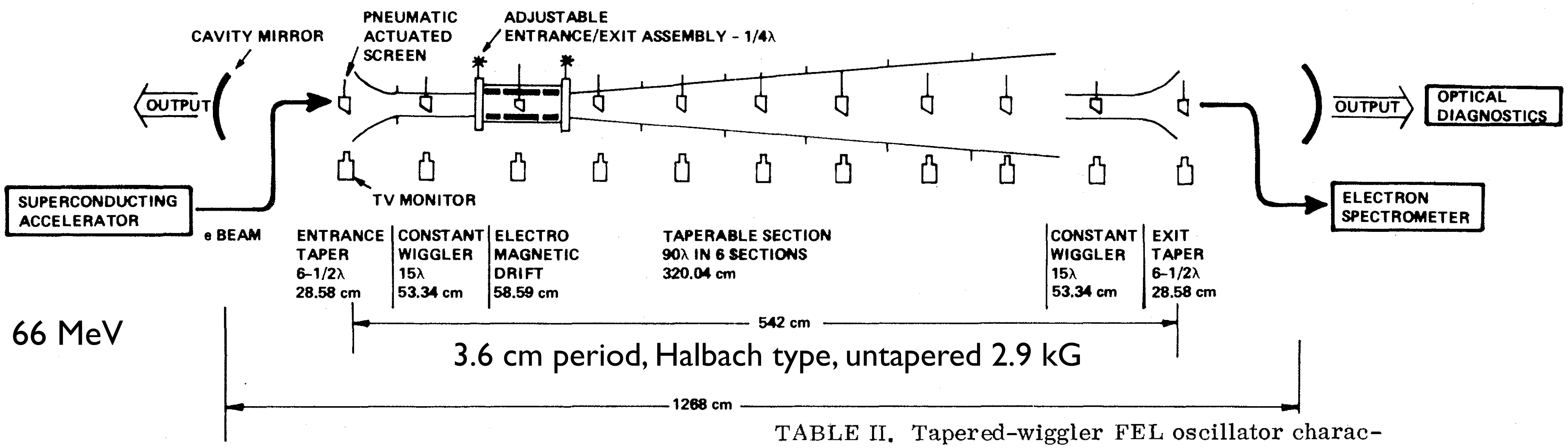
$$\lambda = \frac{\lambda_u}{2\gamma_s^2}\left[1 + \frac{1}{2}\left[\frac{eB_z(s)\lambda_u(s)}{2\pi m_o c^2}\right]^2\right]$$

Kroll, N. M., Morton, P. L., Rosenbluth, M. N :Variable parameter free-electron laser. In Free-Electron Generators of Coherent Radiation, 1, 89–112 (1980)

Storage Ring based FEL :
Renieri limit : $\langle P\rangle \; \alpha \; \chi \, (\Delta\sigma_\gamma/\gamma)^2 \, P_{sync}$, $P_{sync} \; \alpha \; IE^4$

Renieri, A. (1979). Storage ring operation of the free-electron laser: The amplifier. Il Nuovo Cimento B Series 11, 53(1), 160-178.
Dattoli, G., & Renieri, A. (1980). Storage ring operation of the free-electron laser: the oscillator. Il Nuovo Cimento B Series 11, 59(1), 1-39.

The Stanford experiment in the taper configuration



66 MeV

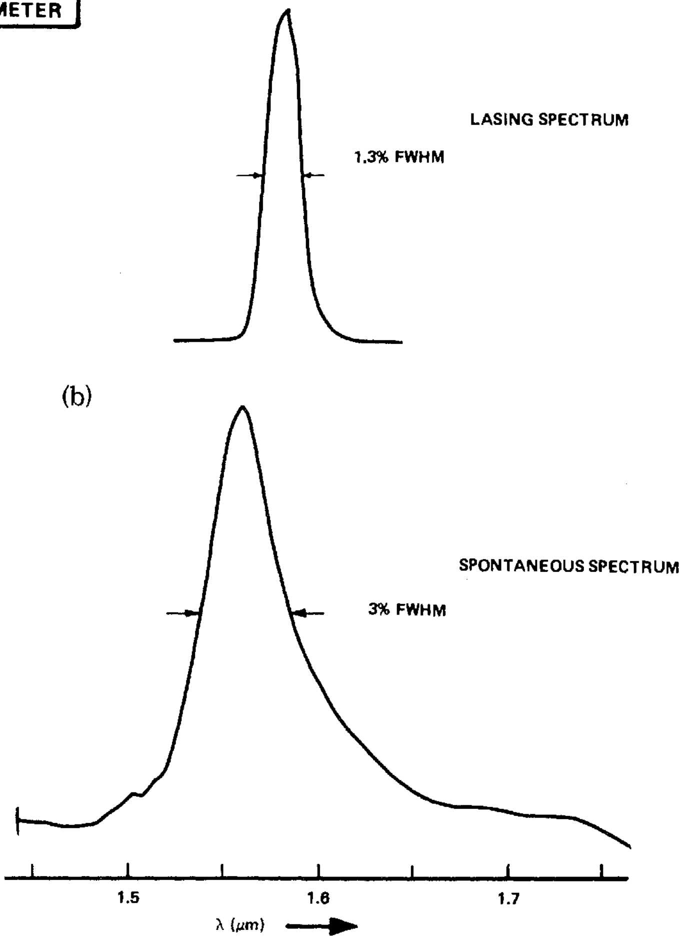
3.6 cm period, Halbach type, untapered 2.9 kG

TABLE I. Characteristics of the superconducting accelerator in the experiment.

Emittance	0.15π mm mrad (at 66 MeV)
Energy spread	0.03%
Bunch length	4.3 ps
Current	0.5–2.5 A
Energy	66 MeV

TABLE II. Tapered-wiggler FEL oscillator characteristics.

Power[a]	4 W[b]
Peak power	1.2 MW[b]
Peak cavity power	460 MW[b]
Peak cavity intensity	11 GW/cm^2[b]
Wavelength	1.57 μm
Micropulse length	4 ps[c]
Macropulse length	5 ms
Repetition rate	10 Hz
Bandwidth[a]	1.3%
Efficiency,[d] constant wiggler	0.2–0.4%
1% taper	1.1%
2% taper	1.2%



To compensate for the average energy loss of the electrons to the optical. wave, the magnetic field is made a function of the wiggler position, compensating for average changes in the electron energy, y, so that X, in the resonant condition remains constant. The reduction of the magnetic field decreases the path length traveled by the el.ectrons to compensate for their slowing down. This tapering allows electrons to remain in resonance as they traverse the wiggler, even as they lose significant amounts of their energy.

J.A. Edighoffer et al., Variable-Wiggler Free-Electron-Laser Oscillation, Phys. Rev. Lett 52, 344 (1984)

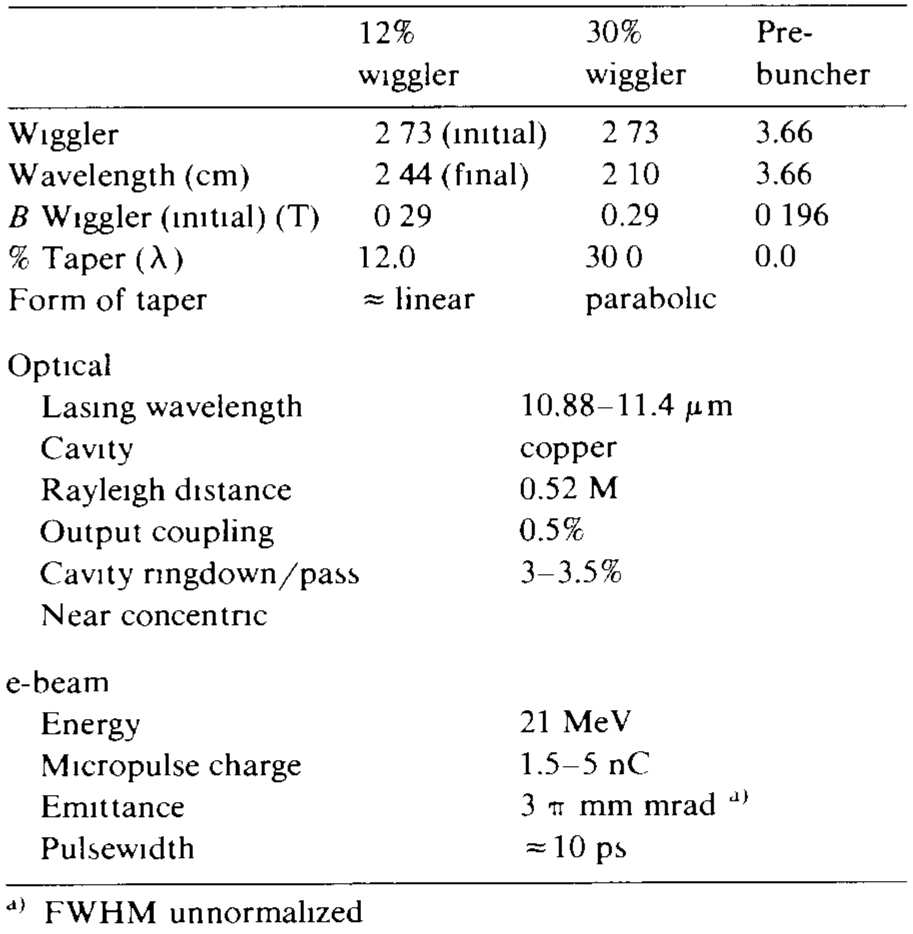
LUNEX5

www.lunex5.com

III. The first Free Electron Laser experimental results

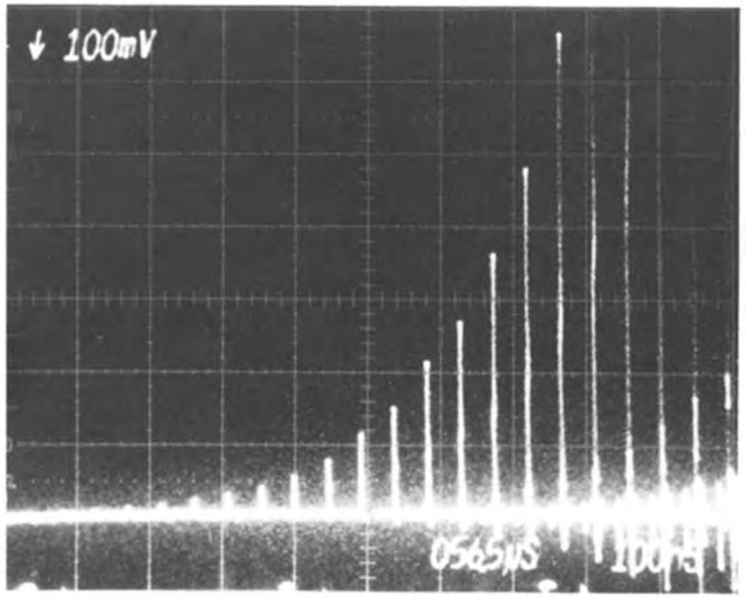
The Los Alamos experiment

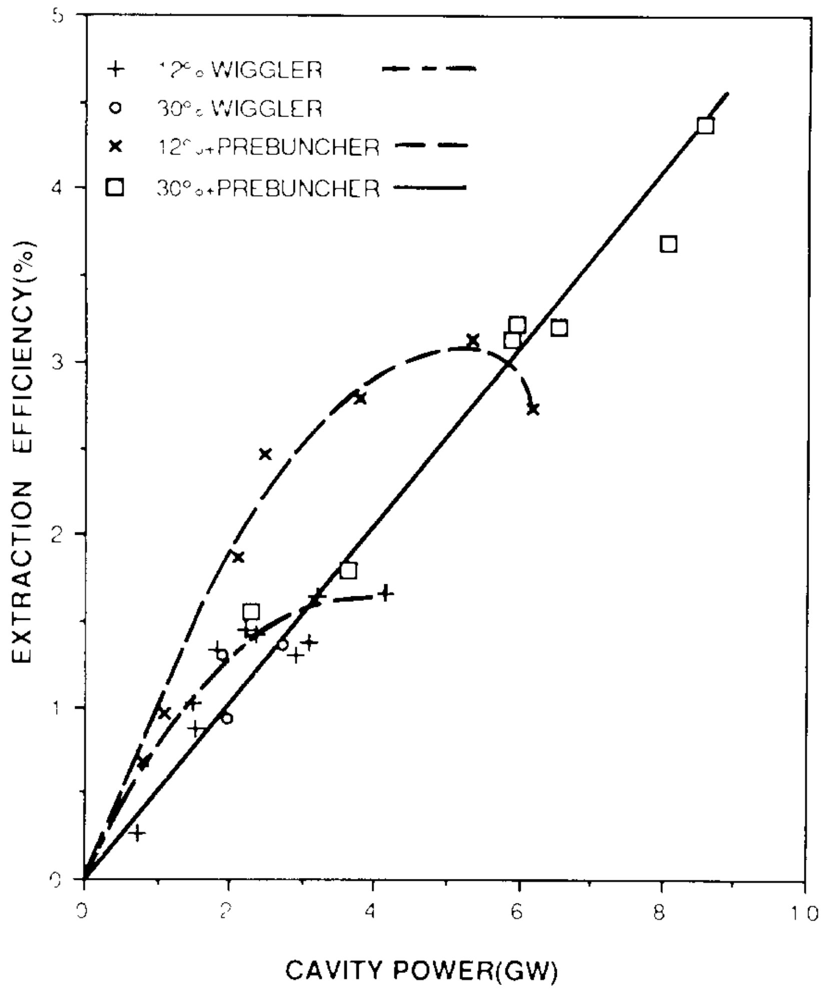
Los Alamos oscillator experiment



	12% wiggler	30% wiggler	Pre-buncher
Wiggler Wavelength (cm)	2.73 (initial) 2.44 (final)	2.73 2.10	3.66 3.66
B Wiggler (initial) (T)	0.29	0.29	0.196
% Taper (λ)	12.0	30.0	0.0
Form of taper	≈ linear	parabolic	
Optical			
Lasing wavelength	10.88–11.4 μm		
Cavity	copper		
Rayleigh distance	0.52 M		
Output coupling	0.5%		
Cavity ringdown/pass	3–3.5%		
Near concentric			
e-beam			
Energy	21 MeV		
Micropulse charge	1.5–5 nC		
Emittance	3 π mm mrad [a)]		
Pulsewidth	≈ 10 ps		

[a)] FWHM unnormalized





40 % gain

Warren, R. W., Newnam, B. E., Winston, J. G., Stein, W. E., Young, L. M., & Brau, C. A. (1983). Results of the Los Alamos free-electron laser experiment. Quantum Electronics, IEEE Journal of, 19(3), 391-401.

B. E. Newnam, R. W. Warren, R. L. Sheffield, J. C. Goldstein, C. A. Brau: The Los Alamos free electron laser oscillator: Optical performance, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 237 (1), 187–198 (1985)

Accelerators for FELs

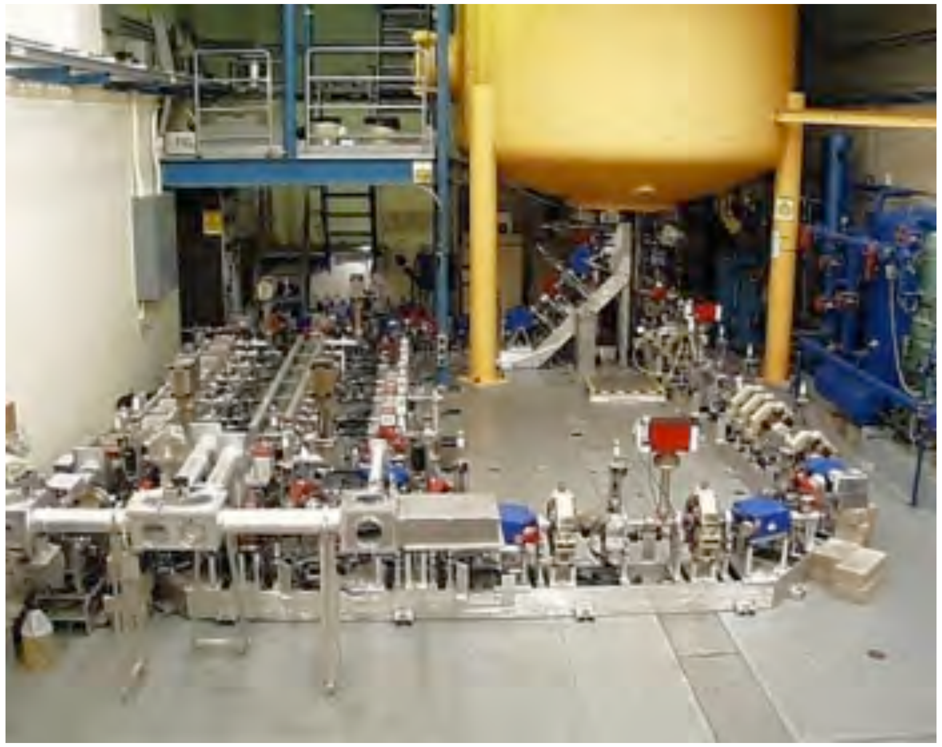
Storage ring

ACO, VEPP 3, Super-ACO, DUKE, NIJI IV, UNSOR, DELTA, ELETTRA...

RF linac

Stanford, Los Alamos, Boing / Spectra Techno...

Electrostatic accelerator



Santa-Barbara, 6 GeV, 2 A
120-800 µm

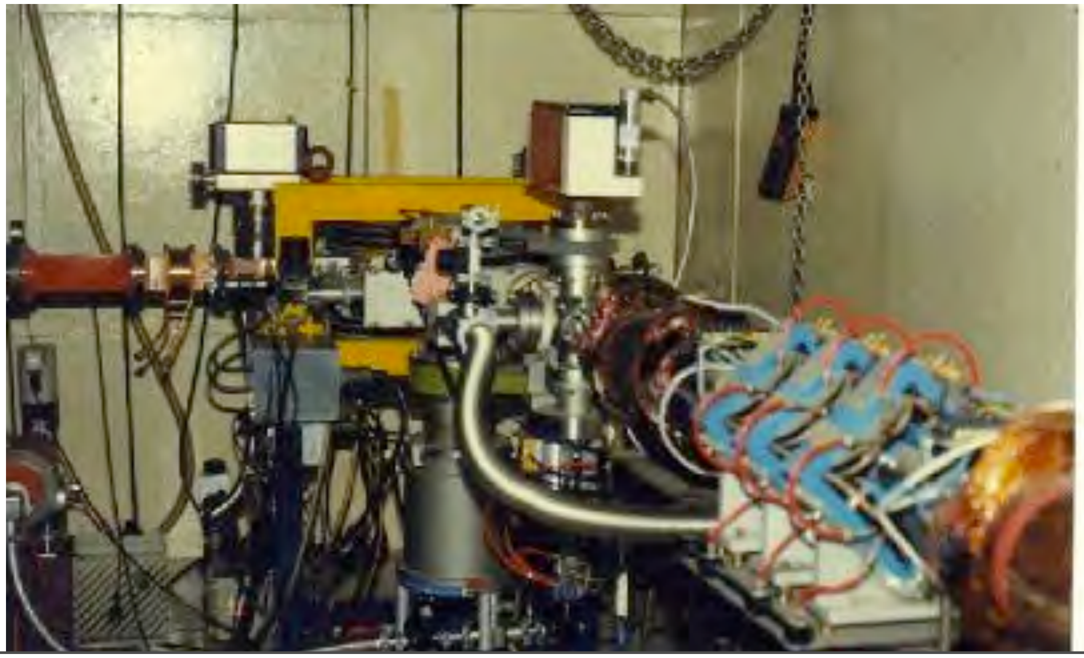
L. Elias et al., The UCSB electrostatic accelerator free electron laser: First operation, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 237, Issues 1–2, 15 June 1985, Pages 203-206

Induction linac

ETA, Lawrence Livermore Nat. Lab.
3.5 MeV, 9 mm, 40 % efficiency
operated as amplifier

T. J. Orzechowski et al. Phys. Rev. Lett. 54, 889 (1985)
T. J. Orzechowski et al. Phys. Rev. Lett. 57, 2172 (1986)

Microtron



ENEA Frascati
2.3 MeV, 2-3.5 mm

Ciocci, F., Doria, A., Gallerano, G. P., Giabbai, I., Kimmitt, M. F., Messina, G., ... & Walsh, J. E. (1991). Observation of coherent millimeter and submillimeter emission from a microtron-driven Cherenkov free-electron laser. Physical review letters, 66(6), 699.

ERL

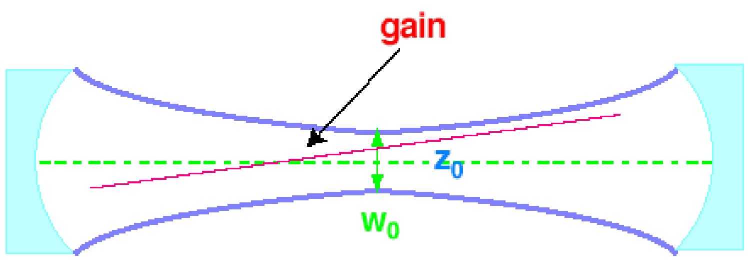
M. Tigner Nuovo Cimento 1965

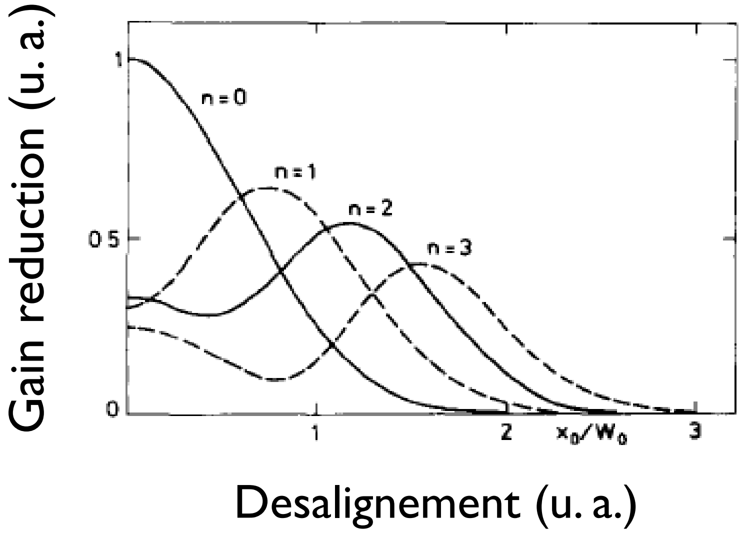
Jefferson Lab.
2.3 MeV, 2-3.5 mm

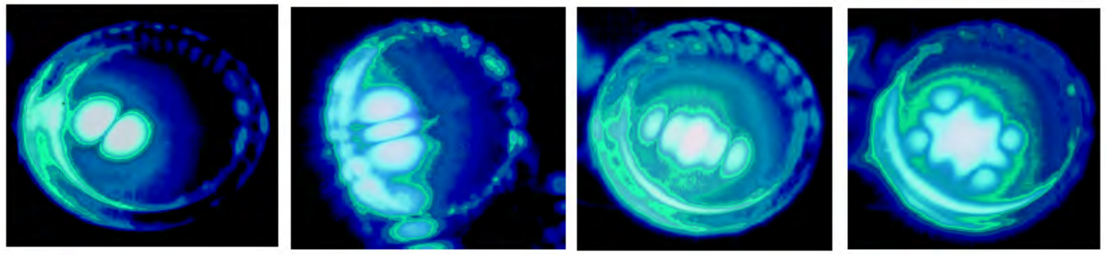
S. Benson et al., NIM A (1999)

FEL oscillator properties

Transverse modes

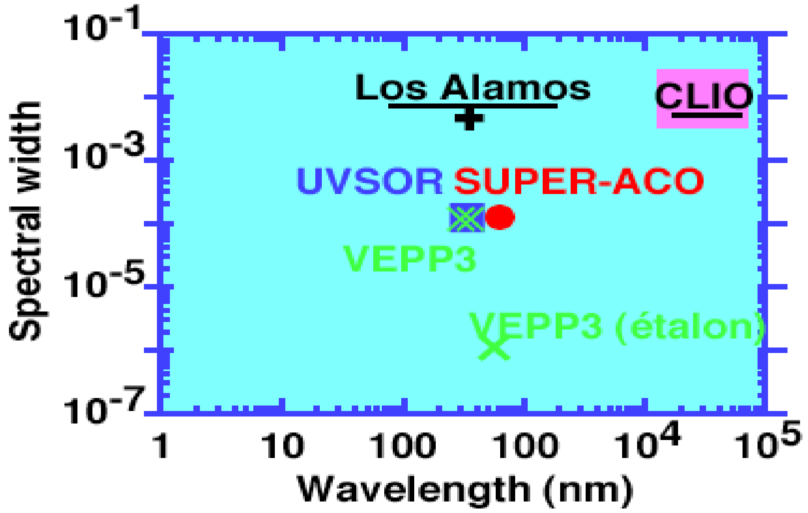


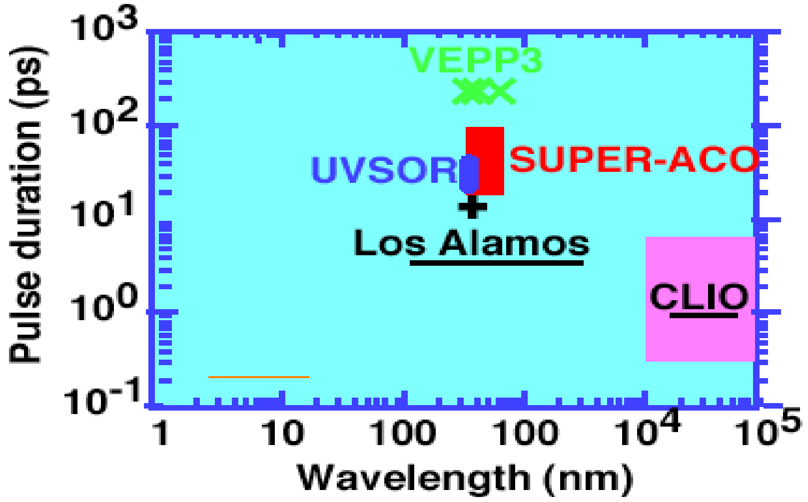




Optical cavities for storage ring FELs in the UV, M.E. Couprie, D. Garzella, M. Billardon, 1995, Nucl. Inst. Meth. A **358**, 382-386 (1995)

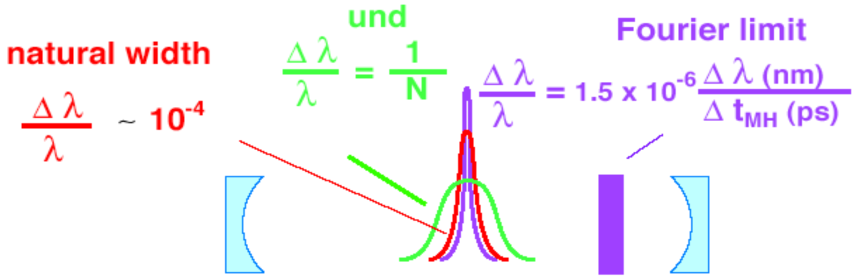
Temporal properties

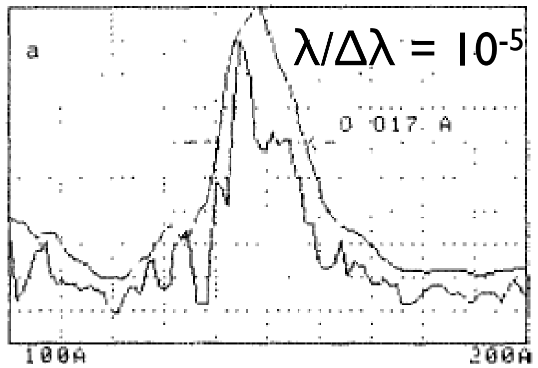




M. E. Couprie et al., NIMA 304 (1991) 47-52

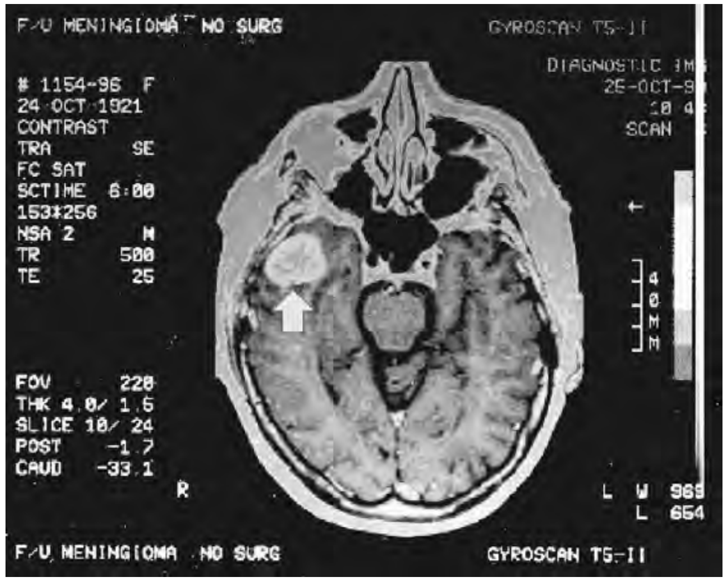
VEPP3 (Russia)





III. The first Free Electron Laser experimental results

User applications started



Human surgery

Edwards, G. S., Austin, R. H., Carroll, F. E., Copeland, M. L., Couprie, M. E., Gabella, W. E., ... & Joos, K. M. (2003). Free-electron-laser-based biophysical and biomedical instrumentation. Review of scientific instruments, 74(7), 3207-3245.

Photon echo

Edwards, G. S., Allen, S. J., Haglund, R. F., Nemanich, R. J., Redlich, B., Simon, J. D., & Yang, W. C. (2005). Applications of Free-Electron Lasers in the Biological and Material Sciences. Photochemistry and photobiology, 81(4), 711-735.

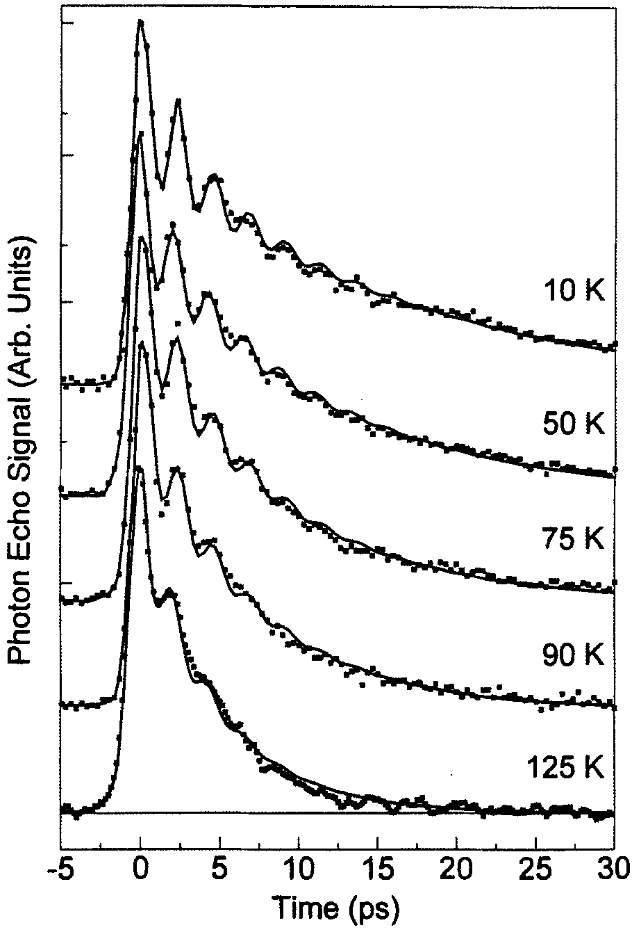
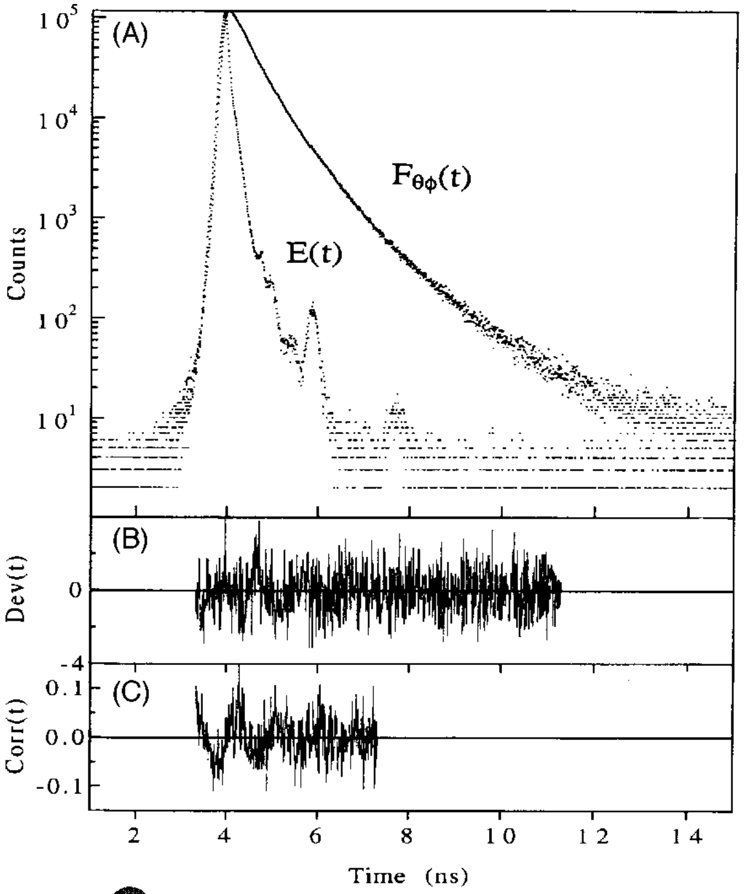
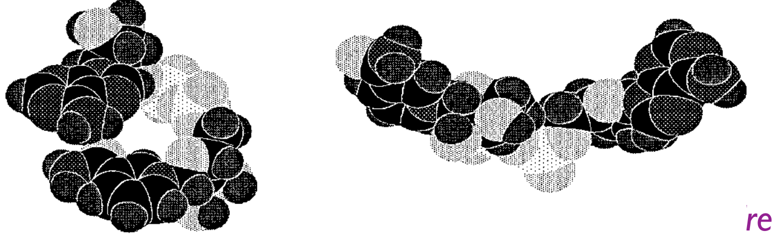


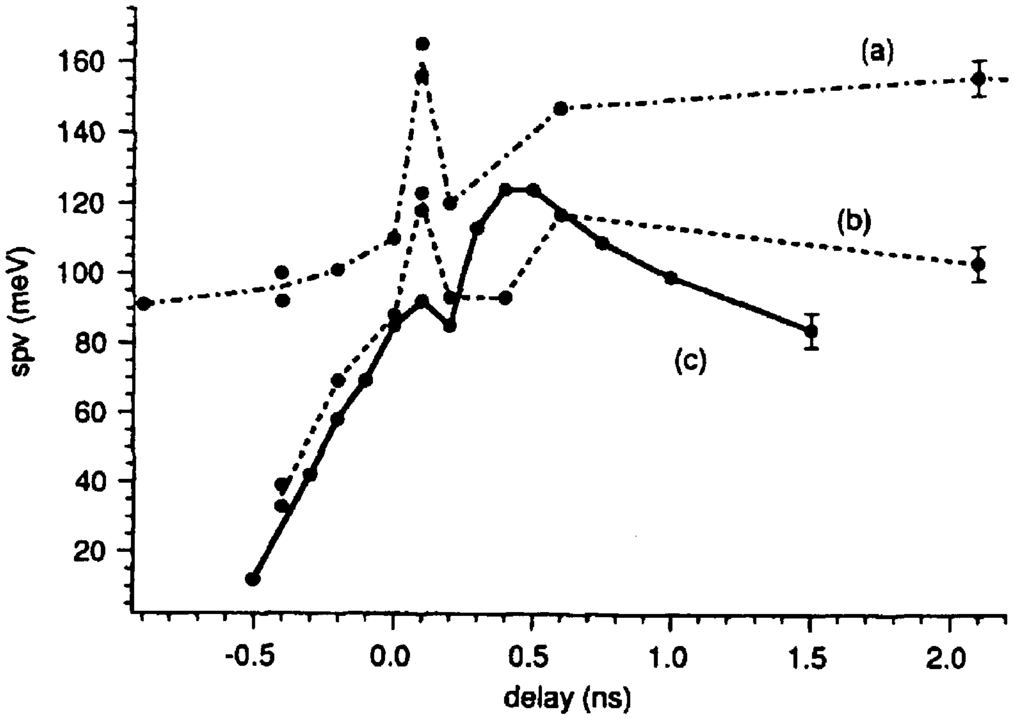
Figure 11. Beating evident in photon echo decays and fits for the asymmetric CO-stretching mode for $W(CO)_6$ in DBP as a function of temperature. Reprinted with permission from reference 37.



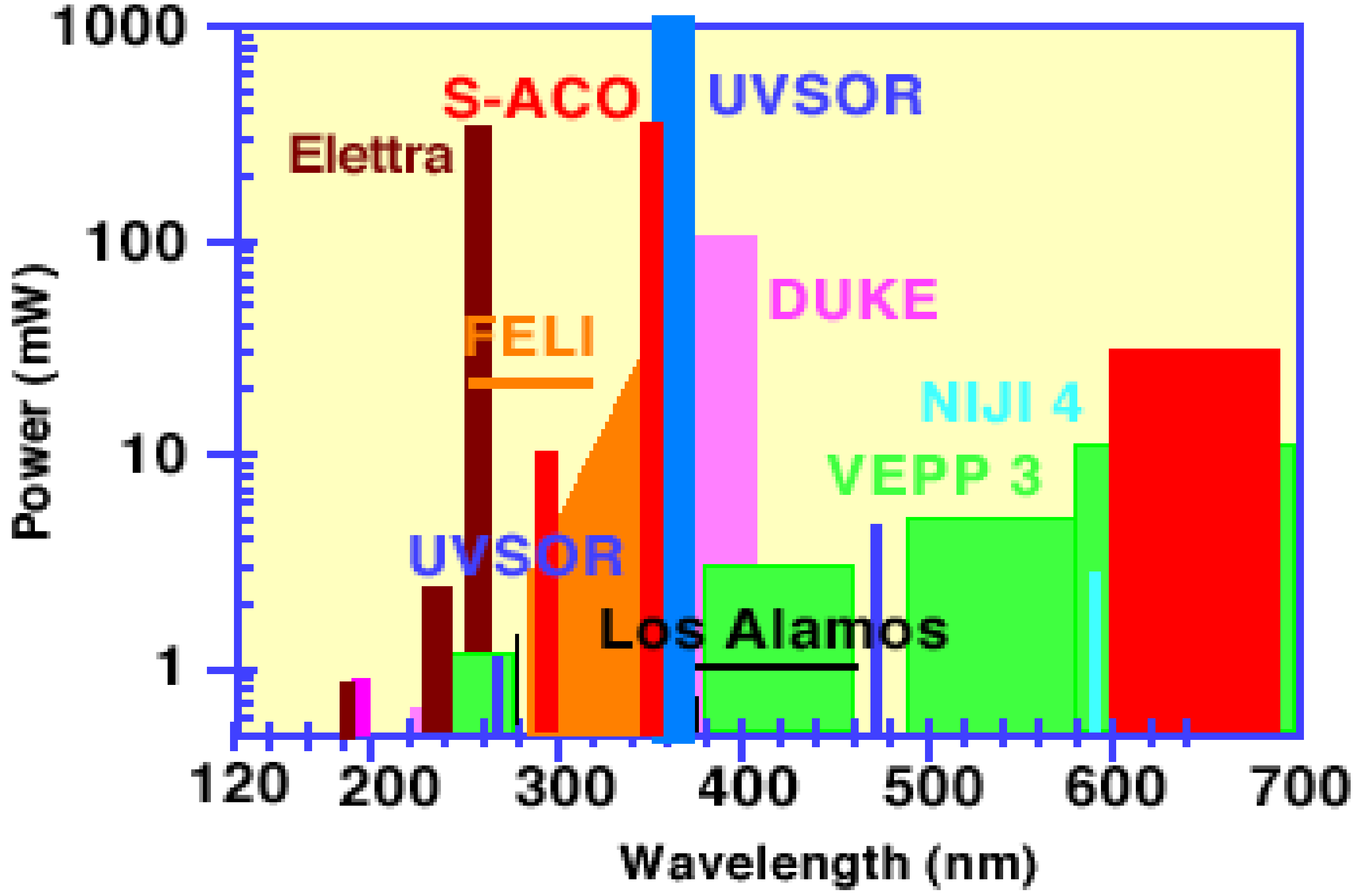


First use of the UV Super-ACO Free Electron Laser : fluorescence decays and rotational dynamics of the NADH coenzyme , M. E. Couprie, P. Tauc, F. Merola, A. Delboulbé, D. Garzella, T. Hara, M. Billardon , Rev. of Scient. Inst., 65(5) May 1994, 1485-1495

Surface States and Space Charge Layer Dynamics on Si (111)2x1 : a Free Electron Laser-Synchrotron radiation study , M. Marsi, M. E. Couprie, L. Nahon, D. Garzella, A. Delboulbé, T. Hara, R. Bakker, G. Indlekofer, M. Billardon, A. Taleb-Ibrahimi, , Appl. Phys. Lett. 70(7) (1997) 895-897



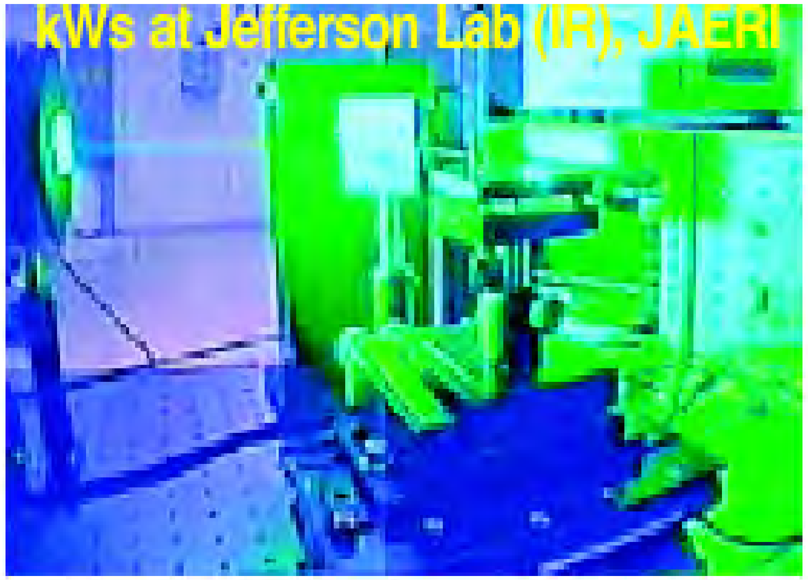
Wavelength limits of oscillator configuration



- Storage rings

VEPP3 (Russia)
Super-ACO (France)
NIJI-IV (Japan)
UVSOR (Japan)
Duke (USA)
ELETTRA (Italy)

- limited straight section length
- planar undulator : mirror degradation due to harmonic content



- Linacs

Stanford
Los Alamos
FELI (Japan)
.....

- ERLs :

Jefferson Lab
JAERI
Novosibirk

Limits in mirror performances

High gain studies

Strong signal case : Case of «long» undulator, «high» current : The change of electric field in one pass can not be neglected

treatment with a set of generalised Bloch equations

F.A. Hopf, P. Meystre, M. O. Scully, W. H. Louisell, Strong-signal theory of a Free Electron laser, Phys. Rev. Lett 17 (30) (1976) 1342-1345

Hamiltonian despcription

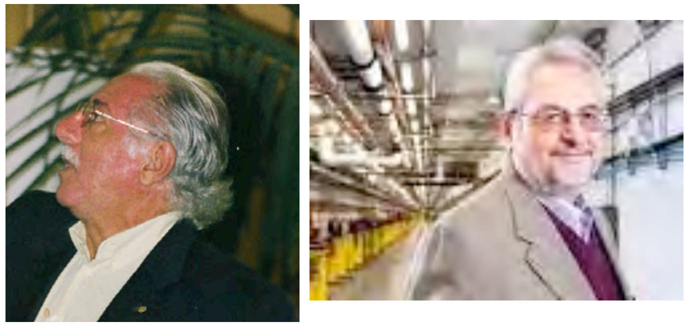
G. Dattoli, A. Marino, A. Renieri, F. Romanelli, Progress in the Hamiltonian Pictoure of the Free-Electron l Laser, IEEE journal of Quantum Electronics QE17 (8) 1371-1387 (1981)

N. M. Kroll, P. L. Morton, M. N. Rosenbluth, in Free Electron generators of coherent radiation, edited by S. F. Jacobs et al. Physics of Quantum Electronics 7 (Addison_Wesley), 147 (1980)
A. Gover, P. Srangle, IEEE J. Quantum Electron. 17, 1196 (1981)

Collective instability

the electron communicate with each other through the radiation and the space charge field.
=> electron «self bunching» on the scale of the radiation wavelength periods.
The electrons have nearly the same phase and emit collectively coherent synchrotron radiation.
Exponential growth of the radiation. Ex of cooperative effect in radiation-matter interaction

R. Bonifacio et al., Cooperative and chaotic transition of a free electron laser Hamiltonian model, Optics Communications 40(3), 1(1982), 219-223
R. Bonifacio, Pellegrini C. and L.M. Narucci, Collective instabilities and high-gain regime in a free electron laser, Opt. Comm. 50, 376 (1984)
Sprangle, P., Tang, C. M., & Roberson, C. W. (1985). Collective effects in the free electron laser. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 239(1), 1-18.
Bonifacio, R., Casagrande, F., Cerchioni, G., de Salvo Souza, L., Pierini, P., & Piovella, N. (1990). Physics of the high-gain FEL and superradiance. La Rivista del Nuovo Cimento (1978-1999), 13(9), 1-69.

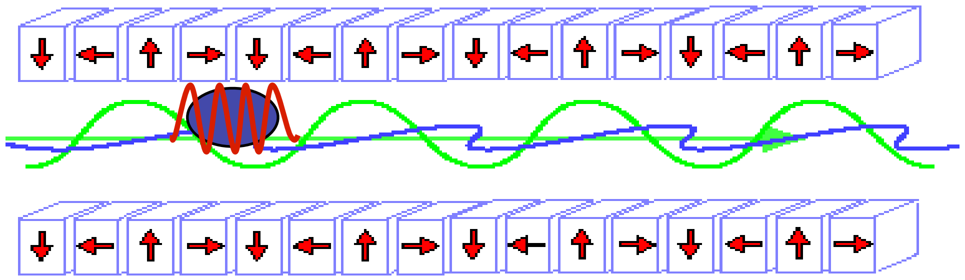


Start-up from spontaneous emission

First considered by Saldin and Kondratenko in order to amplify the emission in the high gain regime until saturation.
Considered cases : infra-red FEL @ 10 MeV, shorter wavelengths (20 GeV, 0.25 keV).

A.M. Kondratenko et al, Sou Phys. Dokl. 24 (12), 1979, 989
Kondratenko A.M., Saldin E.L.: Generation ofCoherent Radiation by a Relativistic Electron Beam in a Undulator. Part. Accelerators 10, 207–216 (1986)
Y.S. Derbenev, A.M. Kondratenko, E.L. Saldin: On the possibility of using a free electron laser for polarisation control in a storage ring, Nucl. Instr. Meth. A 193, 415–421 (1982)
K. J. Kim et al, PRL57, 1986, 1871
C. Pelligrini et al, NIMA475, 2001, 1

Self Amplified Spontaneous Emission (SASE)



High density electron beam and long undulator :

- a strong bunching takes place (space charge)
- the change in electric field can no more be neglected

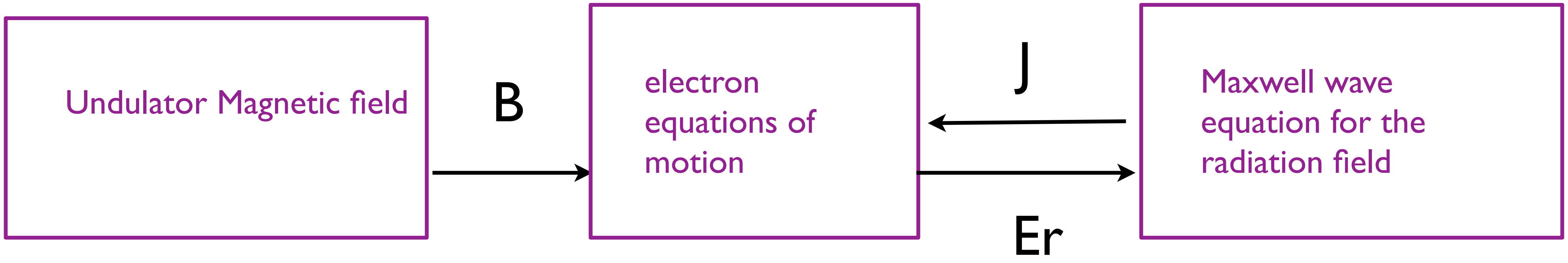
=>

- coupled pendulum equation, describing the phase space evolution of the particules under the combined undulator magnetic field and electric field of the optical wave

- evolution of the optical field

- evolution of the bunching coupled to the longitudinal sapce charge forces

=> evaluation of the electronic density and current
evaluation of the light wave evolution



Undulator Magnetic field

B

electron equations of motion

J

Er

Maxwell wave equation for the radiation field

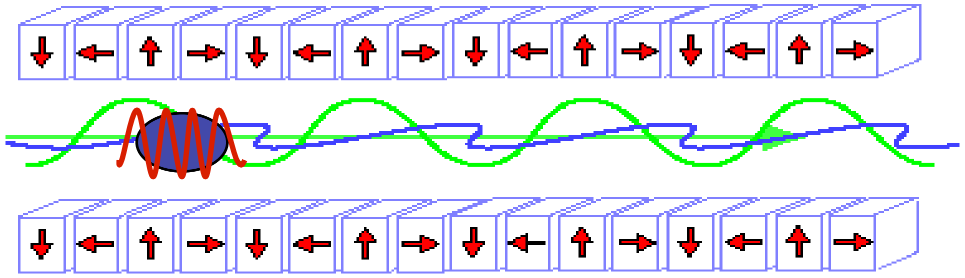
Collective instability

the electron communicate with each other through the radiation and the space charge field

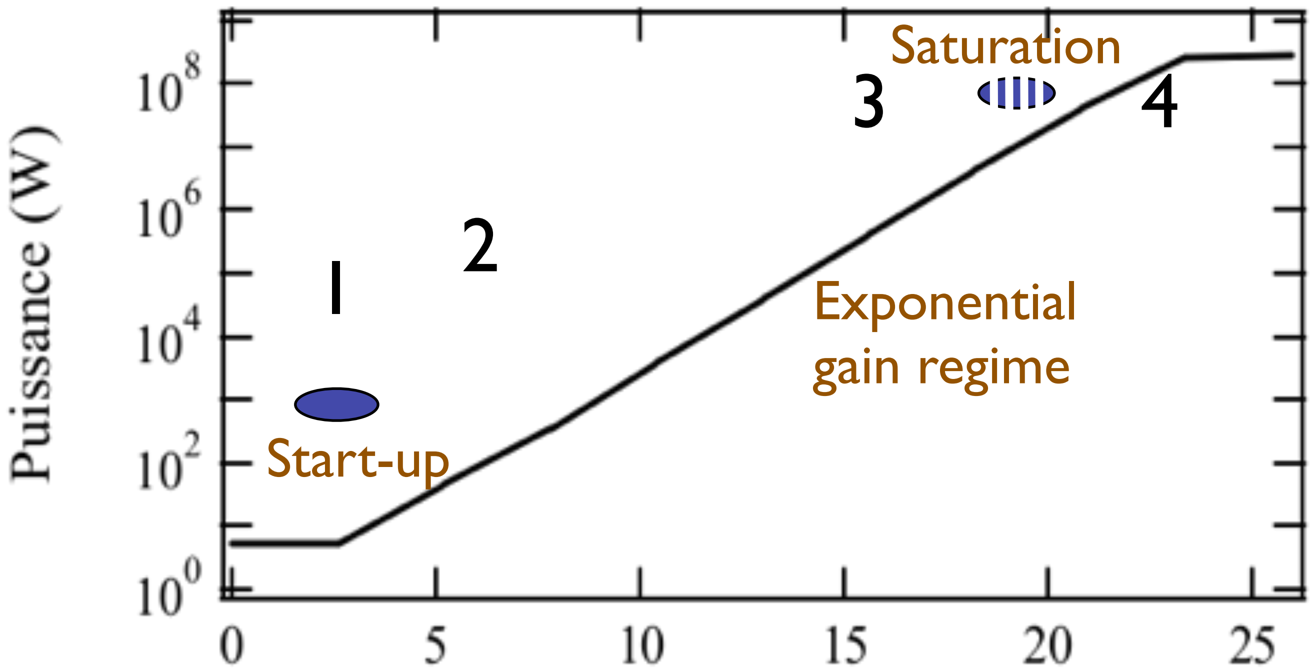
The FEL parameter defines the growth rate, measured in undulator periods

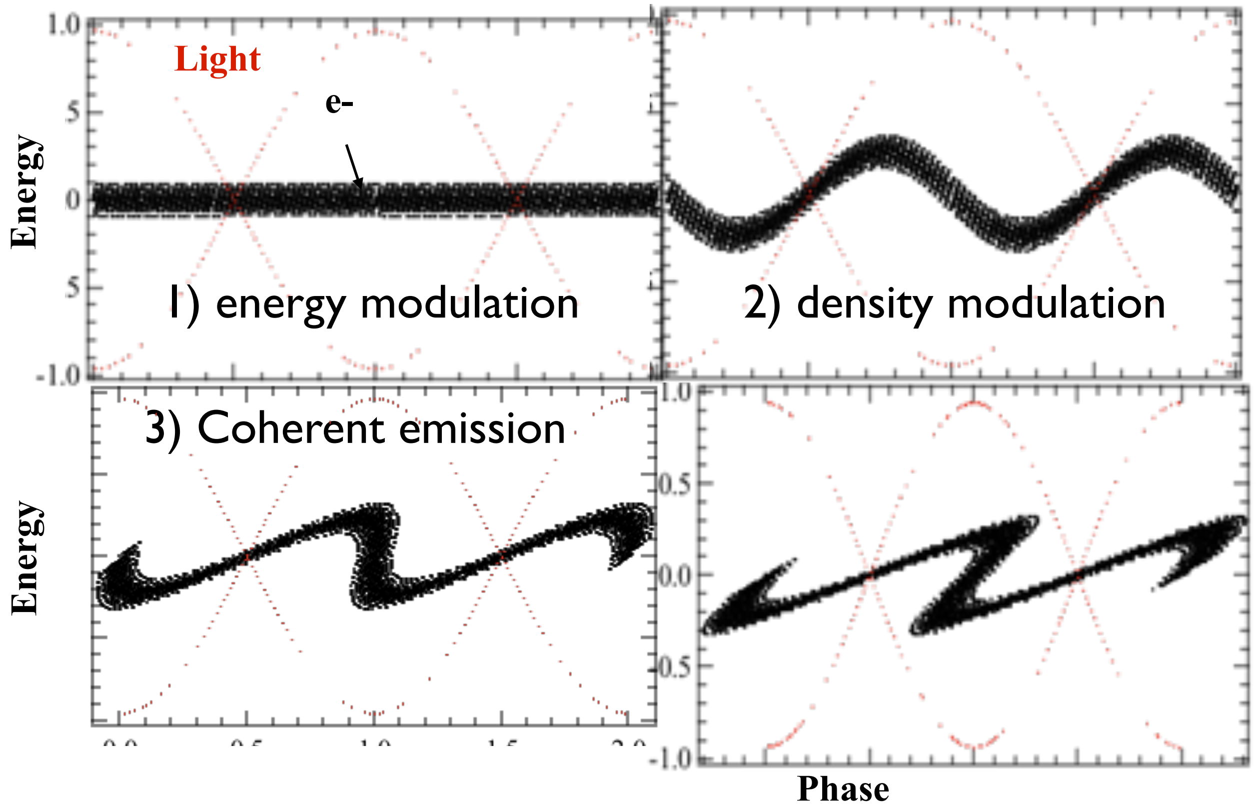
Review papers : Z. Huang, K. J. Kim, Review of the free-electron laser theory, Physical Review Special Topics-Accelerators and Beams, 10(3), 034801.
Pellegrini, C., A. Marinelli, and S. Reiche. "The physics of x-ray free-electron lasers." Reviews of Modern Physics 88.1 (2016): 015006.

Evolution of the light wave in the High gain regime



SASE : Self Amplified Spontaneous Emission
start-up from spontaneous emission noise
exponential growth due to a collective instability (self-organisation of the electrons from a ramdon initial state)
At saturation, the amplification process is replaced by a cyclic energy exchange between the electrons and the radiated field.





Optical guiding

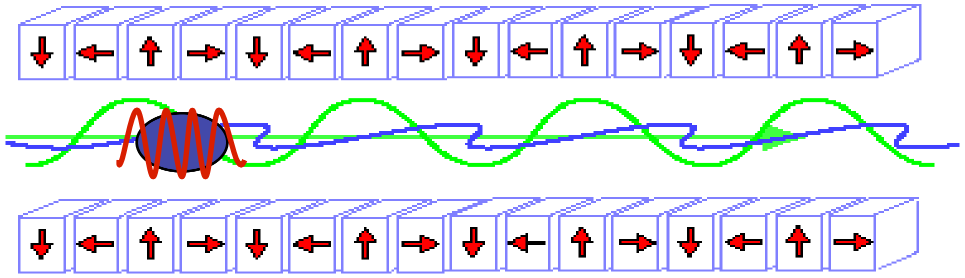
- gain guiding (quadratic gain medium, Kogelnick 1965)
- refractive index

=> undulator longer than a few Rayleigh lengths is possible

Scharlemann, E.T., A.M. Sessler and J.S. Wurtele, 1985, Physical Review Letters 54, 1925.
Scharlemann, E. T., Sessler, A. M., & Wurtele, J. S. (1985). Optical guiding in a free electron laser. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 239(1), 29-35.
Z. Huang, K. J. Kim, A Review of X-ray Free-Electron Laser theory, Phys. Rev. Spe. Topics AB, 10, 034801 (2007)

IV.The high gain Free Electron Laser

Evolution of the light wave in the High gain regime



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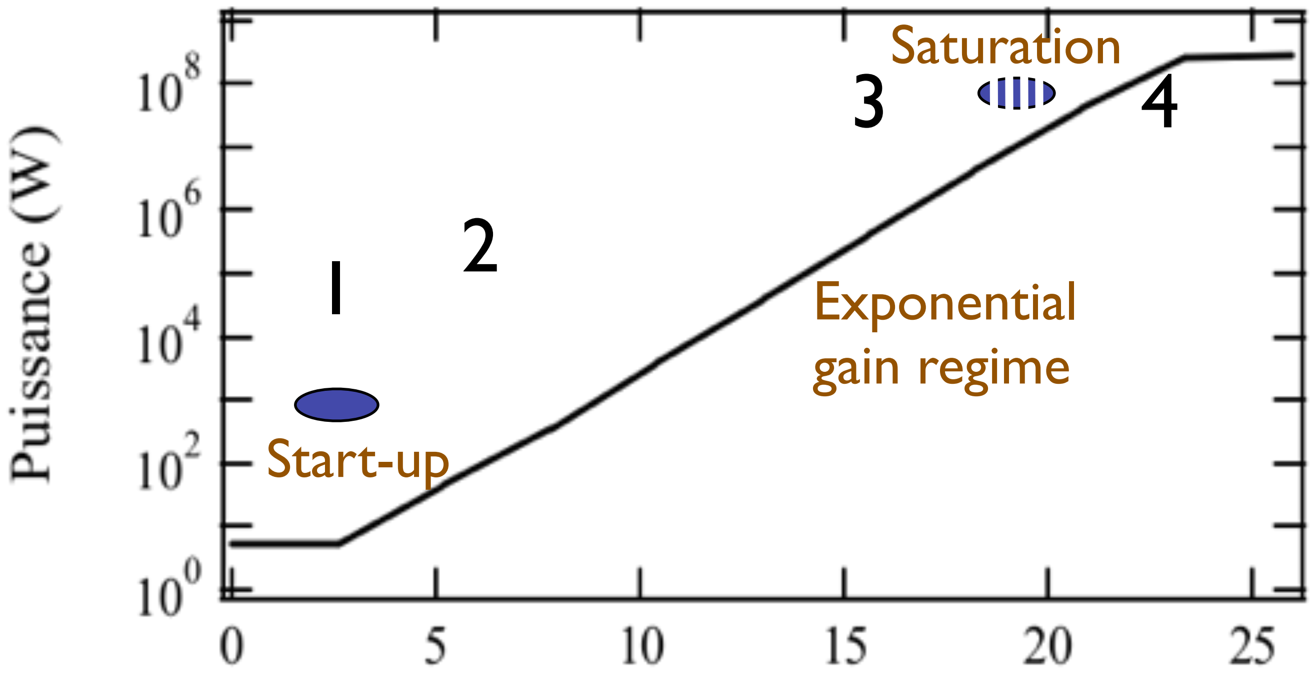

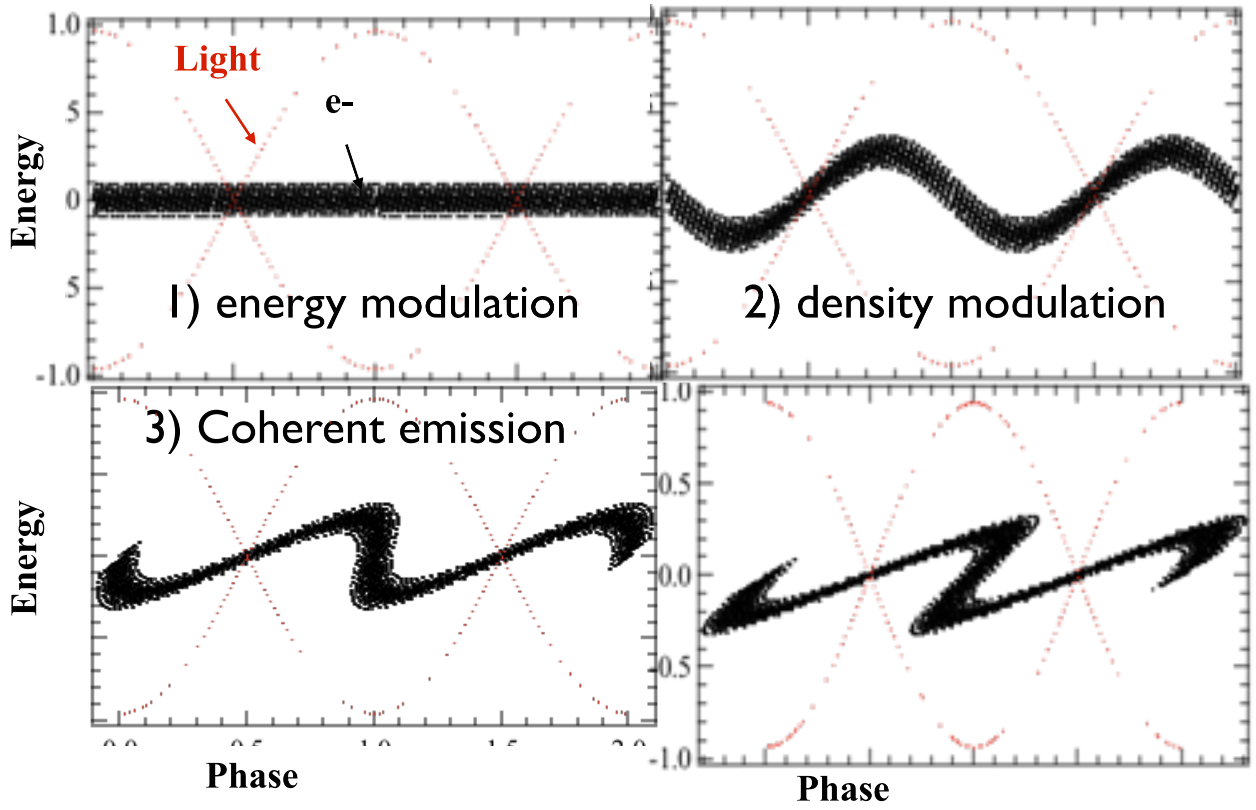

Optical guiding

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Scharlemann, E.T., Sessler, A. M., & Wurtele, J. S. (1985). Optical guiding in a free electron laser. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 239(1), 29-35.
Z. Huang, K. J. Kim, A Review of X-ray Free-Electron Laser theory, Phys. Rev. Spe. Topics AB, 10, 034801 (2007)

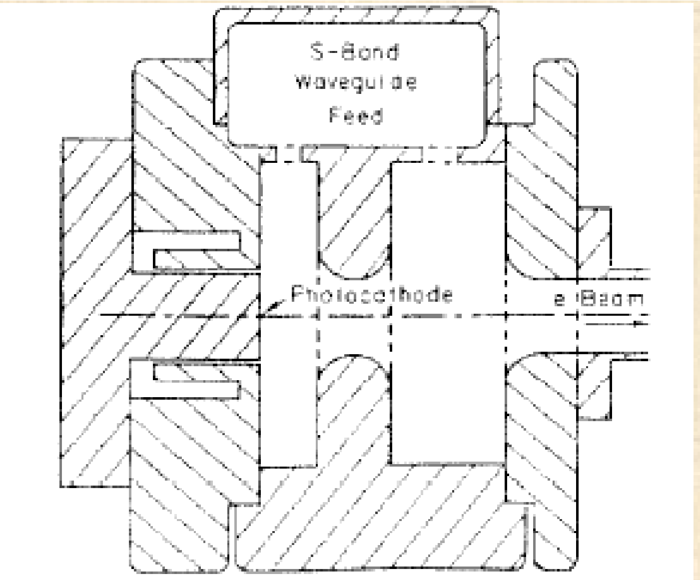
Limits in storage rings and electron gun development

Limits in storage ring

J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B, 2 (1985)

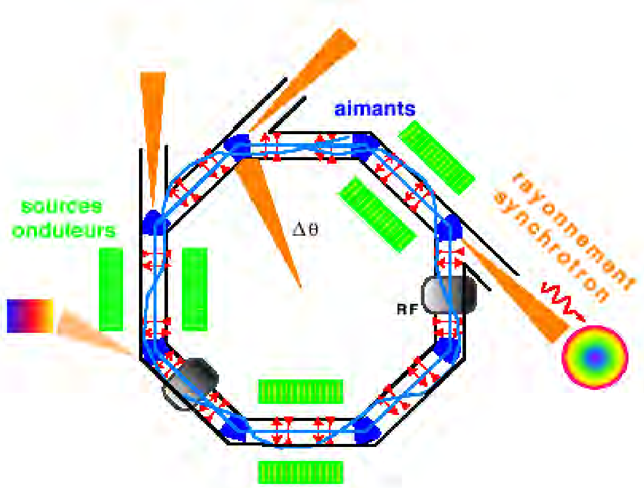
Developments of photo-injectors

Fraser, J.S. and R.L. Sheffield. 1987. High- brightness injectors for RF-driven free-electron lasers. IEEE J. Quantum Electron. QE-23: 1489-1496.
Batchelor, K., H. Kirk, K. McDonald, J. Sheehan and M. Woodle. 1988. Development of a High Brightness Electron Gun for the Accelerator Test Facility at Brookhaven National Laboratory. Proc. of the 1988 European Particle Accelerator Conf., Rome, pp. 54–958.



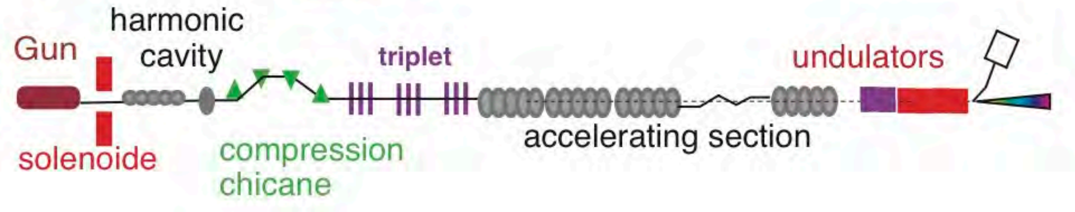
with a linac and a photoinjector it is possible to reach the nm region at a beam energy of 1.5 GeV, with about 6 mJ/pulse starting from noise in an 11 m long undulator

C. Pellegrini Nuclear Instruments and Methods A272, 364-367 (1988).



10–30ps, $\varepsilon \alpha E^2$

Energy spread : 0.1 %



10 fs–10 ps, $\varepsilon \alpha 1/E$

Energy spread : 0.01 %

Repetition rate : depending on the linac (room temperature or superconducting)

IV. The high gain Free Electron Laser

Historical observations of SASE

SASE at saturation mm waves (80's: LLNL, MIT)

T. Orzechowski et al. Phys. Rev. Lett 54, 889 (1985)

SASE at start-up μm (CLIO, L.A., Stanf.)

Prazeres, R., Ortega, J. M., Glotin, F., Jaroszynski, D.A., & Marcouillé, O. (1997). Observation of self-amplified spontaneous emission in the mid-infrared in a free-electron laser. Physical review letters, 78(11), 2124

Bunching (CESTA, 8mm)

Gardelle, J., Lefevre, T., Marchese, G., Rullier, J. L., & Donohue, J.T. (1997). High-power operation and strong bunching at 3 GHz produced by a 35-GHz free-electron-laser amplifier. Physical review letters, 79(20), 3905.

5 orders of magnitude of amplification (IR, UCLA/Los A.) and Saturation at 12 μm (UCLA/L.Alamos, 1998)

M. J. Hogan et al., Phys. Rev. Lett. 80, 289 (1998)
M. J. Hogan et al., Phys. Rev. Lett. 81, 4867 (1998)

Saturation at 530 nm, 385 nm (LEULT, 2000)

Milton, S.V., Gluskin, E., Biedron, S. G., Dejus, R. J., Den Hartog, P. K., Galayda, J. N., ... & Sereno, N. S. (2000). Observation of self-amplified spontaneous emission and exponential growth at 530 nm. Physical review letters, 85(5), 988.
S.V. Milton et al, Exponential gain and saturation of a Self-Amplified Spontaneous Emission Free- Electron Laser, www.sciencexpress.org / 17 May 2001 / Page 1/ 10.1126/science. 1059955

Saturation at 800 nm (UCLA, 2001)

Tremaine, A., Wang, X. J., Babzien, M., Ben-Zvi, I., Cornacchia, M., Nuhn, H. D., ... & Rosenzweig, J. (2002). Experimental characterization of nonlinear harmonic radiation from a visible self-amplified spontaneous emission free-electron laser at saturation. Physical review letters, 88(20), 204801.

Saturation at 100 nm (TESLA-TTF, 2001)

Ayvazyan, Valeri, et al. "A new powerful source for coherent VUV radiation: Demonstration of exponential growth and saturation at the TTF free-electron laser." The European Physical Journal D-Atomic, Molecular, Optical and Plasma Physics 20.1 (2002): 149-156.

SASE operation of the VUV FEL at 30 nm (DESY, 2005), 4 nm (2007)

Ackermann, W.A., Asova, G., Ayvazyan, V., Azima, A., Baboi, N., Bähr, J., ... & Brinkmann, R. (2007). Operation of a free-electron laser from the extreme ultraviolet to the water window. Nature photonics, 1(6), 336-342.

SCSS Test Acceletator at 60-40 nm

Shintake, T., Tanaka, H., Hara, T., Tanaka, T., Togawa, K., Yabashi, M., ... & Goto, S. (2008). A compact free-electron laser for generating coherent radiation in the extreme ultraviolet region. Nature Photonics, 2(9), 555-559.

SASE operation of the LCLS at 0.15 nm

Emma, P., Akre, R., Arthur, J., Bionta, R., Bostedt, C., Bozek, J., ... & Ding, Y. (2010). First lasing and operation of an ångstrom-wavelength free-electron laser. nature photonics, 4(9), 641-647.

SASE operation at SACLA at 0.08 nm

Ishikawa, T., Aoyagi, H., Asaka, T., Asano, Y., Azumi, N., Bizen, T., ... & Goto, S. (2012). A compact X-ray free-electron laser emitting in the sub-angstrom region. Nature Photonics, 6(8), 540-544.

SASE : Conditions for amplification

Conditions for amplification

- The electron beam should be rather "cold", its energy spread should be smaller than the bandwidth, i. e.

$$\frac{\sigma_\gamma}{\gamma} < \rho_{FEL}$$

- There should be a proper transverse matching (size, divergence) between the electron beam and the photon beam along the undulator progression for insuring a proper interaction. It means that the emittance should not be too large at short wavelength. For long undulators, intermediate focusing is then put between undulator segments. It writes :

$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda}{4\pi}$$

It only became possible to reach FEL at short wavelength because of the progresses on electron guns.

- The radiation diffraction losses should be smaller than the FEL gain, i.e. the Rayleigh length should be larger than the gain length.

$$Z_r > L_{go}$$

Corrections terms

M. Xie Nucl. Inst. Meth. A 445, 59 (200)
M. Xie, Porceedings PAC 1995, 183

SASE properties

Limited temporal coherence: start-up from noise, bunching on different trains of the bunch
=> "spikes" in spectral and temporal distribution

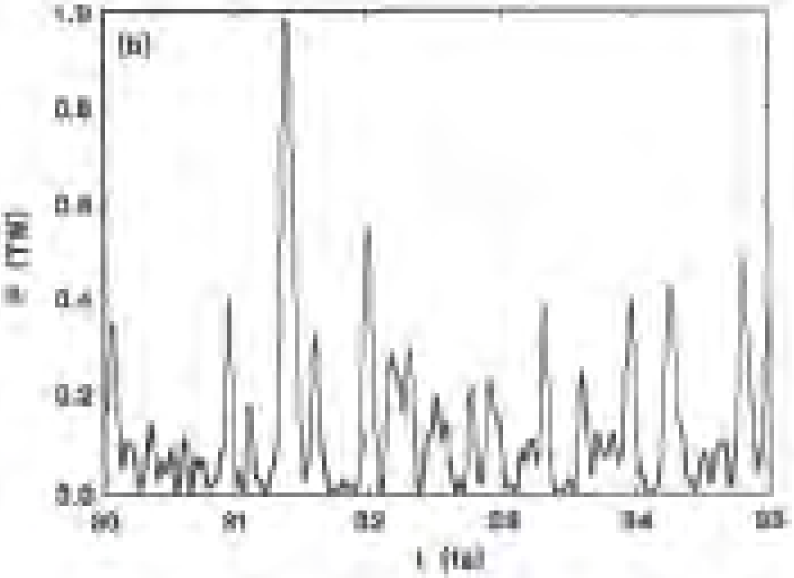
Cooperation length : slippage over one gain length

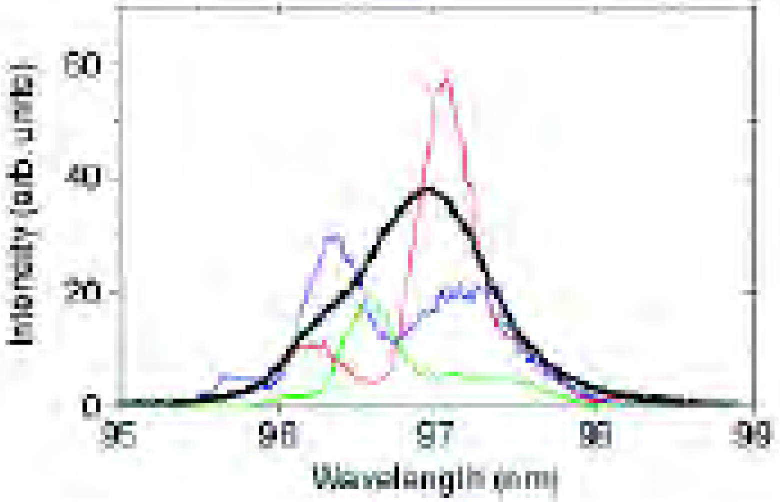
Nber of spikes = bunch length / cooperative length

$$l_c \sim \lambda/4\pi\rho$$

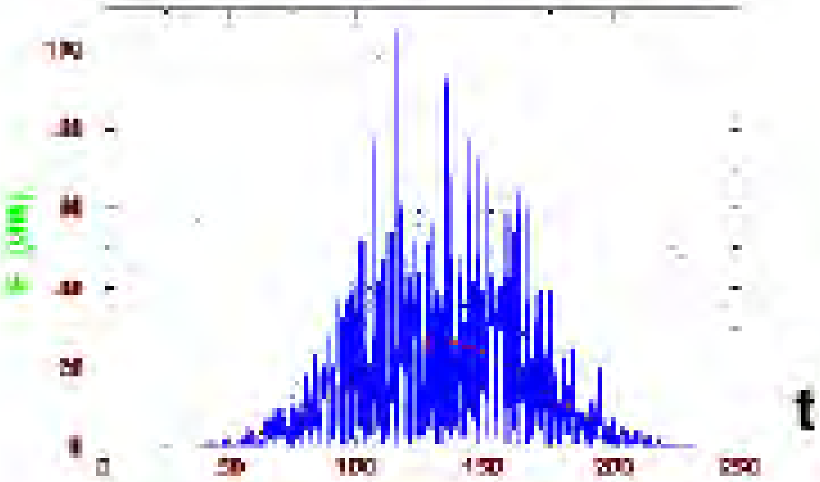
Spikes : separated by one cooperative length
spectral width : ρ

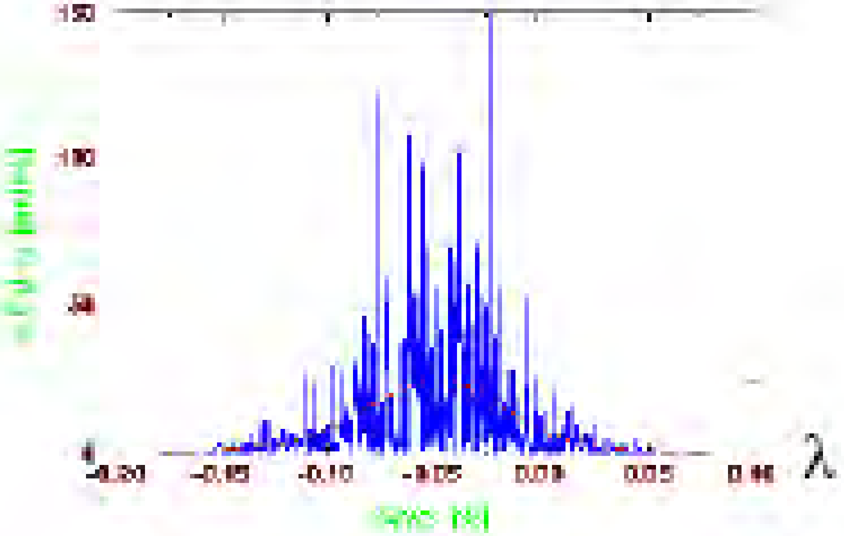
Statistics : Gamma distribution





- jitter from pulse to pulse





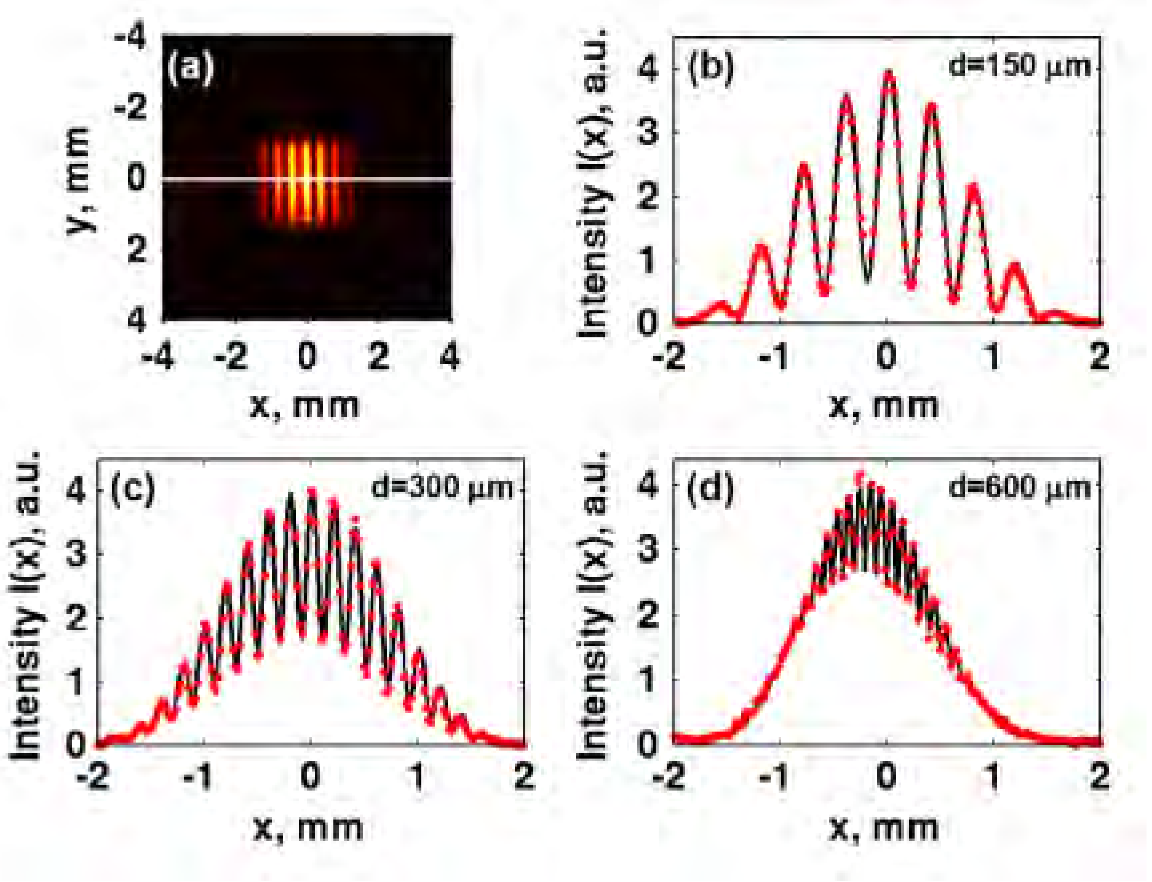
Handling :
single spike
taper
seeding and self seeding

S. Reiche et al., NIMA 593 (2008) 45-48
L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)

IV. The high gain Free Electron Laser

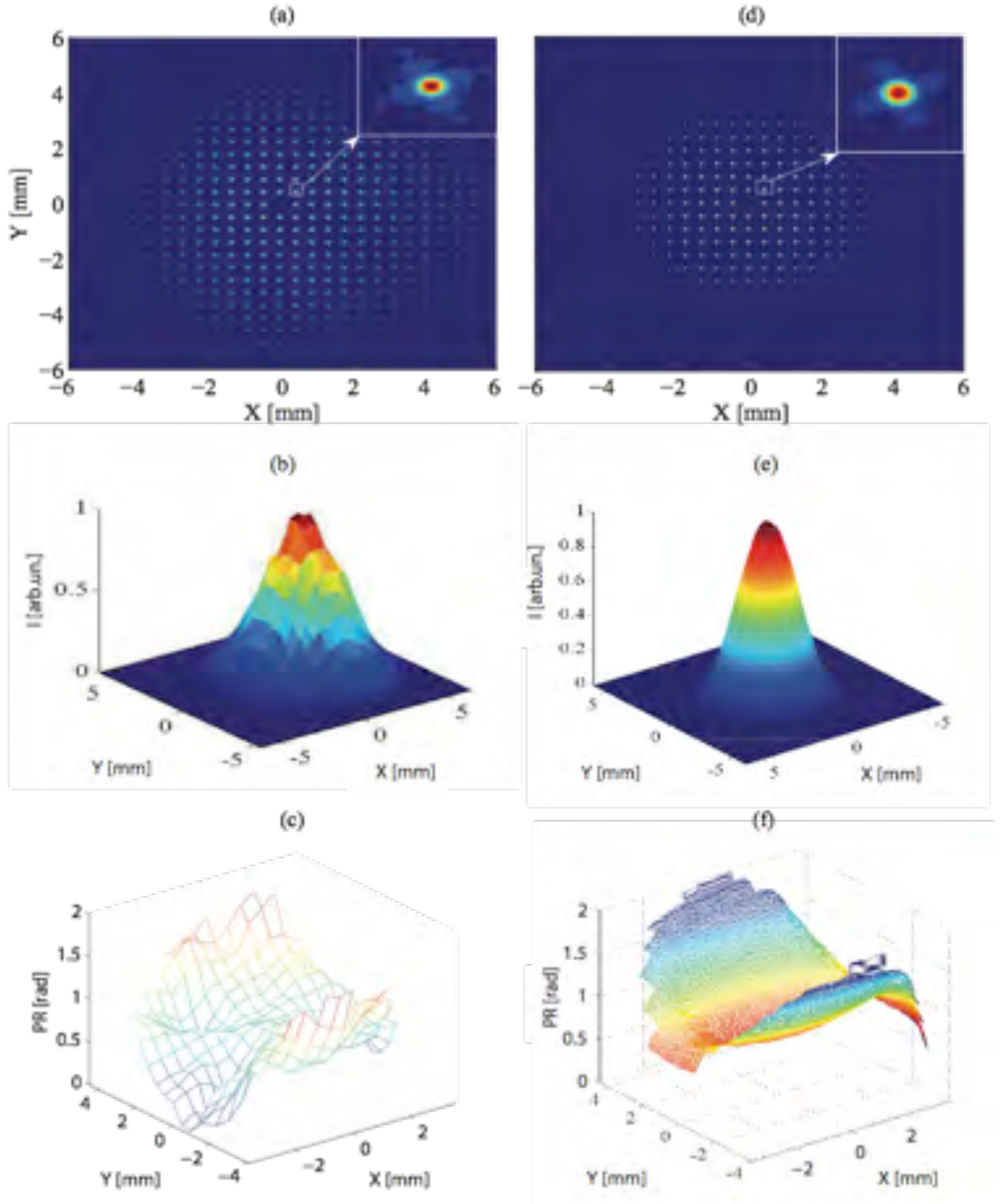
SASE properties

FLASH



M. Kuhlmann et al, FEL06
P. Mercère et al, , Optics Letters, 28 (17), 1534-1536 (2003)
A. Singer et al. PRL 101, 254801 (2008)

SCSS Test Accelerator : 60-40 nm

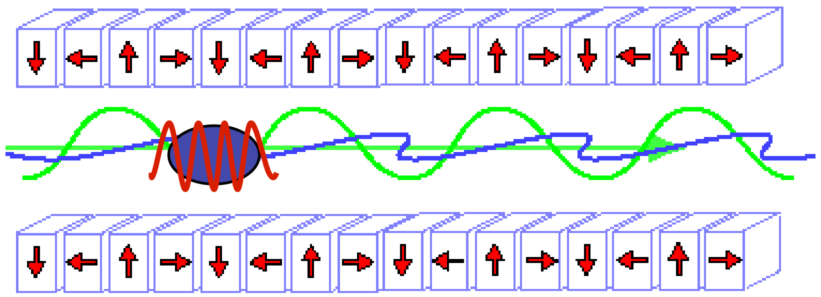


Single-shot wavefront analysis of SASE harmonics in different FEL regimes, R. Bachelard, P. Mercere, M. Idir, M. E. Couprie, M. Labat, O. Chubar, G. Lambert, P. Zeitoun, H. Kimura, H. Ohashi, A. Higashiya, M. Yabashi, N. Nagasono, T. Hara, T. Ishikawa, accpeted in Phys. Rev. Lett. 2011

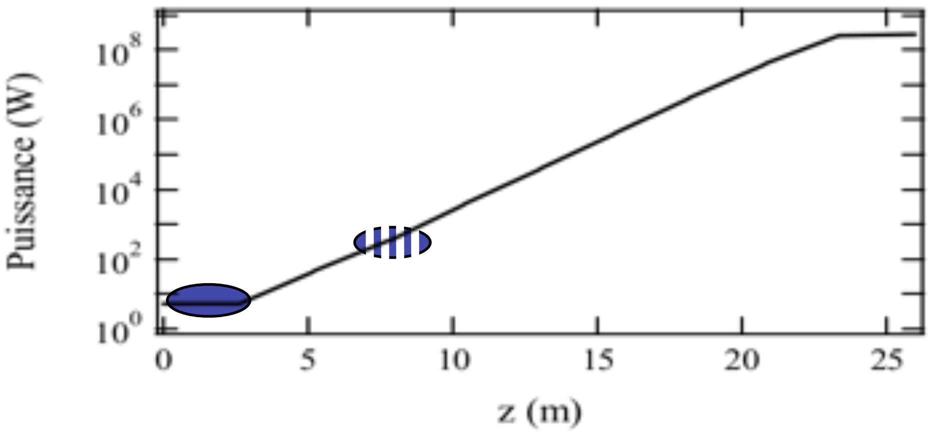
Wavefront quality : ability to properly focus

SASE Versus seeding and echo

SASE (Self Amplified Spontaneous Emission) : no laser - electron interaction



$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad K = 0.94\,\lambda_0\,(\text{cm})\,B_0\,(\text{T})$$



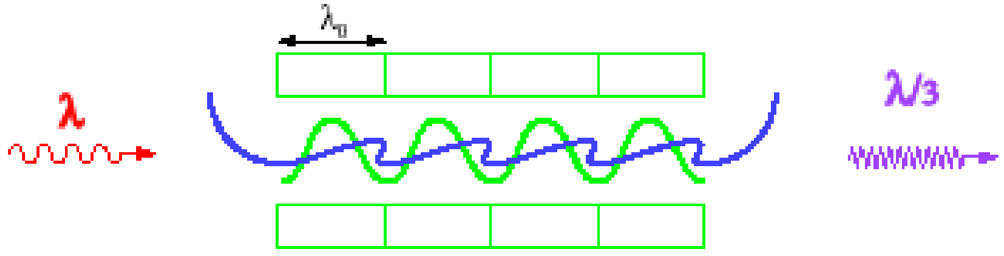
R. Bonifacio et al, Opt. Comm. 50, 1984, 376, K. J. Kim et al, PRL57, 1986, 1871, C. Pelligrini et al, NIMA475, 2001, 1, A.M. Kondratenko et al, Sou Phys. Dokl. 24 (12), 1979, 989

- short wavelength operation (1 Å)
- good transverse coherence => low emittance required=> gun, energy
- spike
- single spike (low charge, chrip/taper), self-seeding

S. Reiche et al., NIMA 593 (2008) 45-48

L. Giannessi et al., Phys. Rev. Lett. 106, 144801 (2011)

Seeding : one laser-electron interaction



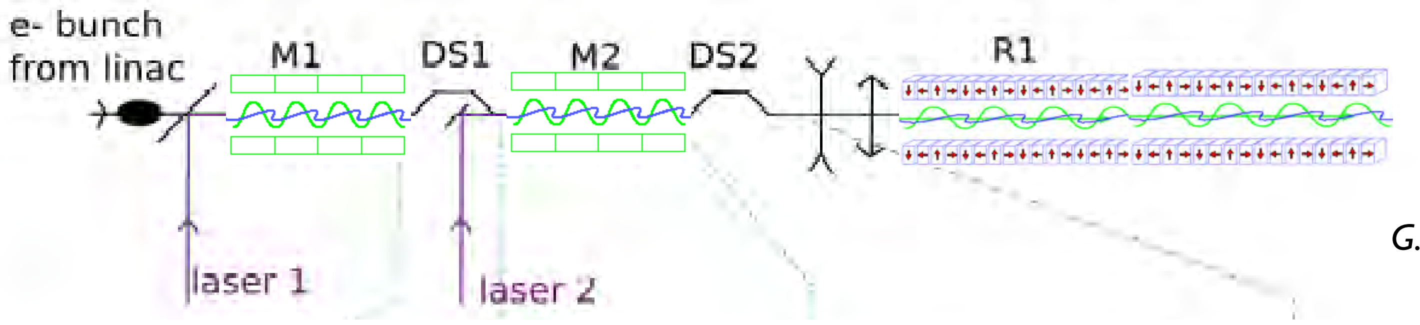
- temporal coherence given by the external seed laser
- improved stability (intensity, spectral fluctuations and jitter) => pump-probe experiments
- quicker saturation => cost and size reduction
- good transverse coherence
- Seed : laser and HHG (60 nm)

L. H. Yu et al, Science 289, 2000, 932

L. H. Yu et al, PRL91 2003, 074801

T. Saftan APAC 2004, Gyeongu

Echo : Echo Enable Harmonic Generation : two laser - electron interactions



$$\frac{1}{\lambda_{echo}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

G. Stupakov., PRL 102, 074801 (2009)

high order harmonics reached in a compact manner

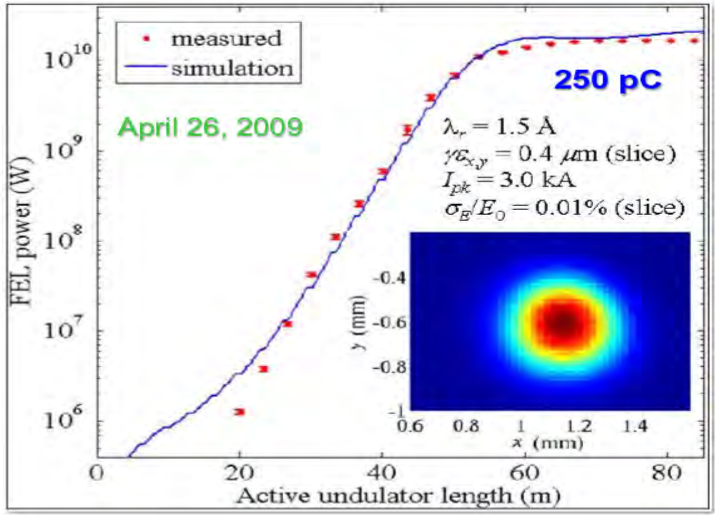
Zhao et al., Proceed FEL conf, Mamö (2010)

D. Xiang et al., PRL 105, 114801 (2010)

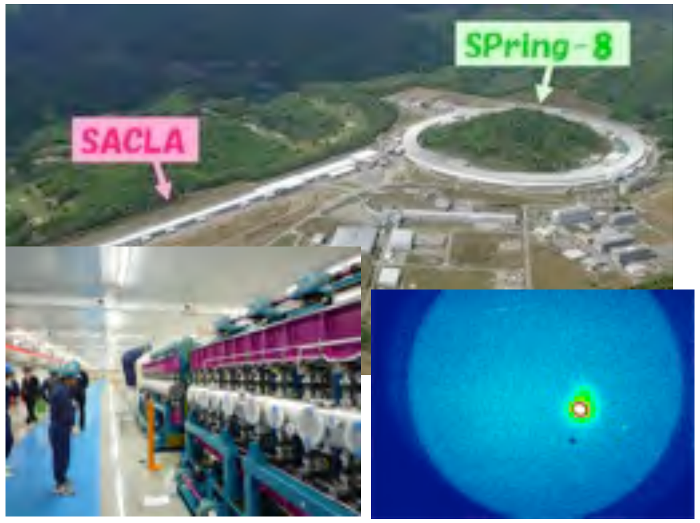
IV. The high gain Free Electron Laser

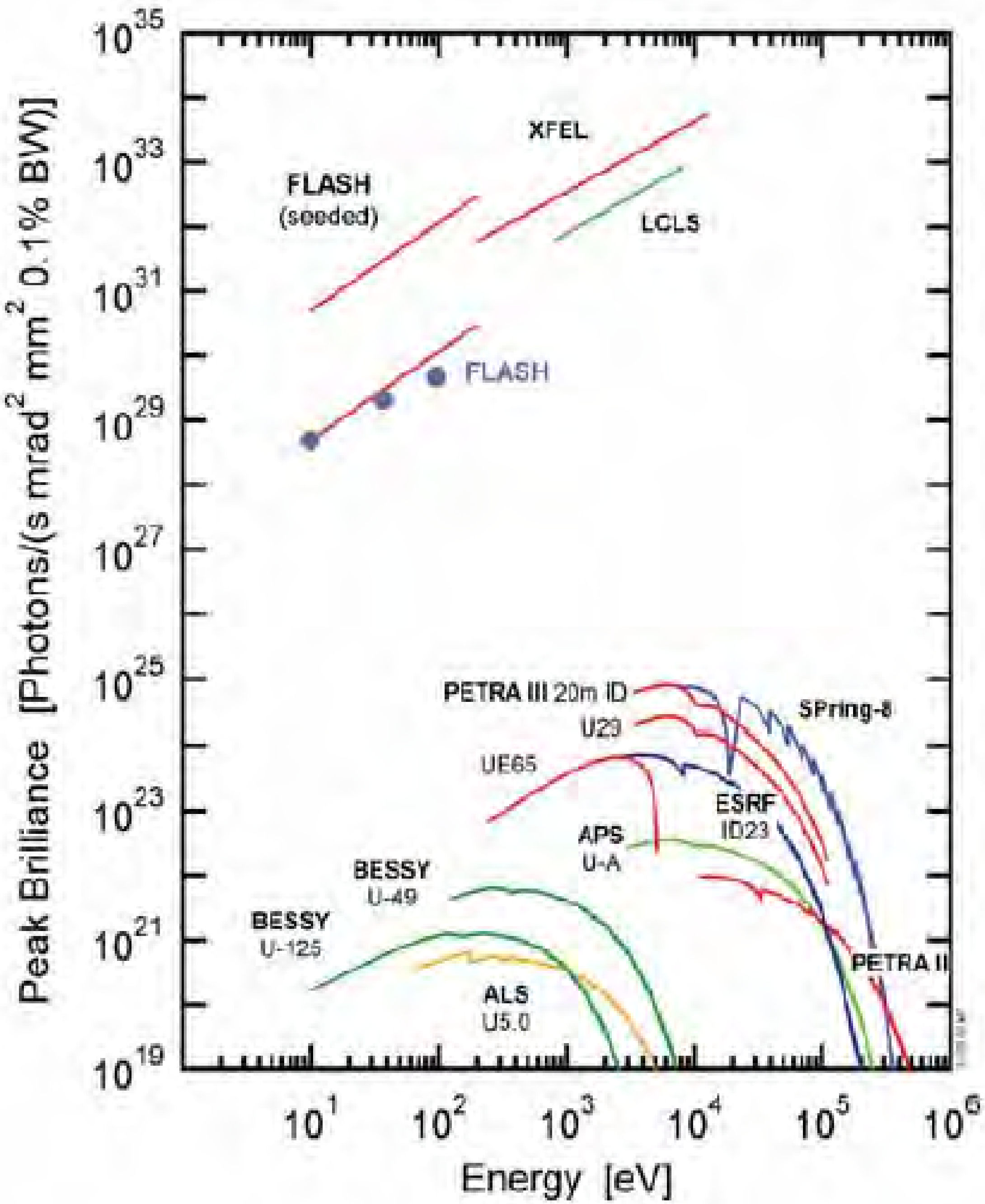
X-ray FELs

LCLS 2 mJ, 1.4 Å
1.5 Å saturation at 65 m (of 112 m)
now 6 mJ, 96.7 % availability

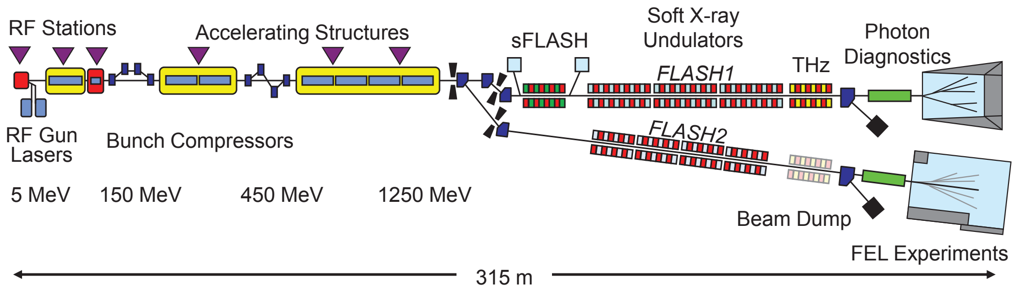


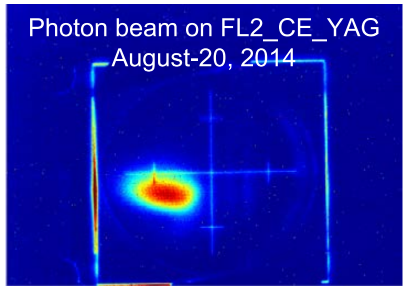
SACLA



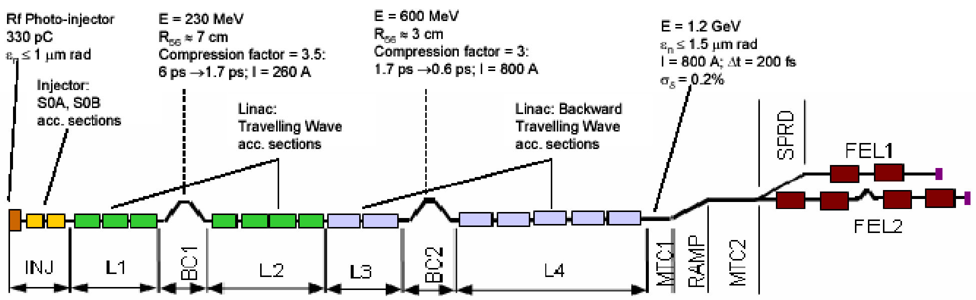


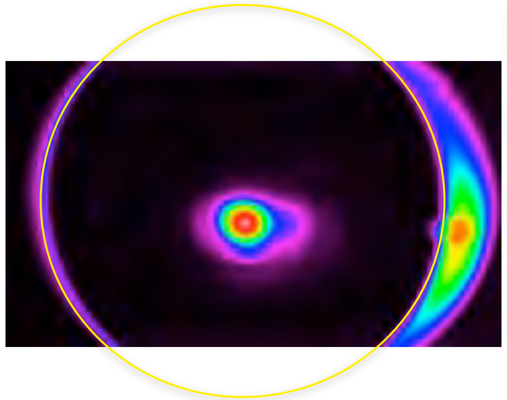
FLASH





FERMI



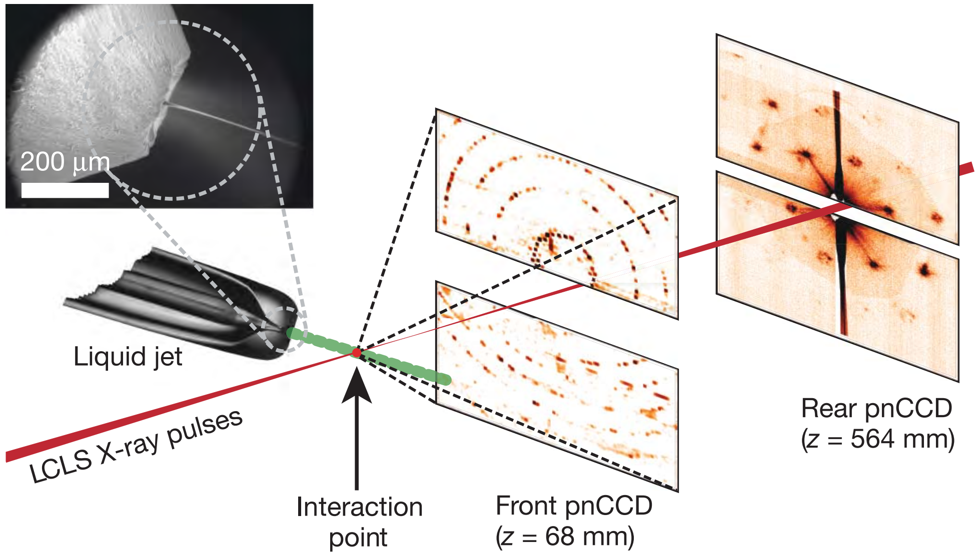


to come : E XFEL, PAL FEL, Swiss FEL ....

Applications of FELs in the X-ray domain

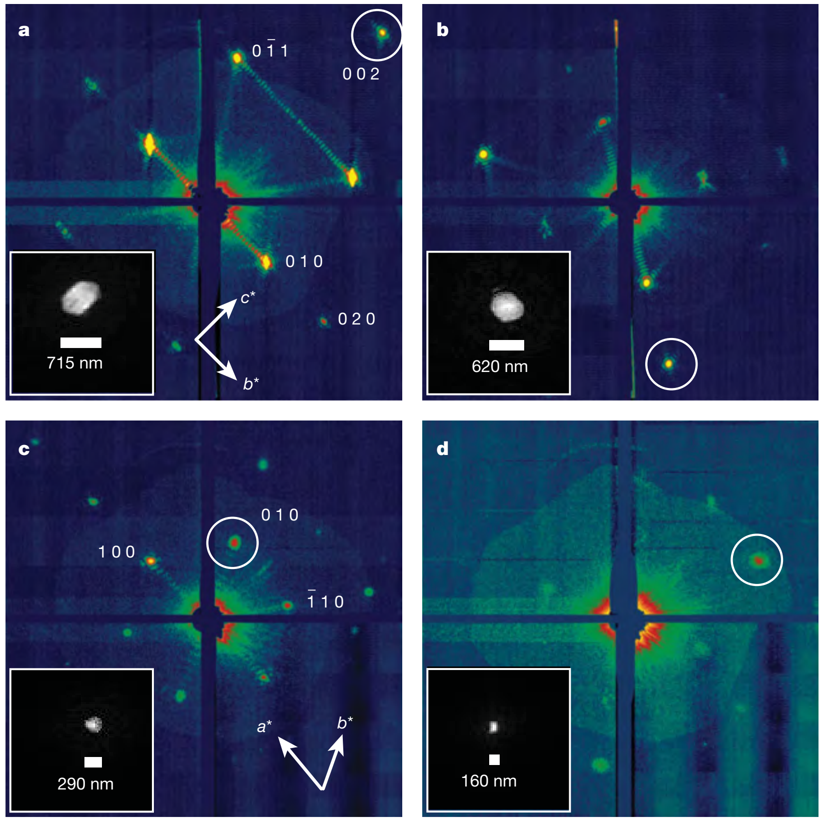
Towards imaging of living cells

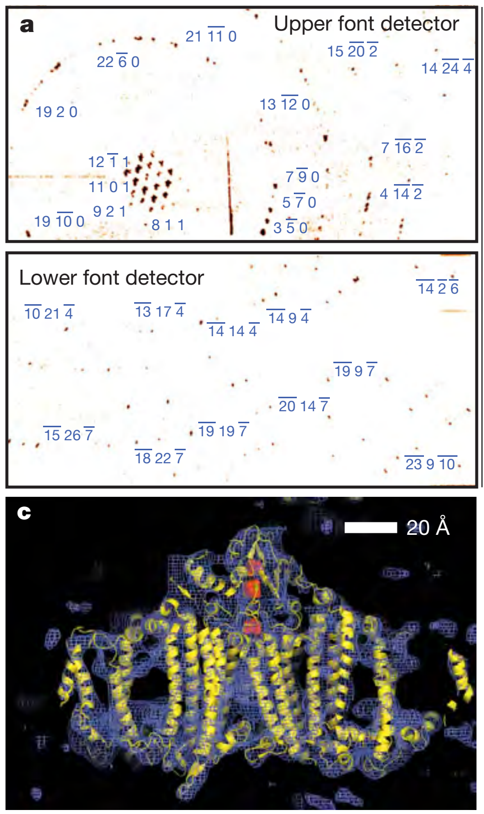
Jet (10 m/s)



Membran protein photosystem I

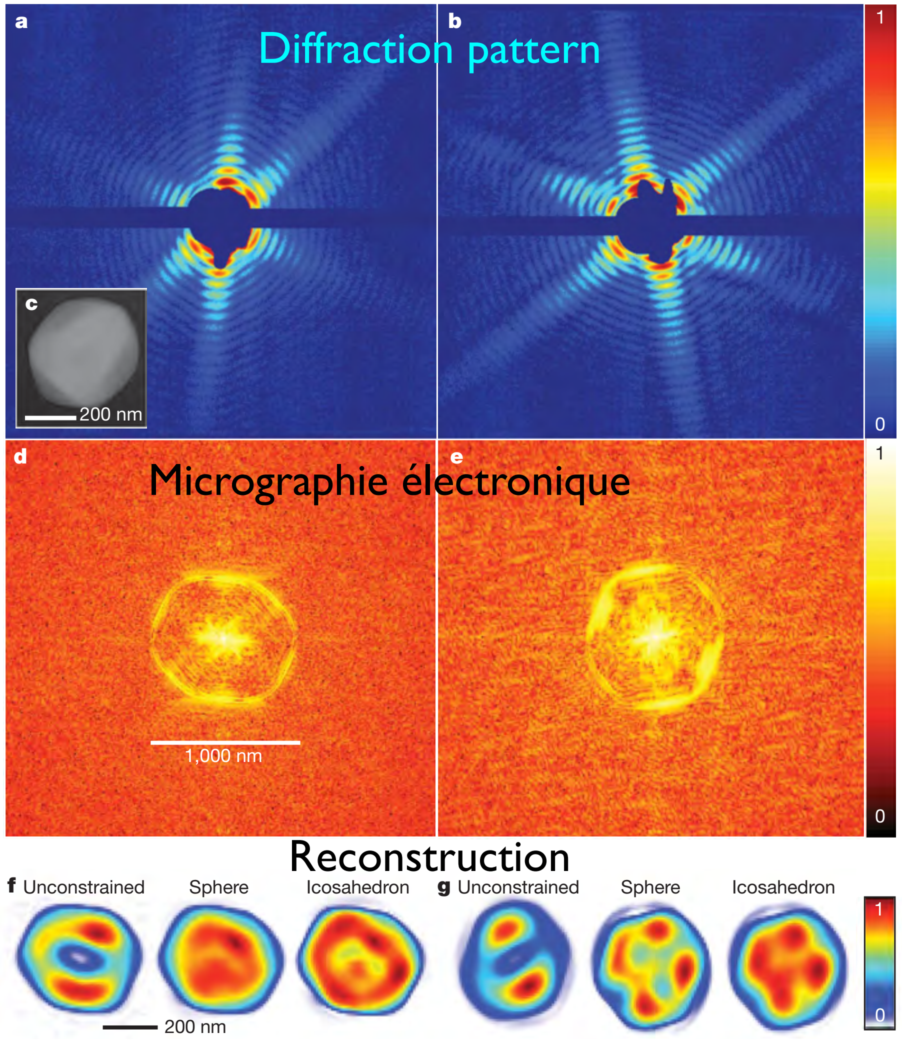
Diffraction pattern





H. Chapman et al., *Femtosecond X-ray protein nanocrystallography*, Nature, 470, 2011, 73

Mimivirus (Acanthamoeba polyphaga) : le plus gros virus connu (diamètre de 0.75 µm)

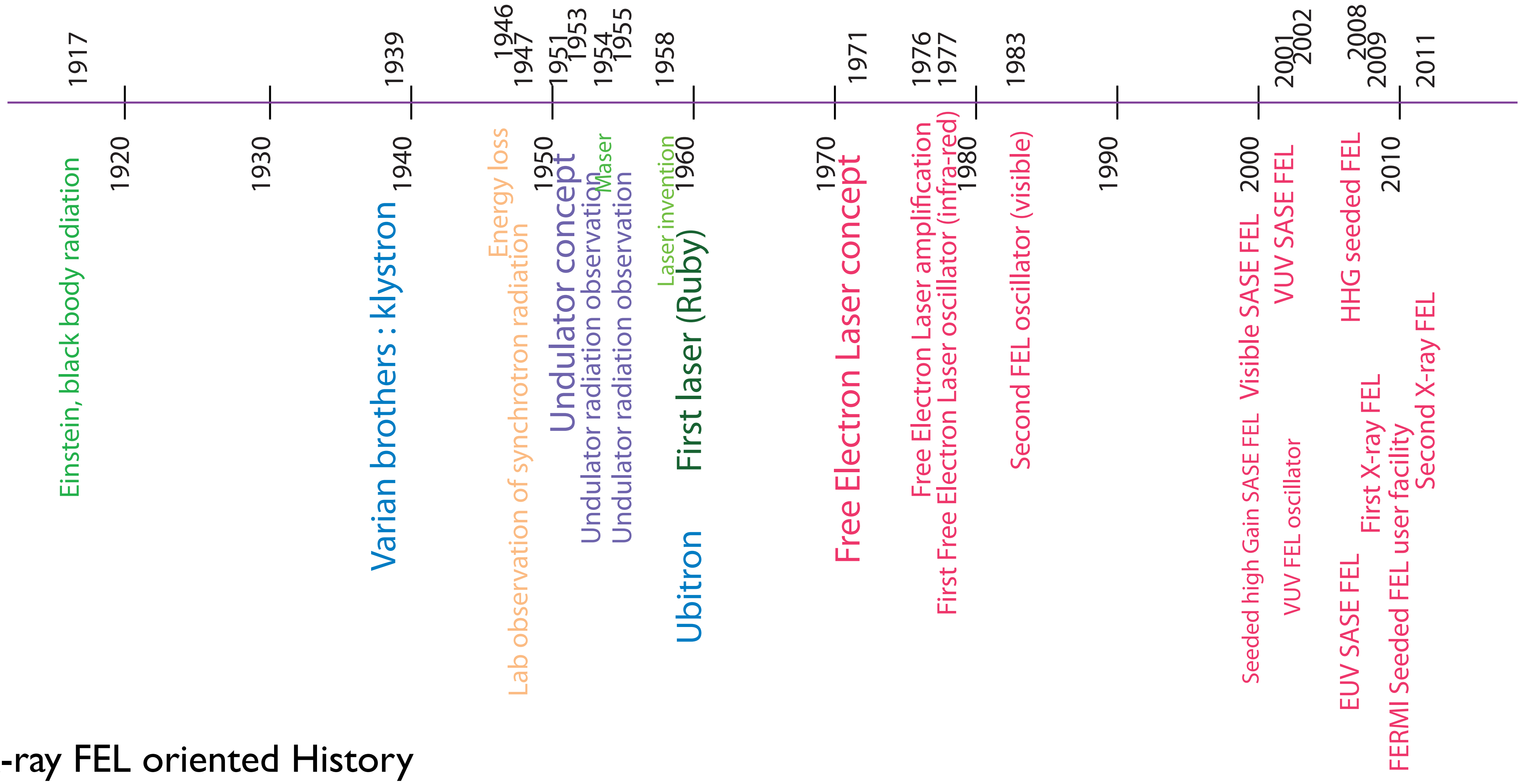


M. M. Seibert et al., Single mimivirus particles intercepted and imaged with an X-ray laser, Nature, 470, 2011, 78

Conclusion

Historical survey of FELs :

- exchange of ideas and concepts in various domains : creativity !
- attempting to show how the new ideas arise
- subjective (apologize for cherished non cited papers...)



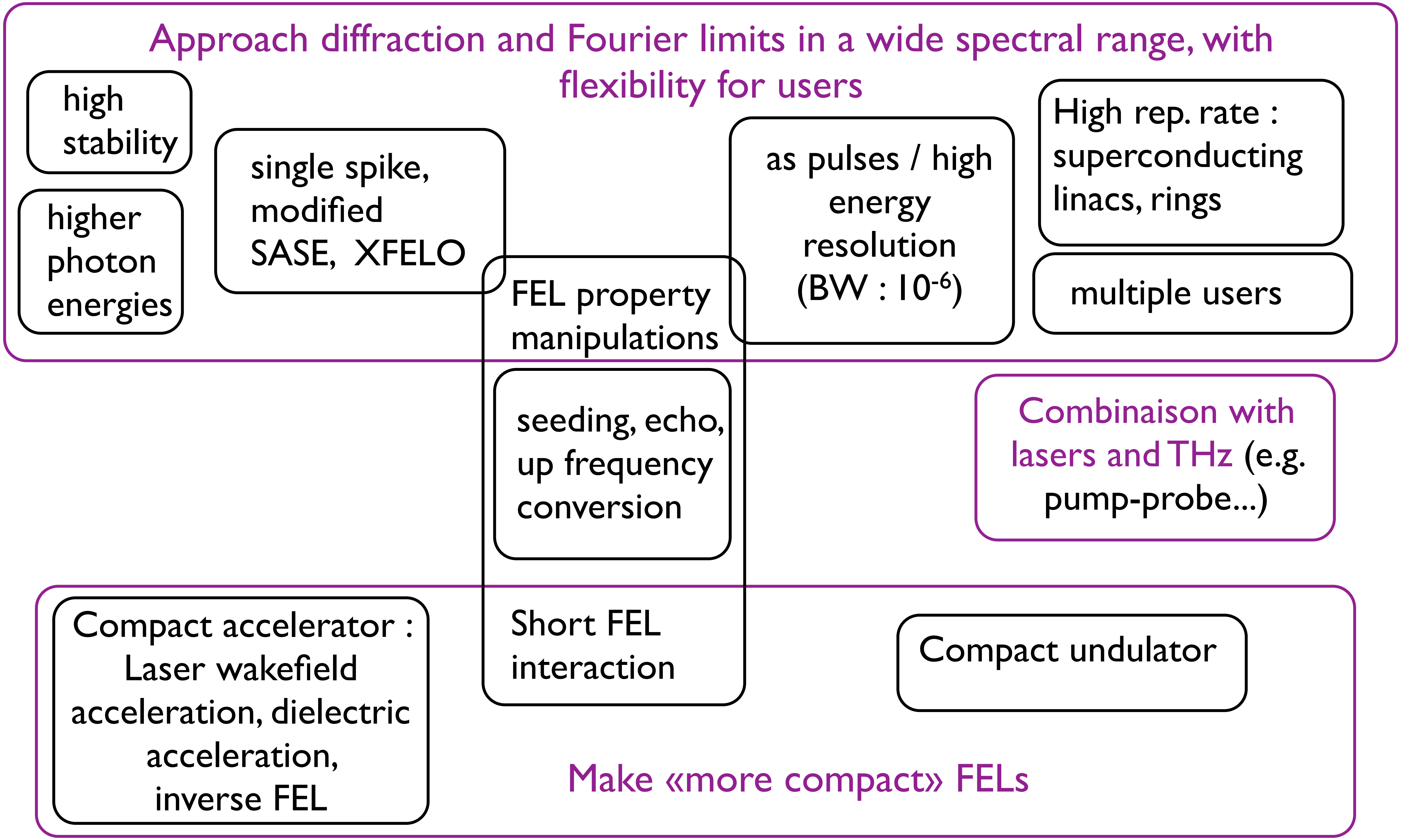
X-ray FEL oriented History

C. Pellegrini, The history of X-ray free-electron lasers, Eur. Phys. J. H, 37(5), 659-708. DOI: 10.1140/epjh/e2012-20064-5

Maturity of X-FEL => X-ray FEL applications for new investigation of matter are blooming up

Bostedt, C., Boutet, S., Fritz, D. M., Huang, Z., Lee, H. J., Lemke, H. T., ... & Williams, G. J. (2016). Linac Coherent Light Source: The first five years. Reviews of Modern Physics, 88(1), 015007.

Conclusion and prospects



Approach diffraction and Fourier limits in a wide spectral range, with flexibility for users

high stability

higher photon energies

single spike, modified SASE, XFELO

FEL property manipulations

as pulses / high energy resolution (BW : 10^{-6})

High rep. rate : superconducting linacs, rings

multiple users

seeding, echo, up frequency conversion

Combinaison with lasers and THz (e.g. pump-probe...)

Compact accelerator : Laser wakefield acceleration, dielectric acceleration, inverse FEL

Short FEL interaction

Compact undulator

Make «more compact» FELs

Physics and applications of High Brightness Beams : towards a fifth generation light source, Puerto-Rico, March 25-28, 2013

Conclusion

Various regimes and studies

- MOPA
- Regerative FEL
- Mode locking
- Q-switching
- Super-radiance
- CPA
- limit cycles
- 2 color operation....

- Chaos and control

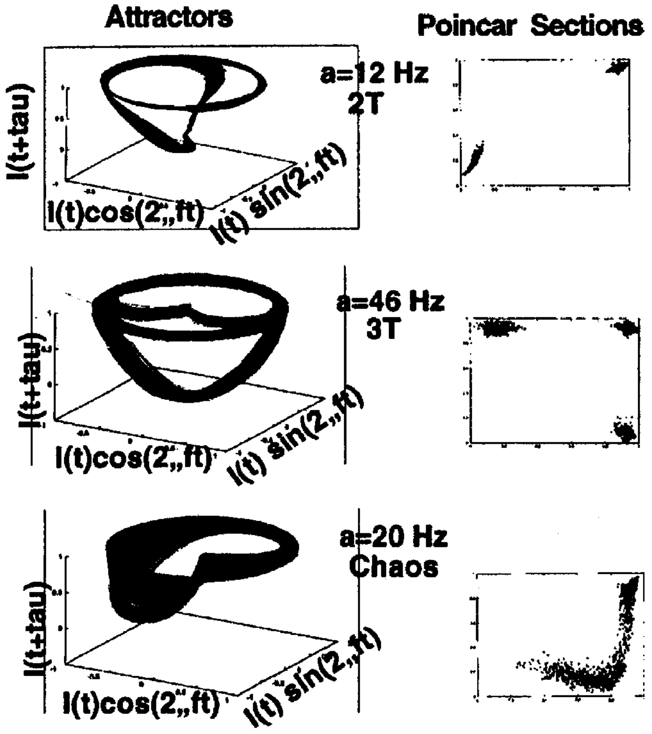
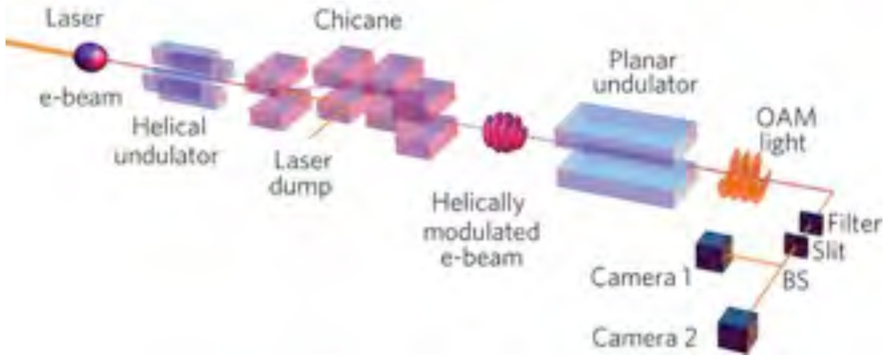
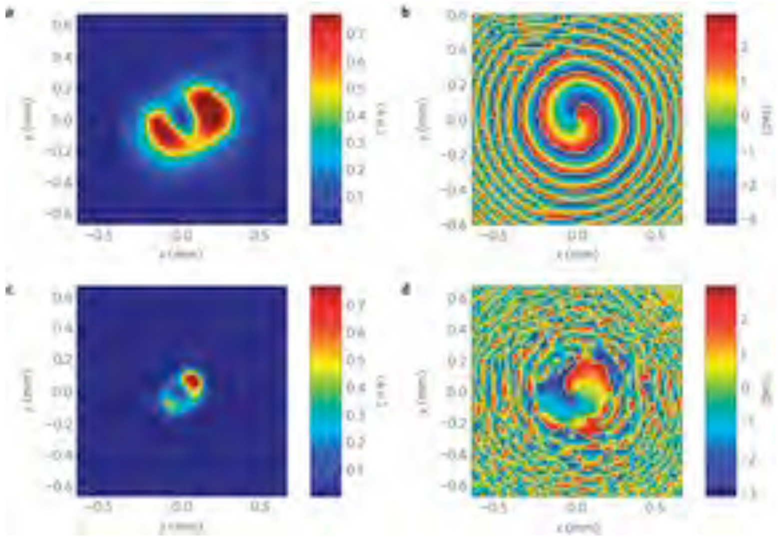


Fig. 6. (a) $I(t)\cos(2\pi ft)$, $I(t)\sin(2\pi ft)$, $I(t+\tau)$ attractors reconstructed from intensity evolution of Fig. 3. 2T regime for $a = 12$ Hz, chaos for $a = 20$ Hz, 3T regime for $a = 46$ Hz. (b) Corresponding Poincaré sections.

M. Billardon, PRL 65 (6) , 713 (1990)
M. E. Couprie, NIM A 507 (2003) 1-7

- Vortives





E. Hemsing et al. , Nature Physics 9, 549–553 (2013)

Question for the end

Is FEL a real laser?

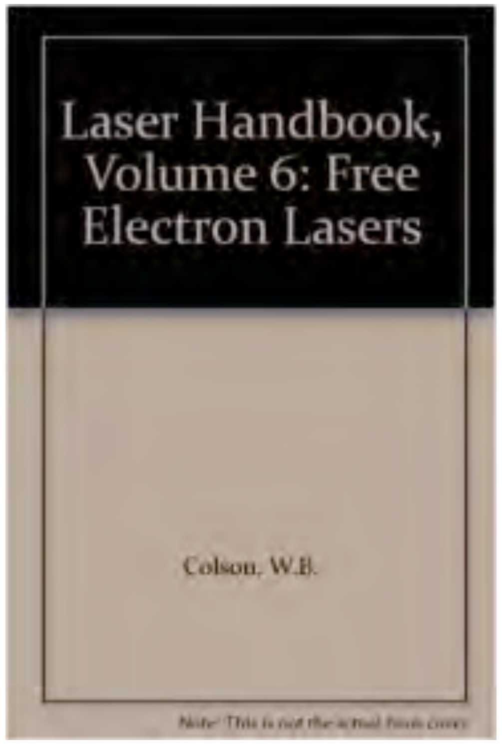
Question for the end

Is FEL a real laser?

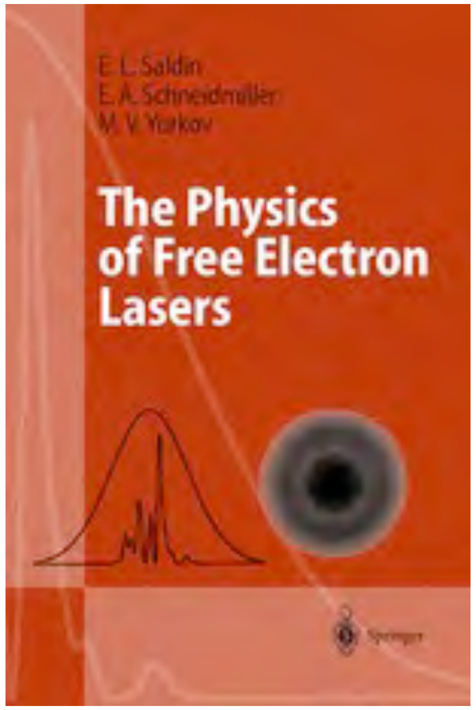
Quantum description ?	yes very heavy.... needed for some particular effects (electromgantic undulator...)
Macroscopical quantum system?	no
Light Amplification by Stimulated Emission ?	theoretically : yes if stimulated diffusion considered as stimulated emission
	experimentally : light amplifier (with optical resonator, SASE...)
Spatial and longitudinal coherence properties	yes

M. Orzag, R. Ramirez, Quantum features of a fre electron laser, J. Opt. Soc. Am. B , 3 (6) , 895-900 (1986)
C. B. Schroeder, C. Pelligrini, P. Chen, Quantum effects in high gain FELs, Phys. Rev. E (64), 056502

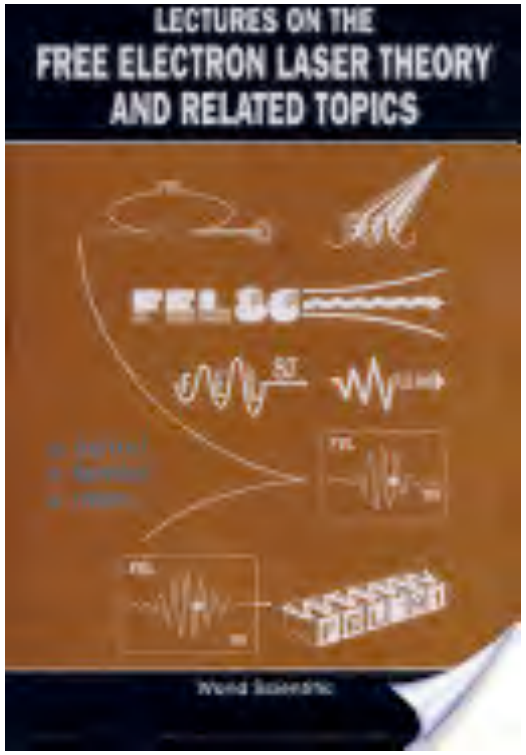
Books....



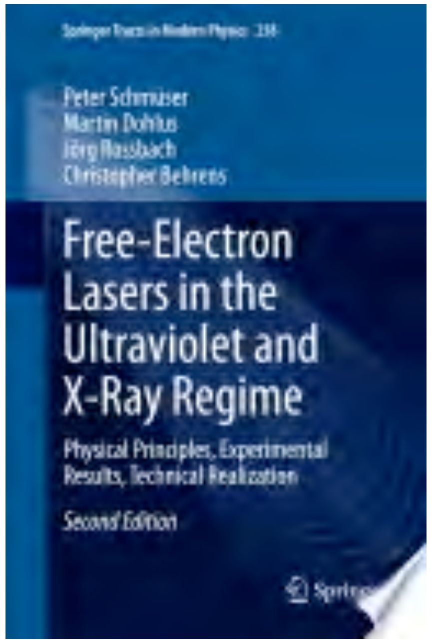
Laser Handbook, Volume 6: Free Electron Lasers by W.B. Colson, A. Renieri, Claudio Pellegrini Noth Holland



The Physics of Free Electron Lasers Authors: Saldin, Evgeny, Schneidmiller, E.V., Yurkov, M.V.

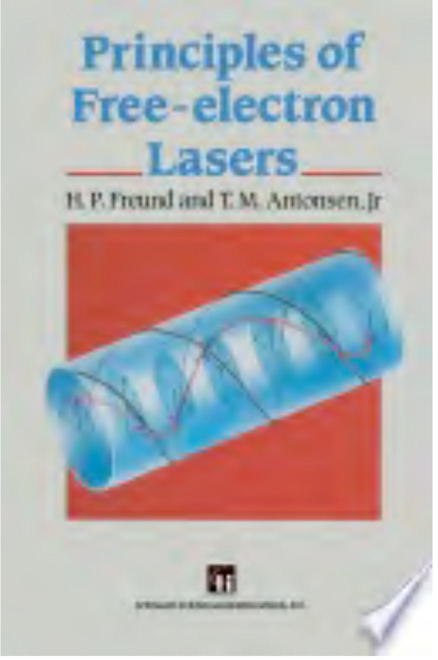


Lectures on the Free Electron Laser Theory and Related Topics, <u>G. Dattoli</u>, <u>A. Renieri</u>, <u>A. Torre</u>, World Scientific, 1 janv. 1993 - 637 pages



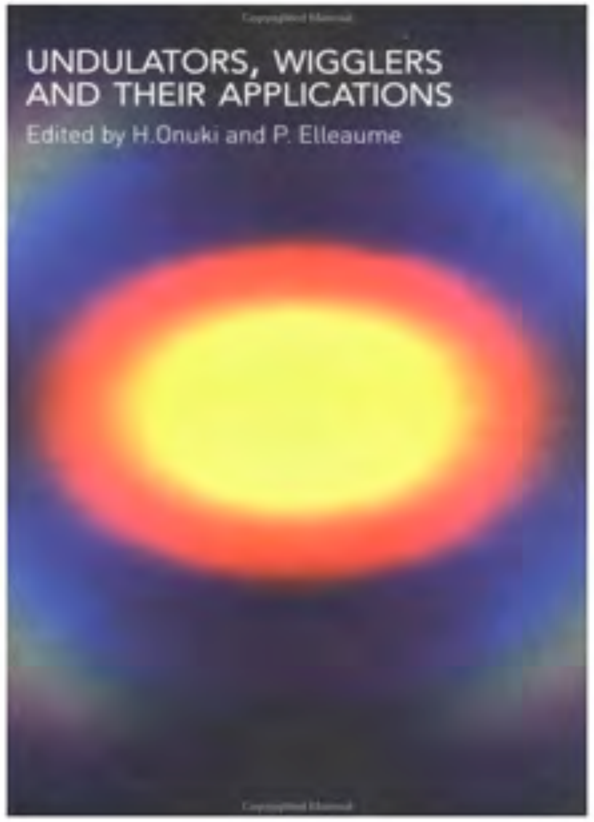
Free-Electron Lasers in the Ultraviolet and X-Ray Regime Physical Principles, Experimental Results, Technical Realization Authors: Schmüser, P., Dohlus, M., Rossbach, J., Behrens, C.

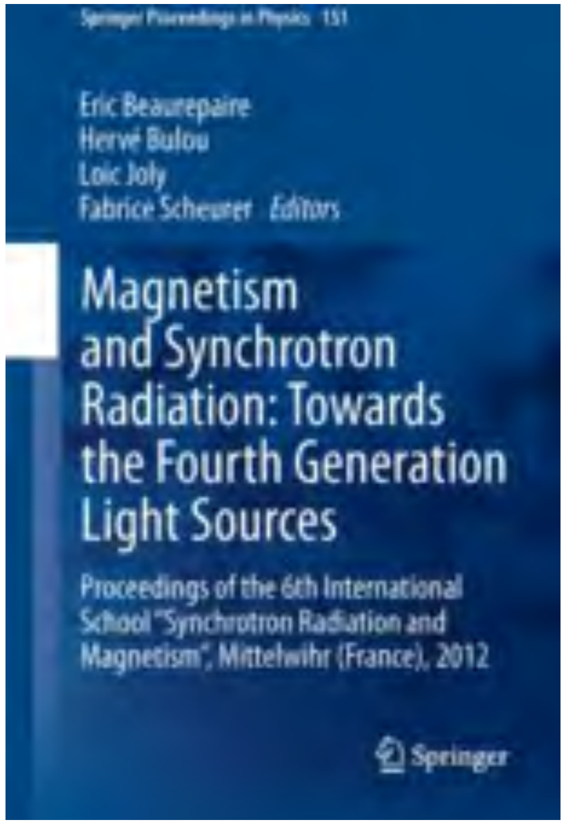
Introduction to the physics of Free electron laser and comparison with conventional laser sources, G. Dattoli et al., ENEA, RT / 2009 / 44/FIM

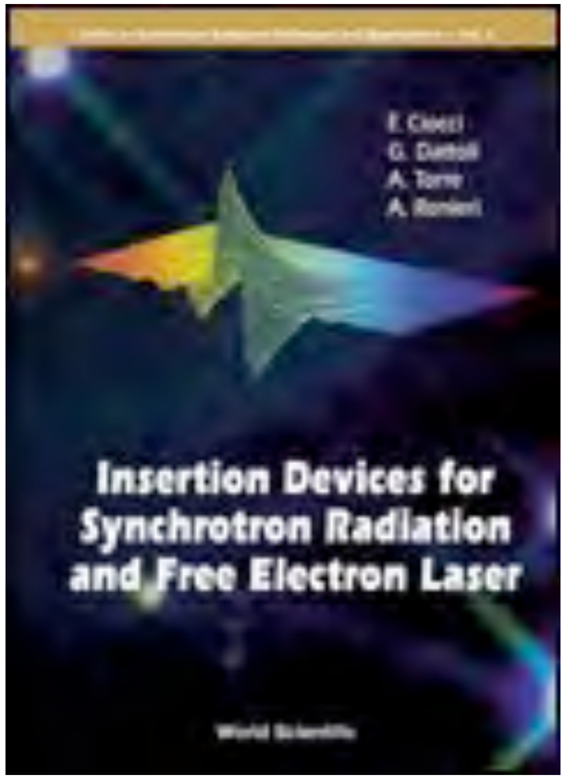


Principles of Free-Electron Lasers H. P. Freund

Books....







Elleaume P., Onuki H. : Undulators, wigglers and their applications. Taylor and Francis, London (2003)

Synchrotron Radiation, Polarisation, Devices and New Sources, M. E. Couprie, M. Valléau, in "Magnetism and Synchrotron Radiation: Towards the Fourth Generation Light Sources", Proceedings of the 6th International School "Synchrotron Radiation and Magnetism", Mittelwihr (France), 2012, edited by E. Beaurepaire, H. Bulou, L. Joly, F. Scheurer Springer Proceedings in Physics Volume 151, 2013, pp 51-94

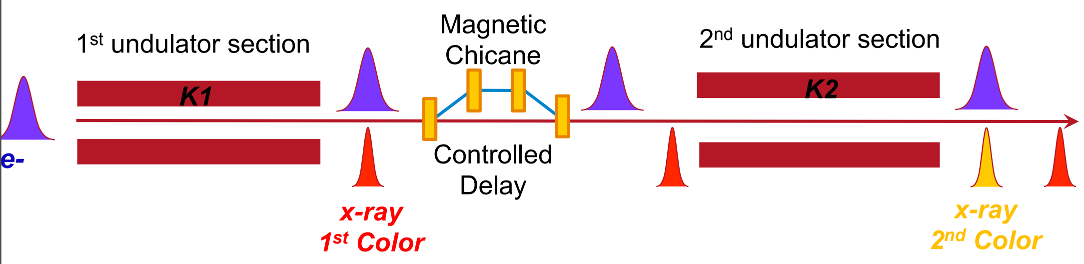
S. Krinsky, M.L. Perlman and R.E. Watson Characteristics of Synchrotron Radiation and Its Sources "Handbook on Synchrotron Radiation", Vol 1 ... A. Hofmann, Proc. of CERN-Accelerator School (CAS) on Synchrotron Radiation and free Electron Lasers, 90-03, 115 (1990).

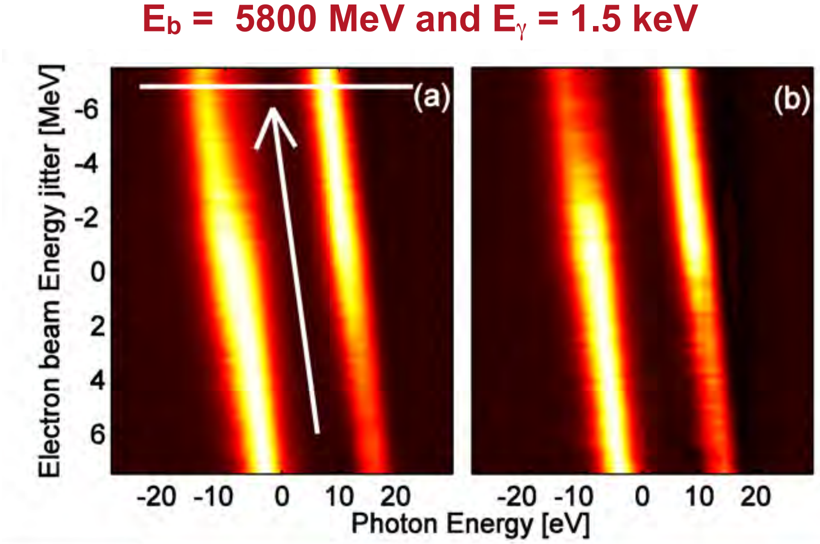
Two-color operation (SASE)

First two color operation at CLIO on a FEL oscillator

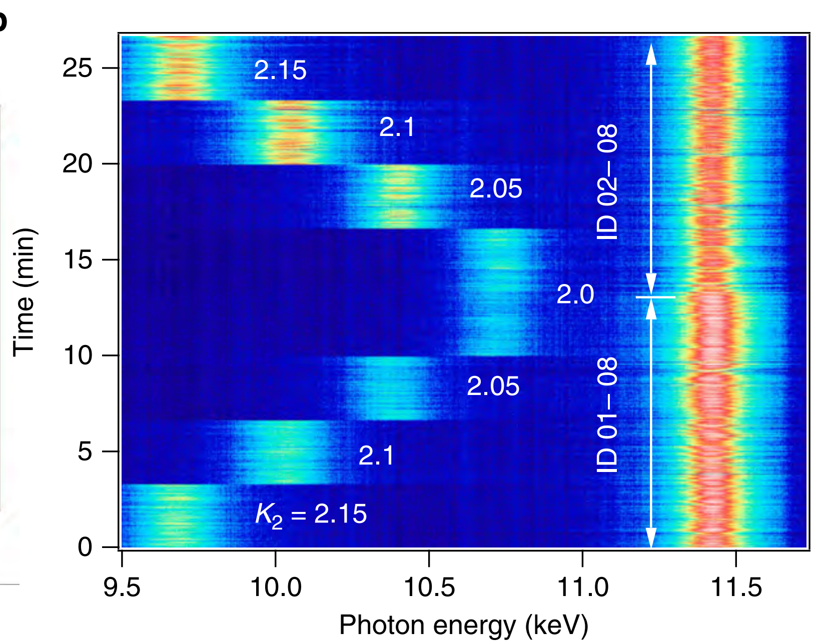
R.Prazeres et al. Nuclear Instr. and Methods, A407, 464 (1998), R.Prazeres, et al., Eur. Phys. J. D3, 87 (1998)

Delay by chicane and different K





A.A. Lutman et al.,, PRL 110, 134801 (2013)
A. Marinelli et al., Phys. Rev. Lett. 111, 134801 (2013)



T. Hara et al., Nature Communications, 4, 2919, 2013

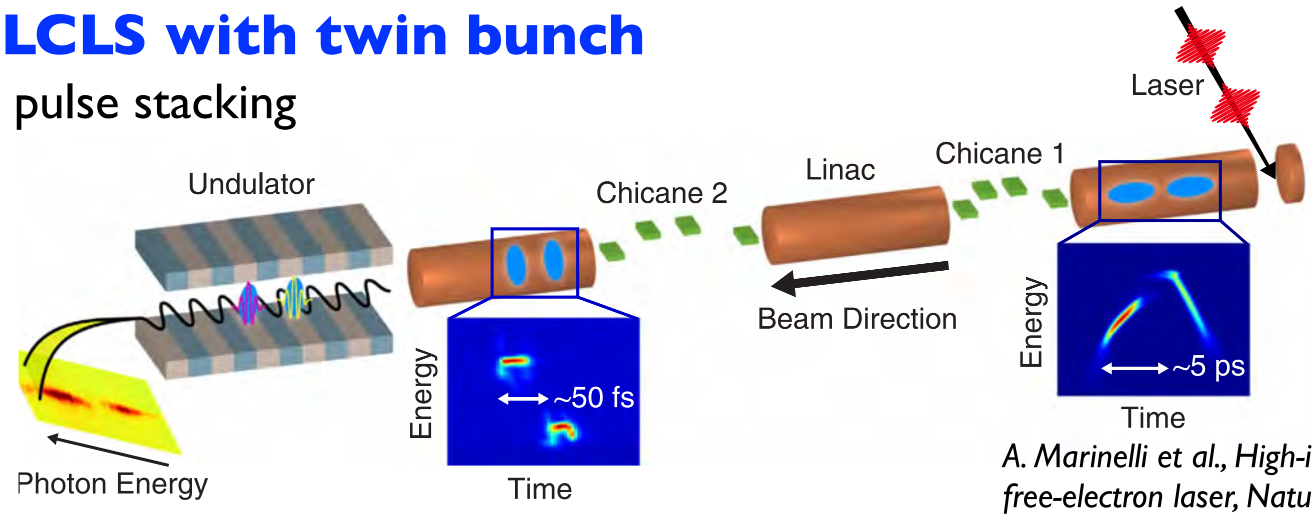
\+ variants

- double slotted emittance spoiler enabling to control the delay (fresh bunch)

- iSASE with delay (phase shifter), undulators slightly detuned to act as phase shifters. U1 (K1), U2 (K2), U1(K1), U2(K2)

LCLS with twin bunch

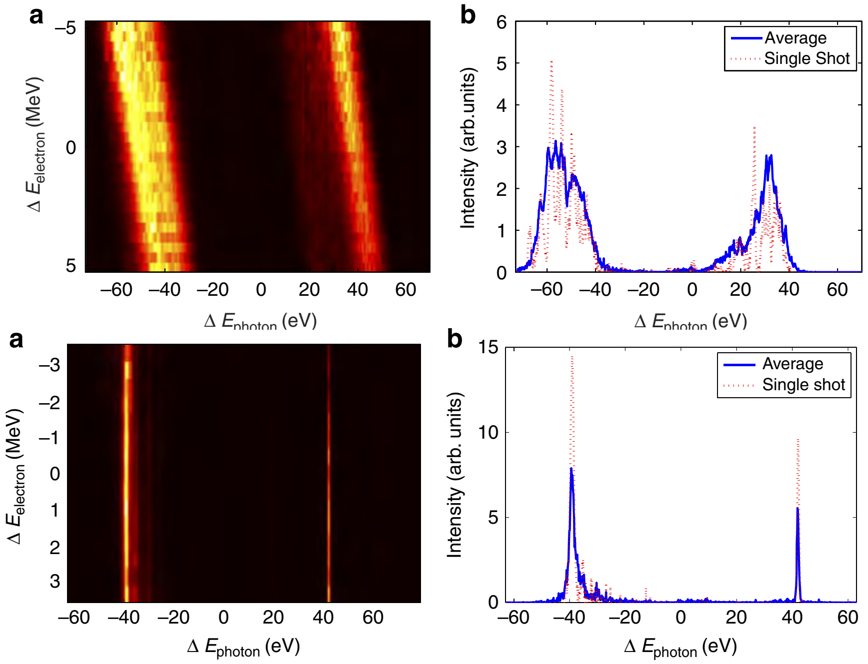
pulse stacking



A. Marinelli et al., High-intenisty double-pulse X-ray free-electron laser, Nature Comm. 6:6369 (2015)

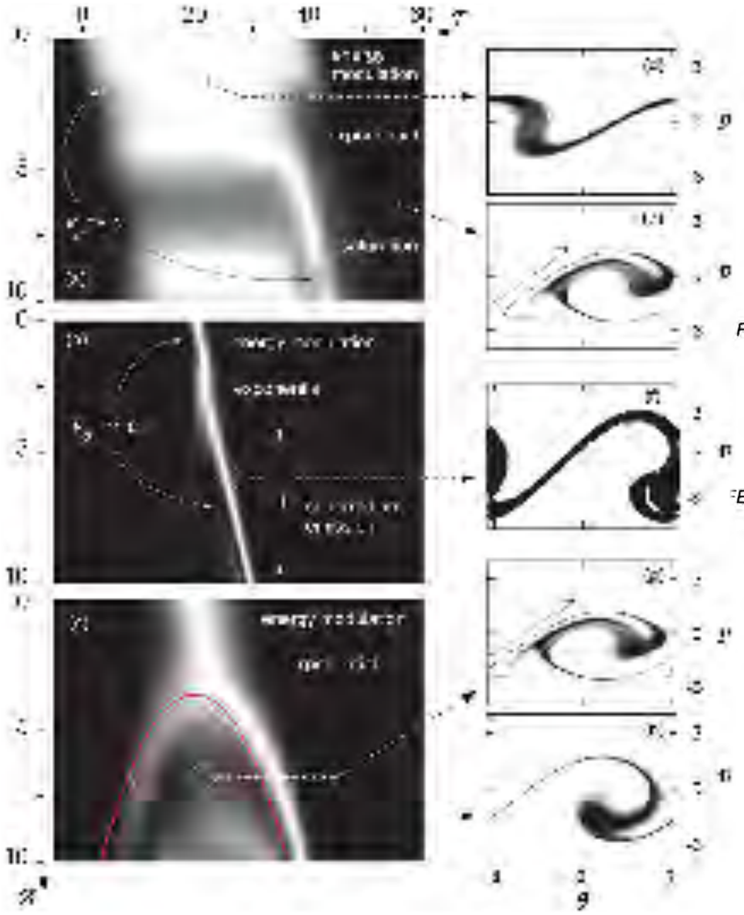
SASE

Self-seeded

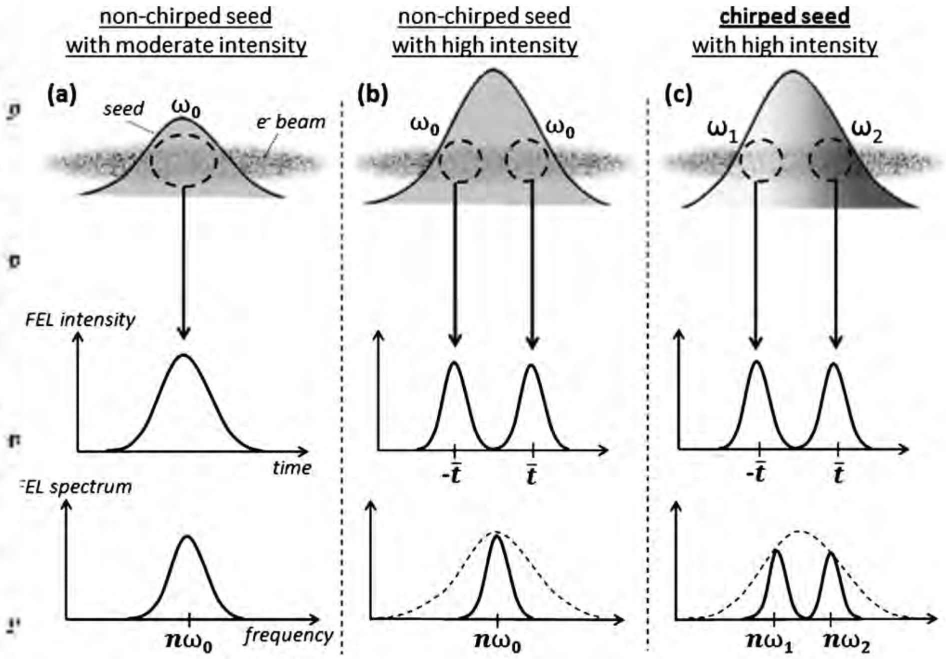


Two-color operation (seeded)

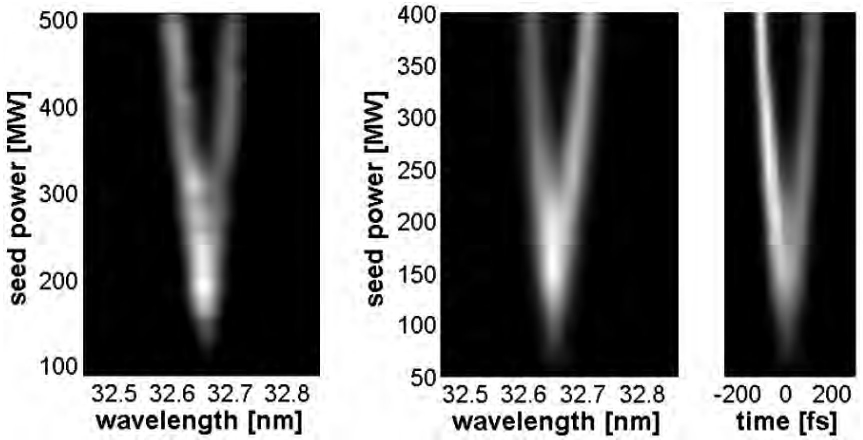
Pulse splitting + chirp @ FERMI



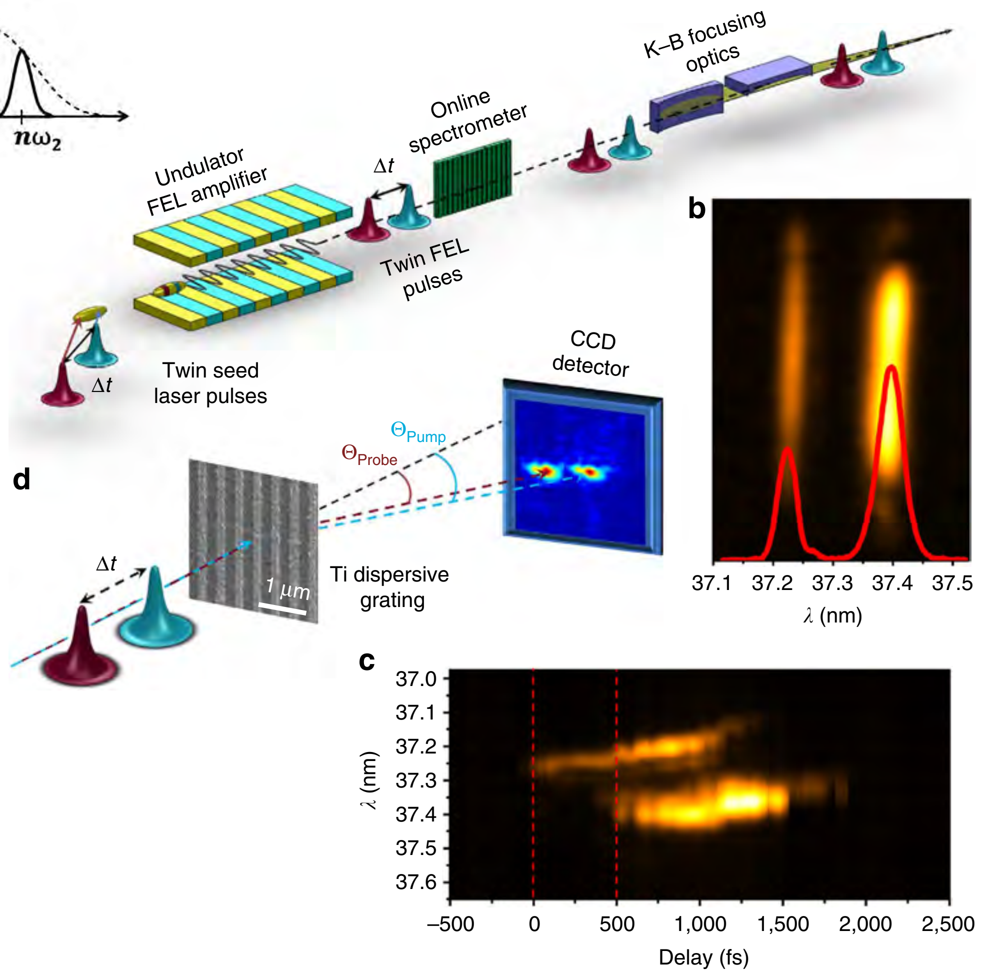
M. Labat et al. Phys. Rev. Lett. 103 (2009) 264801



G. De Ninno et al. PRL, 110, 064801 (2013)

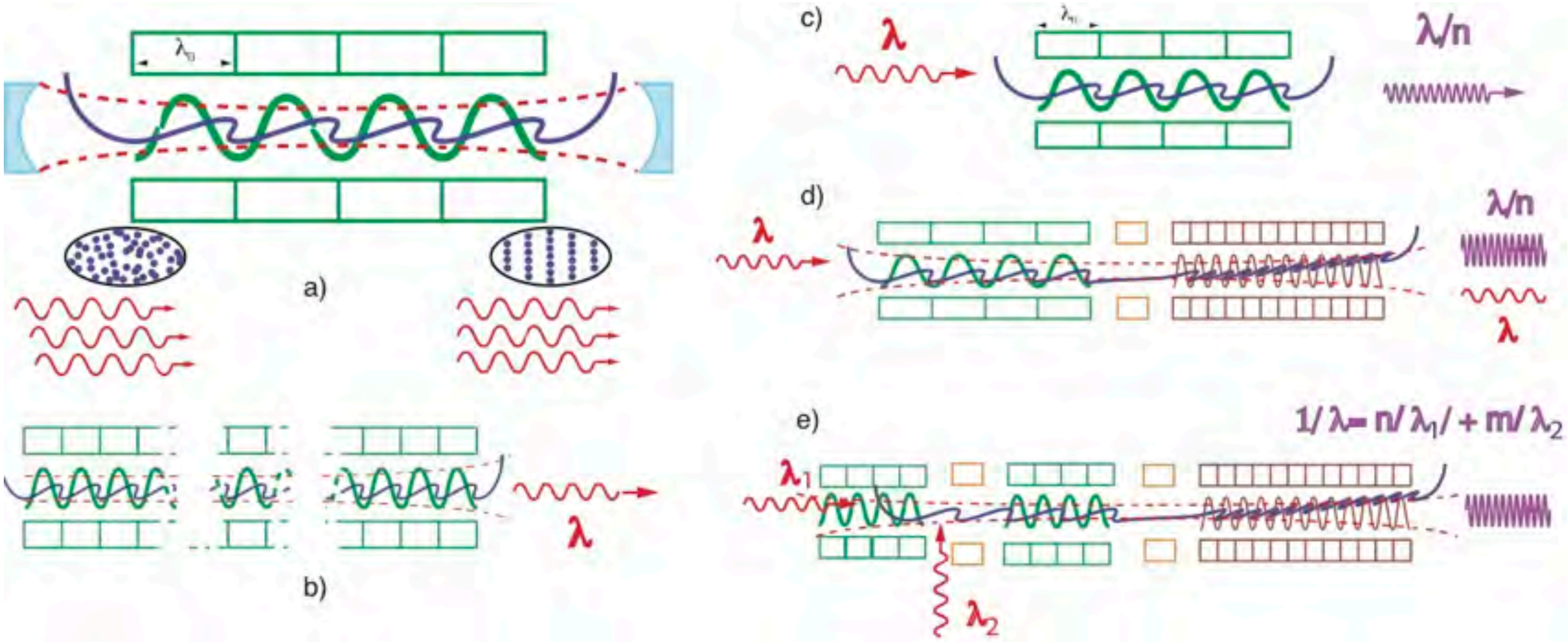


Two delayed pulses @ FERMI and SPARC



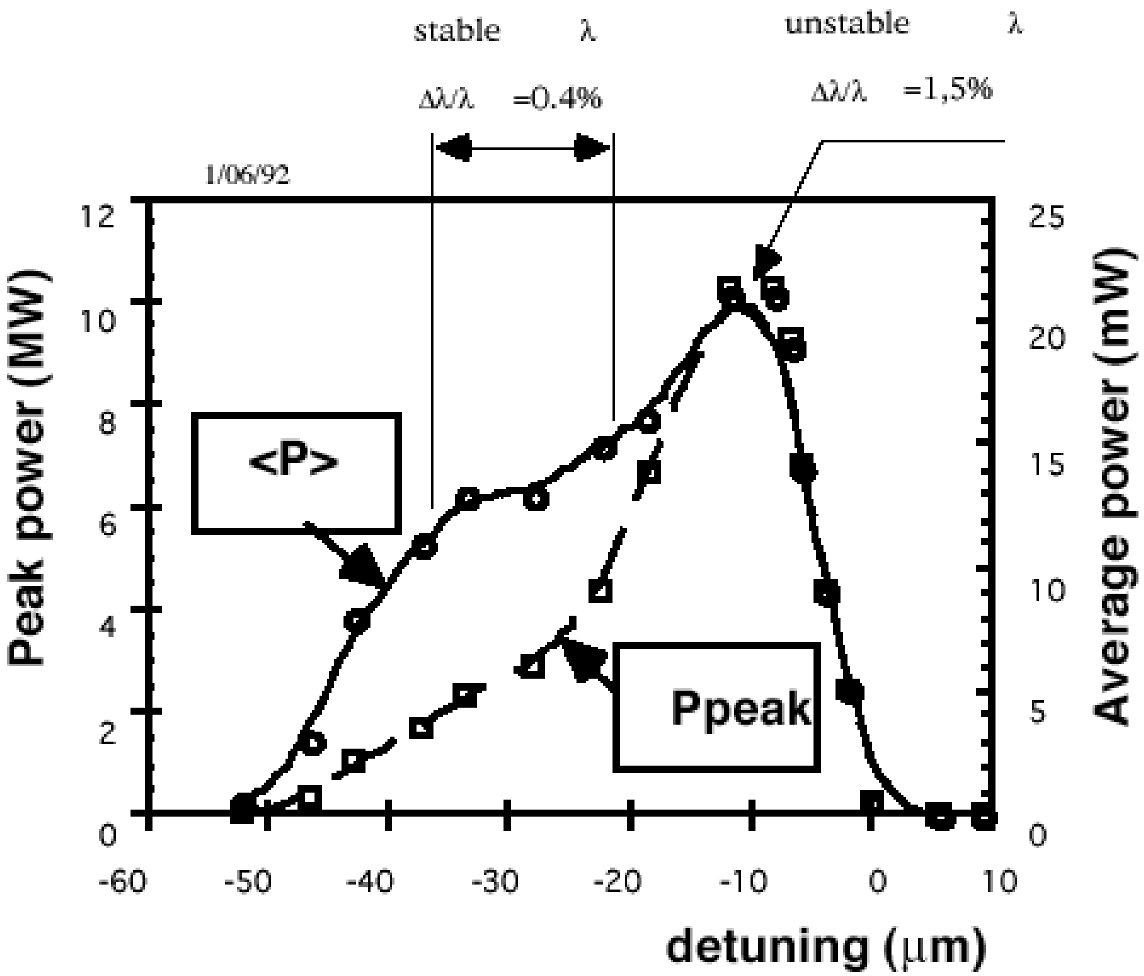
E. Allaria et al., Nature Com. 3476 (2013).
A. Petralia et al., Phys. Rev. Lett. 115, 014801 (2015)

FEL configurations



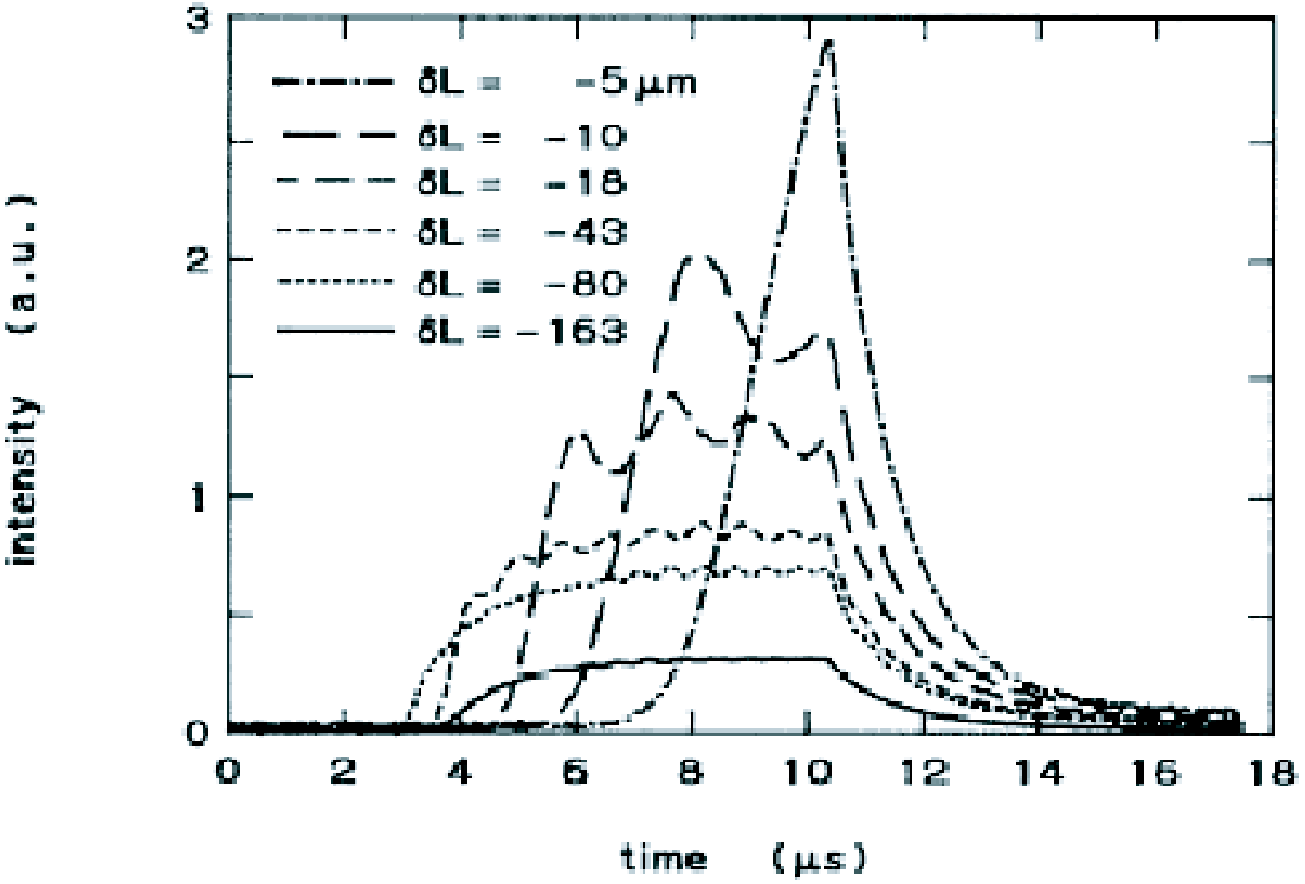
$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad K = 0.94\,\lambda_0\,(\mathrm{cm})\,B_0\,(\mathrm{T})$$

First FELs : Linac based detuning curve



Limit cycle regime on FELIX

(D. Jarosynski et al, PRL 70 (20), 1993, 3412)



First FELs : storage ring based FEL, detuning curve

laser intensity longitudinal profile

cavity losses

gain at each pass n

spontaneous emission

$$y_{n+1}(\tau) = (1- L)\,[\,1 + G_n(\tau + \delta\tau_n)]\, y_n(\tau) + L\eta G_n(\tau + \delta\tau_n)$$

τ : longitundal coordinate

single pass gain in units of L

energy spread (n : pass n, o off, e : equilibrium)

$$\text{with } G_n(\tau) = G_i \frac{\sigma_o}{\sigma_n} \exp\left(- \frac{\sigma^2_n - \sigma^2_o}{\sigma^2_e - \sigma^2_o}\right) \exp\left(- \frac{\tau^2}{2\sigma^2_\tau}\right)$$

cavity round trip time

electron bunch length

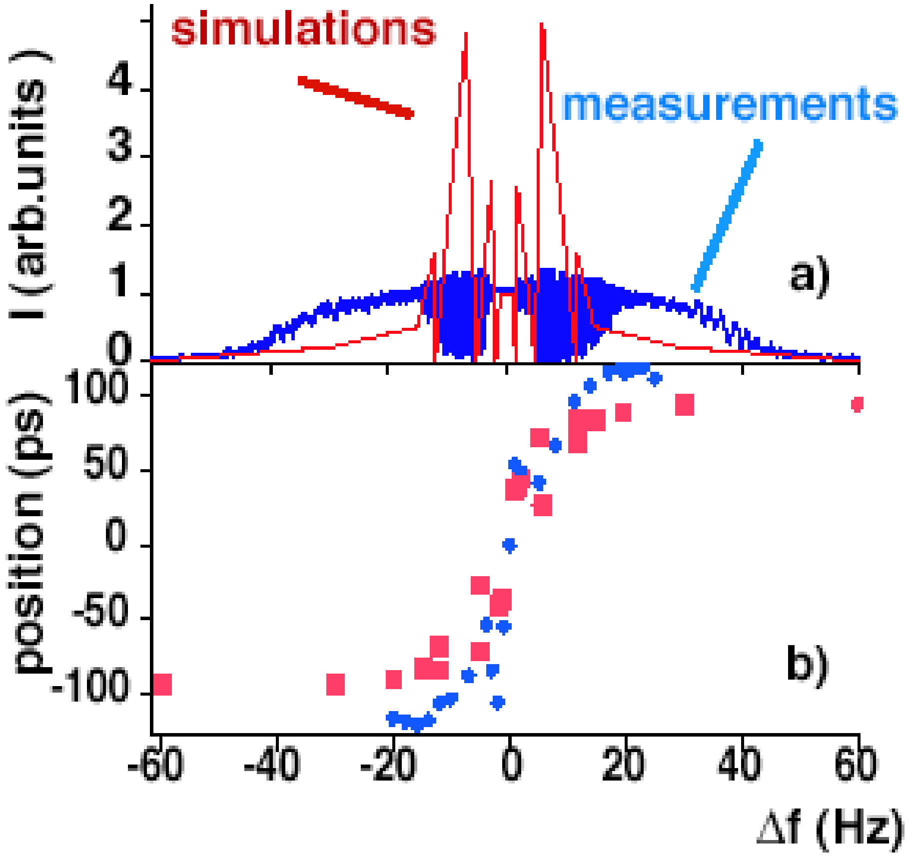
$$\text{and } \sigma^2_{n+1} = \sigma^2_n + \frac{2\tau_R}{\tau_s}\left[\sigma^2_o - \sigma^2_n + (\sigma^2_e - \sigma^2_o)\, I_n\right]$$

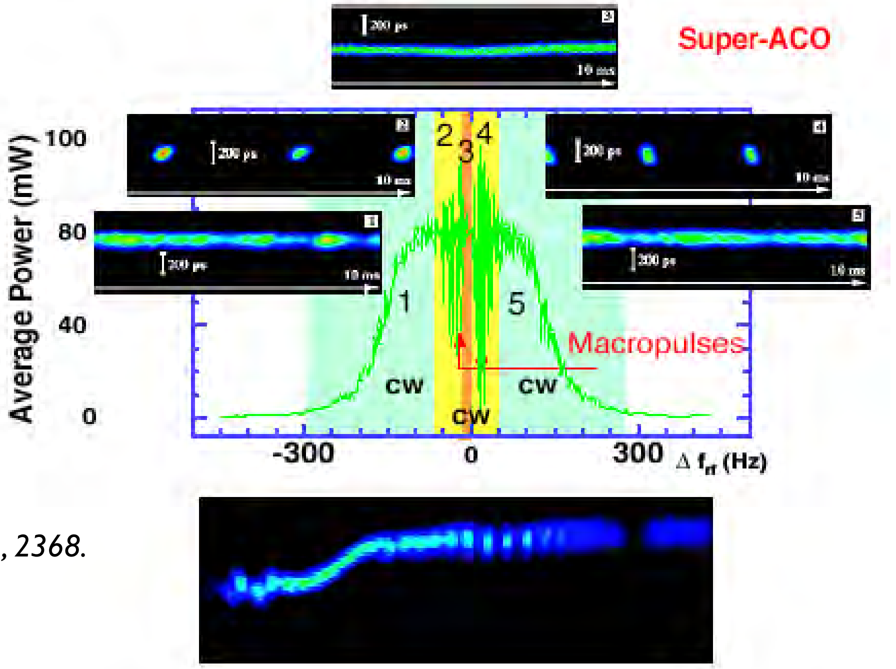
synchrotron damping time

detuning

delay e. bunch / laser round trip time $\delta\tau_n = \delta\tau_{n-1} + \tau^2_R \Delta\omega_n$

laser intensity $I_n = \int_{-\tau_R/2}^{\tau_R/2} y_n(\tau)\, d\tau$





Billardon, M., Garzella, D., & Couprie, M. E. (1992). Saturation mechanism for a storage-ring free-electron laser. Physical review letters, 69(16), 2368.

Limits of the classical approach : quantum effects

Quantum recoil

When a electron emits a photon $\hbar\omega_{ph}$, its energy is reduced by such an amount due to the quantum recoil. If the energy change due to the recoil is of the order or larger than the FEL gain bandwidth i.e. given by the spontaneous emission width $\frac{\Delta\omega}{\omega} \approx \sqrt{(\frac{\Delta\omega}{\omega})^2_h + (\frac{\Delta\omega}{\omega})^2_{inh}}$, then the quantum recoil may significantly affect the FEL gain. Consider a typical gain bandwidth of 10^{-3}, for a short wavelength FEL, the fraction of the energy change $\frac{\hbar\omega_{ph}}{E}$ is more than 10^{-6}, the quantum electron recoil is then negligible. It can then start to play a role with low energy electron beams and high energy emitted photons (for example in the X-ray range), such as in using an optical undulator (created by an optical wave).

Quantum diffusion

The emission of spontaneous emission radiation, if not affecting the electron energy by a significant amount, introduces an energy loss. In addition, the discrete nature of photon emission (over a wide energy spectrum) increases the uncorrelated energy spread. It is similar to the quantum excitation in a storage ring.

$$\frac{d<(\Delta\gamma)>^2}{ds} = -\frac{7}{15} r_e \lambda_{Compton} \gamma_o^4 K_u^2 k_u^3 F(K_u)$$

with $F(K_u) = 1.2K_u + \frac{1}{1+1.33K_u+0.40K_u^2}$ and $\lambda_{Compton} = \hbar/m_o c \approx 3.86\ 10^{-13}$ the Compton wavelength.

In the LCLS case, the quantum diffusion process increases the uncorrelated energy spread in the 110 m long undulator to more than 1 10−4 assuming an initial energy spread equal to zero. Despite in such a case, the effect is not too large, the quantum diffusion process is likely to impose limits in achievable wavelength for given beam parameters.