VIII. Ultrafast Optics

Introduction

Coherent light

The spectrum of electromagnetic waves stretches from radio waves to gamma rays (Fig. VIII-1).

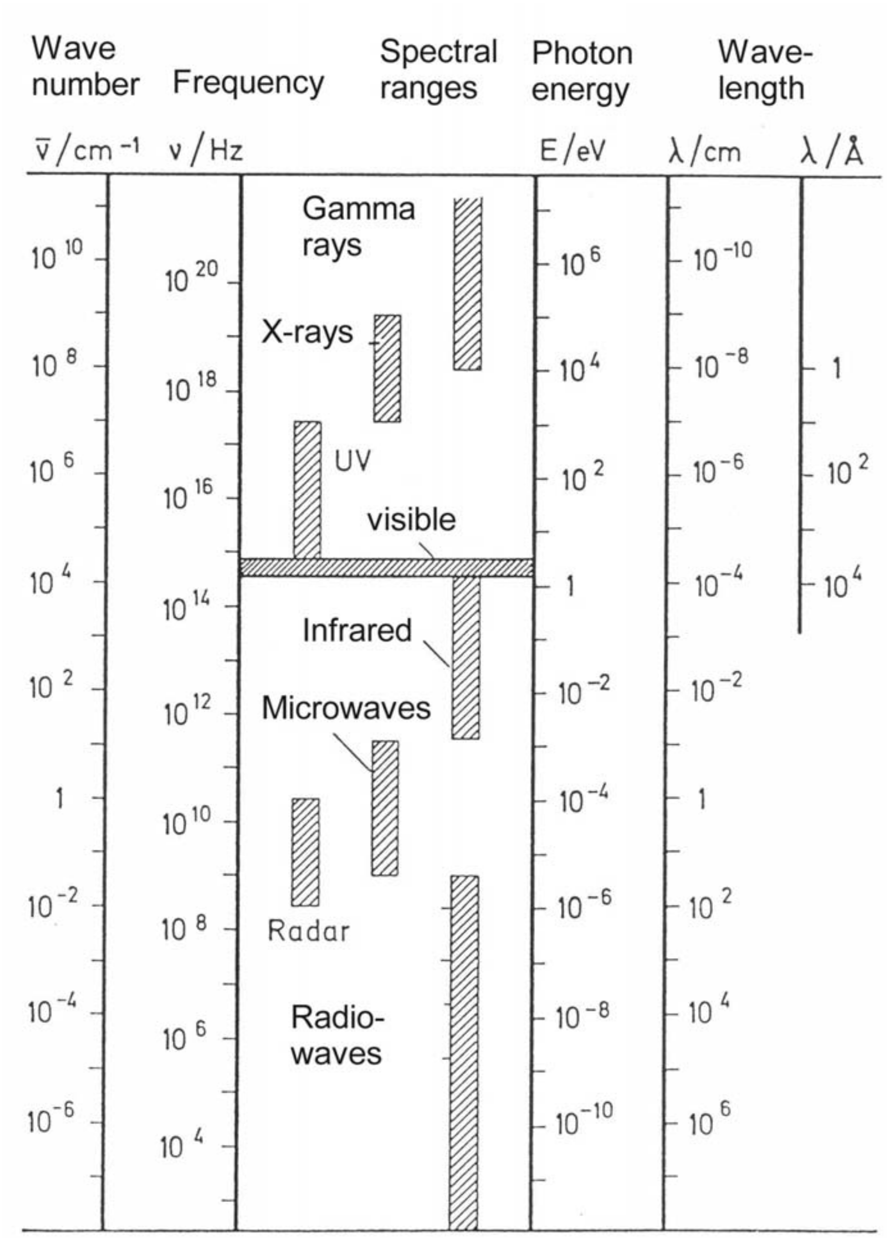

Fig. VIII-1

Thanks to their long wavelengths, radio waves and microwaves can be generated and emitted by fast varying macroscopic electric currents in a well controlled manner. This control results in good spatial and temporal coherence. By spatial coherence of a wave we mean that from having measured the field amplitude at a certain position **r** and time *t*, it can be predicted at another position $\mathbf{r} + \Delta\mathbf{r}$ at the same instant. Temporal coherence implies a similar predictability at the same position for a future instant $t + \Delta t$ (Fig. VIII-2).

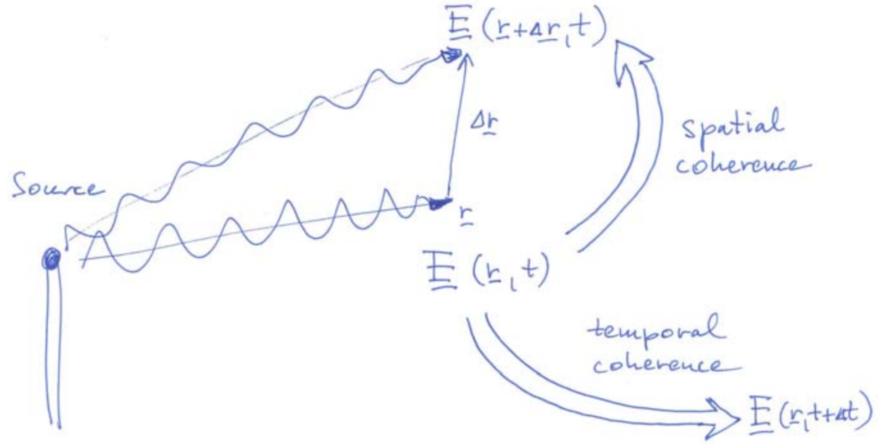

Fig. VIII-2

The wavelength of infrared, visible, ultraviolet and x-ray radiation (often termed light) becomes ever shorter from sub-millimetre (far-infrared) to sub-nanometre (hard x-ray) waves. The generation of coherent light waves call for controlling ac currents within dimensions smaller than the respective wavelength. This has been made feasible with the invention of the laser in 1960. A light wave impinging into an ensemble of excited atoms with a frequency $\omega \approx (E_{exc} - E_{lower})/\hbar$,(where E_{exc} and E_{lower} stand for the energy of the electronic shell in the excited and in some lower-energy state, respectively) makes the electron density distribution oscillate unisono. The microscopic currents induced within these tiny atomic dipoles then radiate in phase, resulting in light amplification by stimulated emission of radiation and thus in the emergence of *coherent light radiation*.

Efficient and powerful coherent light sources can be realized only in the visible and nearby spectral ranges (wavelength range ~ 0.1 – 10 μm) because of the requirement of high dipole oscillator strength and long lifetime of the excited atoms, which nature can fulfil simultaneously only in this relatively narrow spectral range. The oscillator strength and the excited state lifetime decrease rapidly for increasing and decreasing wavelengths, respectively.

Spatial coherence: efficient transport & spatial concentration of light energy

owing to emission in a Gaussian light beam with amplitude

$$F_{\text{Gaussian}}(\mathbf{r}) = F_0 \frac{w_0}{w(z)} e^{-\rho^2/w^2(z)} \, e^{ik\rho^2/2R(z) - i\varphi(z)} \tag{VIII-1}$$

where $w(z)$, $R(z)$, and $\varphi(z)$ are given by

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \tag{VIII-2}$$

$$R(z) = z + \frac{z_R^2}{z} \tag{VIII-3}$$

$$\varphi(z) = \tan^{-1} \frac{z}{z_R} \qquad \text{(VIII-4)}$$

and

$$w_0 = \sqrt{\frac{\lambda z_R}{\pi}} \Rightarrow z_R = \frac{\pi w_o^2}{\lambda} \qquad \text{(VIII-5)}$$

The properties of Gaussian light beams are determined by the laser resonator parameters (Fig. VIII-3) and analyzed in Chapter III-2, with the electric and magnetic fields of a linearly polarized Gaussian beam being expressed in terms of *F*(**r**) in Chapter IV (Eqs. IV-41-43).

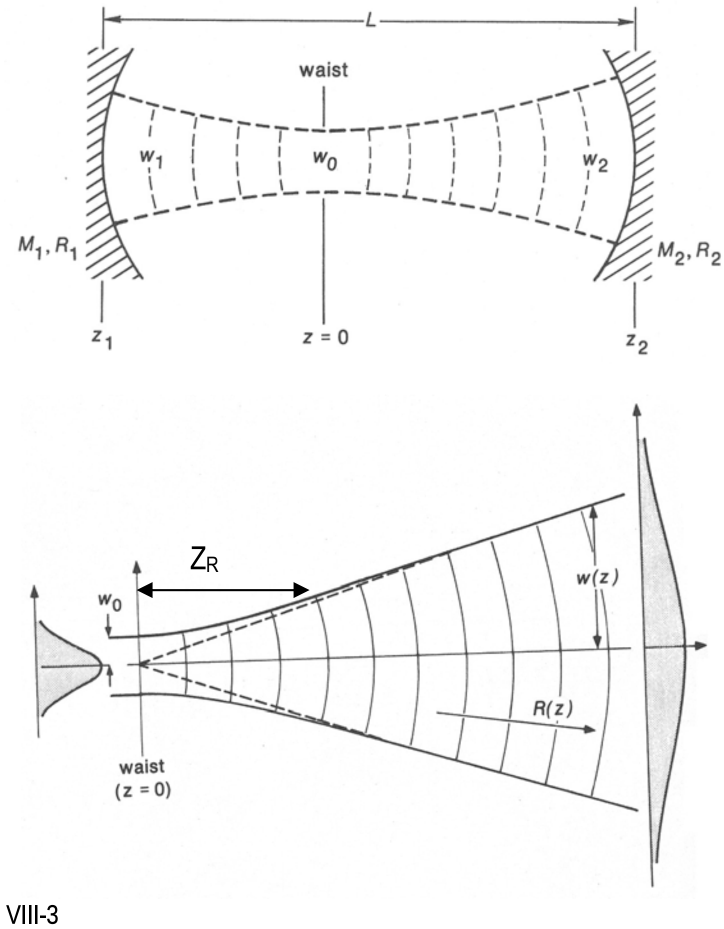

Fig. VIII-3

Temporal coherence: unparalleled spectral purity, definition of oscillation frequency with unmatched precision

in a single-axial-mode (single-frequency) laser oscillator

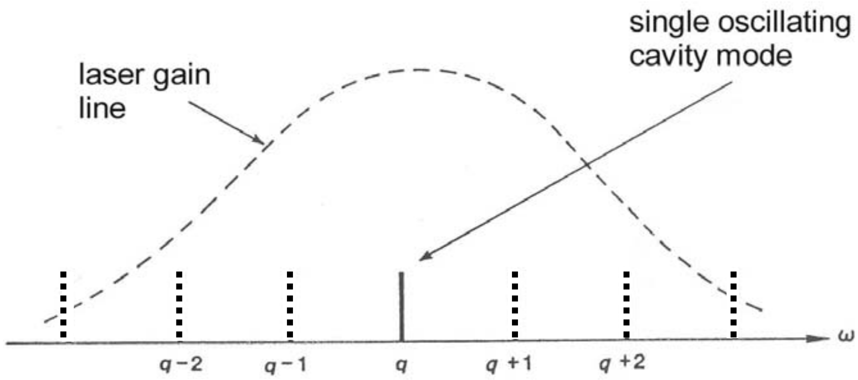

Fig. VIII-4

With single-frequency lasers line widths of the order of $\Delta\nu \approx 1$ Hz have been demonstrated. At the frequency of visible light this corresponds to a relative bandwidth of

$$\frac{\Delta\nu}{\nu} \approx 10^{-15}$$

exceeding the precision of the best quartz oscillators by more than a factor of a million!

Temporal & spatial coherence: phase-coherent generation of light waves at equidistant frequencies $\Rightarrow$ laser mode locking

In a free-running multi-axial-mode laser

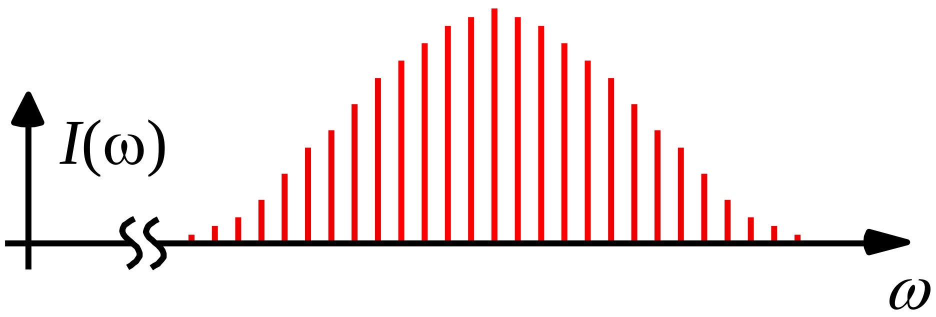

Fig. VIII-5

the axial cavity modes are spaced by

$$\Delta\omega_{ax} = 2\pi \frac{c}{2Ln} = \frac{2\pi}{T_\phi(\omega_q)} \tag{VIII-6}$$

where

$$T_\phi(\omega_q) = 2L \frac{n(\omega_q)}{c} = \frac{2L}{v_\phi(\omega_q)} \tag{VIII-7}$$

is the time it takes the light wave in mode q to complete a round trip in the resonator, n is the refractive index of the resonator medium and L is the resonator length. By a technique called *laser mode locking*[1] the axial cavity modes can be frequency- and phase-locked so that they become equidistant in frequency spaced by

$$\Delta\omega_{m\ell} = \frac{2\pi}{T_r} \tag{VIII-8}$$

where T_r is the round-trip group delay in the resonator at the centre frequency ω_0 and the resultant electric field can be written as

$$E(z,t) = \sum_q \frac{1}{2} a_q e^{i(k_q z - \omega_q t) + i\phi_q} + c.c. \tag{VIII-9}$$

with

$$\omega_q = \omega_0 + q\Delta\omega_{m\ell} \qquad ; \qquad q = -\frac{N-1}{2}, \; ....., 0, ... + \frac{N-1}{2} \tag{VIII-10}$$

and

$$\phi_q = \phi_0 \tag{VIII-11}$$

At a position z=0 (Fig. VIII-6) the electric field then varies in time as

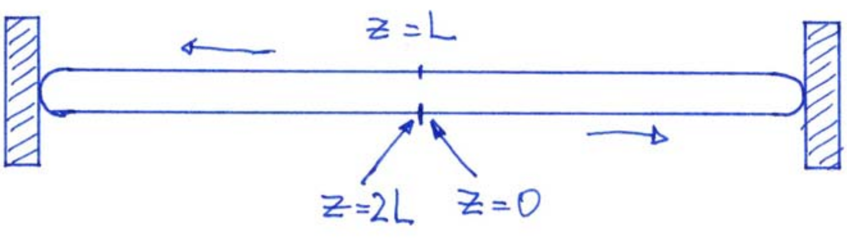

Fig. VIII-6

$$E(t) = \sum \frac{1}{2} a_q e^{-i(\omega_0 + q\Delta\omega_{m\ell})t + i\phi_q} + c.c. \tag{VIII-12}$$

[1] M. Didomenico, *J. Appl. Phys. Lett.* 35, 2870 (1964); L. Hargrove *et al.*, *Appl. Phys. Lett* 5, 4 (1964)

which, with $a_q = a_0$ yields

$$E(t) = \frac{1}{2}\, a_0\, e^{-i\omega_0 t + i\phi_0}\, \frac{\sin(N\Delta\omega_{m\ell} t/2)}{\sin(\Delta\omega_{m\ell} t/2)} + c.c. \tag{VIII-13}$$

and

$$I(t) \propto |E(t)|^2 = a_0^2\, \frac{\sin^2(N\pi t/T_r)}{\sin^2(\pi t/T_r)} \tag{VIII-14}$$

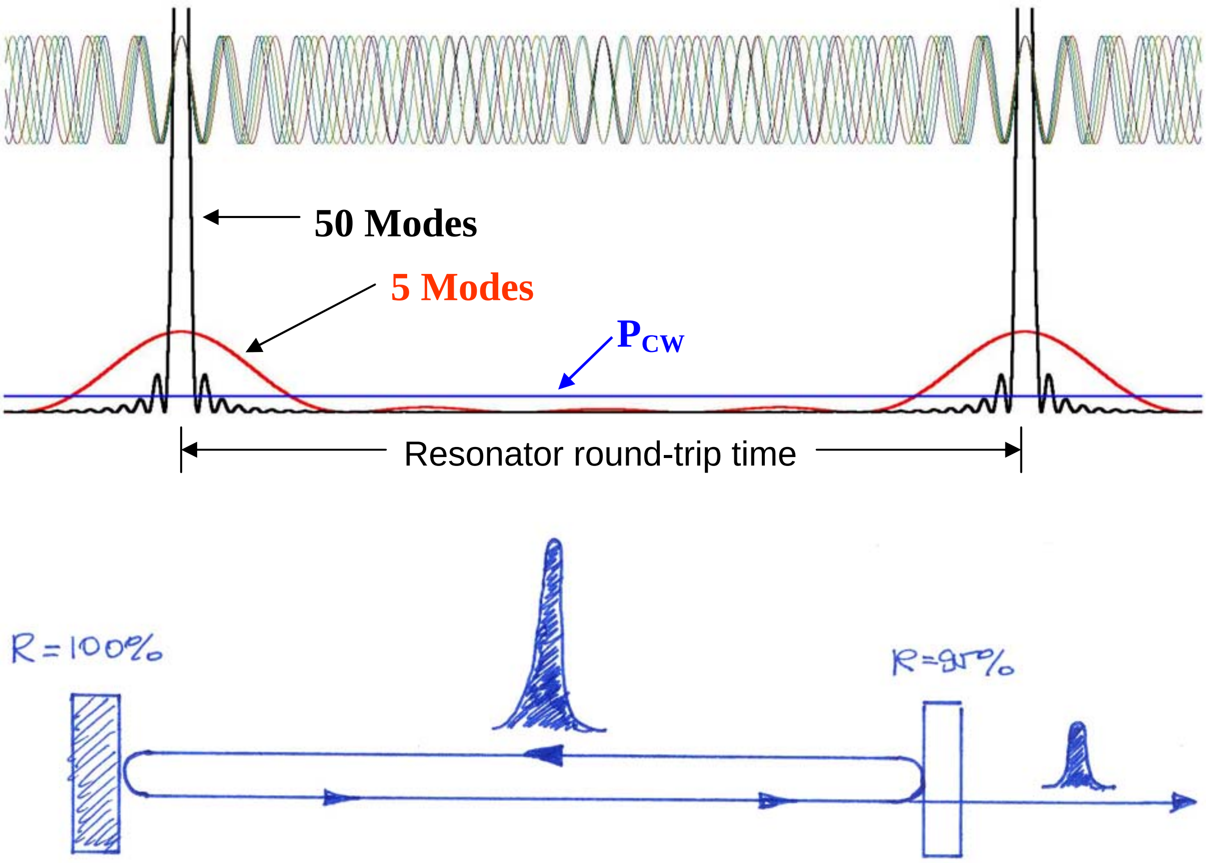

Fig. VIII-7

Ultrashort pulse duration, ultrahigh peak power

As a result, a light pulse emerges, circulating in the resonator, with a duration, pulse energy and peak power of

$$\tau_p \approx \frac{T_r}{N} \tag{VIII-15}$$

$$W_p \approx P_{average}\, T_{eff} \tag{VIII-16}$$

$$P_{\text{peak}} \approx \frac{W_p}{\tau_p} = N P_{\text{average}} \qquad \text{(VIII-17)}$$

In state-of-the-art mode-locked lasers, up to N = 1 000 000 modes can be phase- and frequency-locked to yield a million-time temporal concentration of the light energy distributed evenly over the $T_r \approx 10$ ns round-trip time in the freely running laser to $\tau_p \approx 10$ fs, implying a million-time enhancement of power as compared to the average power of the same laser running freely in the absence of mode locking. As a result, even a pulse energy of merely several nano-Joules can result in a peak power that approaches 1 Megawatt. The nano-Joule pulse energy delivered by typical mode-locked laser oscillators can be boosted by 10-100 million times in compact femtosecond amplifiers systems. These techniques result in femtosecond light pulses with peak powers that can far exceed 1 Terawatt and approach even 1 Petawatt.

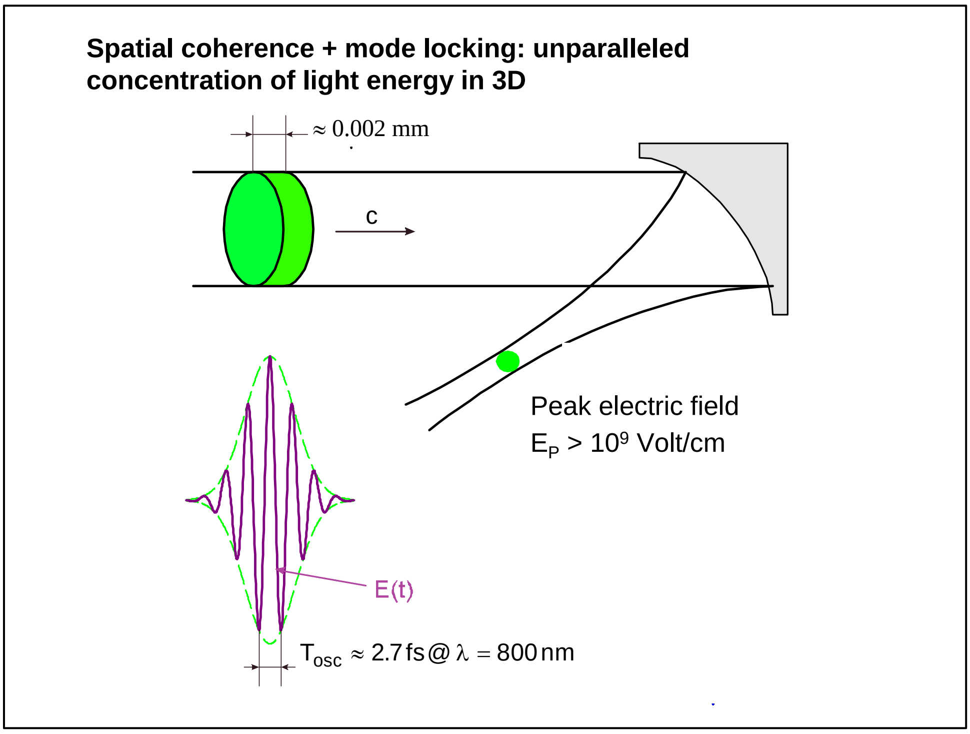

Fig. VIII-8

Impact of ultrafast optics on science and technology

Ultrafast optics pushes the frontiers of

- telecommunications: picosecond pulses allow up to 100-Gbit/s transmission rate, which can be multiplied by several orders of magnitude in hundreds of WDM channels to result in transmitting *multi-Terabit information per second through one single optical fibre over thousands of kilometres* (see Chapter IV-4)

- industrial and biological-medical technologies & instrumentation: ultrashort-pulsed laser sources have dramatically improved the resolution of optical microscopy (from sub-micrometers to the ten nanometre range with visible light: diffraction limit is vastly overcome by exploiting optical nonlinearities!); provide the only means of machining and structuring materials with nanometre precision ($\Longrightarrow$ nanophotonics); offer new diagnostic and therapic tools for medicine;….

- frequency and time metrology: the equidistant spectral lines of a stabilized femtosecond laser can form a "frequency ruler" of unprecedented simplicity and precision, constituting a "clockwork" for referencing frequency measurements to the Caesium frequency standard and paves the way towards a much more accurate optical frequency clock.

- ultrafast metrology: the resolution limit (dictated the probing pulse duration) of ultrafast optics surpasses that of the fastest electronic devices by several thousand times (Figs. VIII-9); at the frontier of ultrafast science, attosecond metrology allows to observe the motion of electrons on atomic length scales *in real time* and record the electric field of visible light (Figs. VIII-10)

- high-field science: focused gigawatt-terawatt-petawatt light pulses are able to expose matter to unprecedented electric fields ranging from billion to trillion V/cm; these field strengths ionize matter instantly, accelerate electrons to relativistic speeds within micrometers and pave to way towards compact laboratory-scale particle accelerators

- coherent light sources: by inducing polarisation that depends nonlinearly on the driving light field, femtosecond lasers allow creating powerful sources of coherent light in wavelength ranges where no efficient laser sources are available; femtosecond-laser-driven coherent light sources now cover the wavelength range of ~1 mm – 1 nm (frequency: 0.3 THz – 300 PHz), all the way from the far infrared to the regime of soft x-rays! With femtosecond-laser-accelerated electrons even a laboratory source of coherent hard x-rays (~0.1 nm) may become possible!

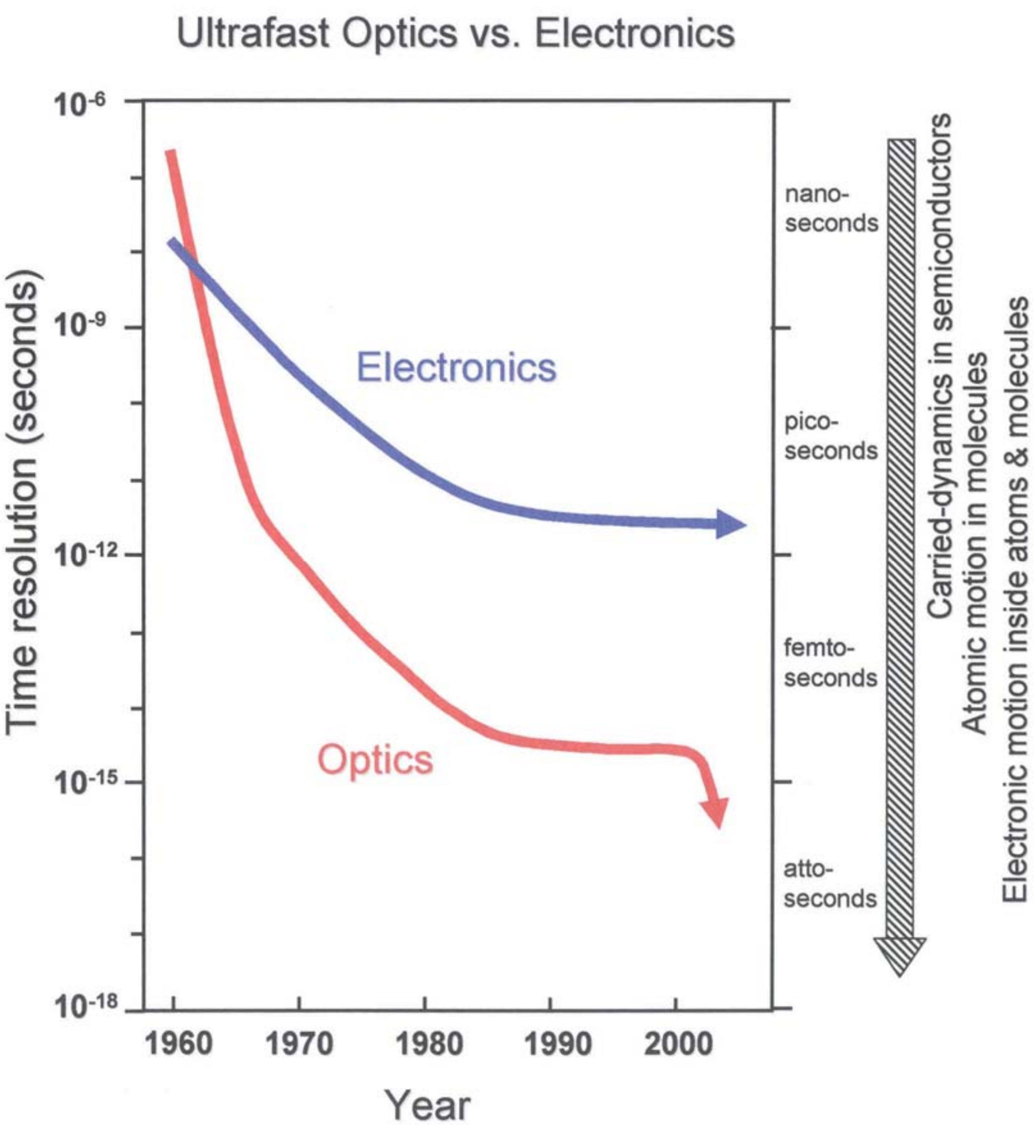

Fig. VIII-9

Frontier of ultrafast science: attosecond “oscilloscope”

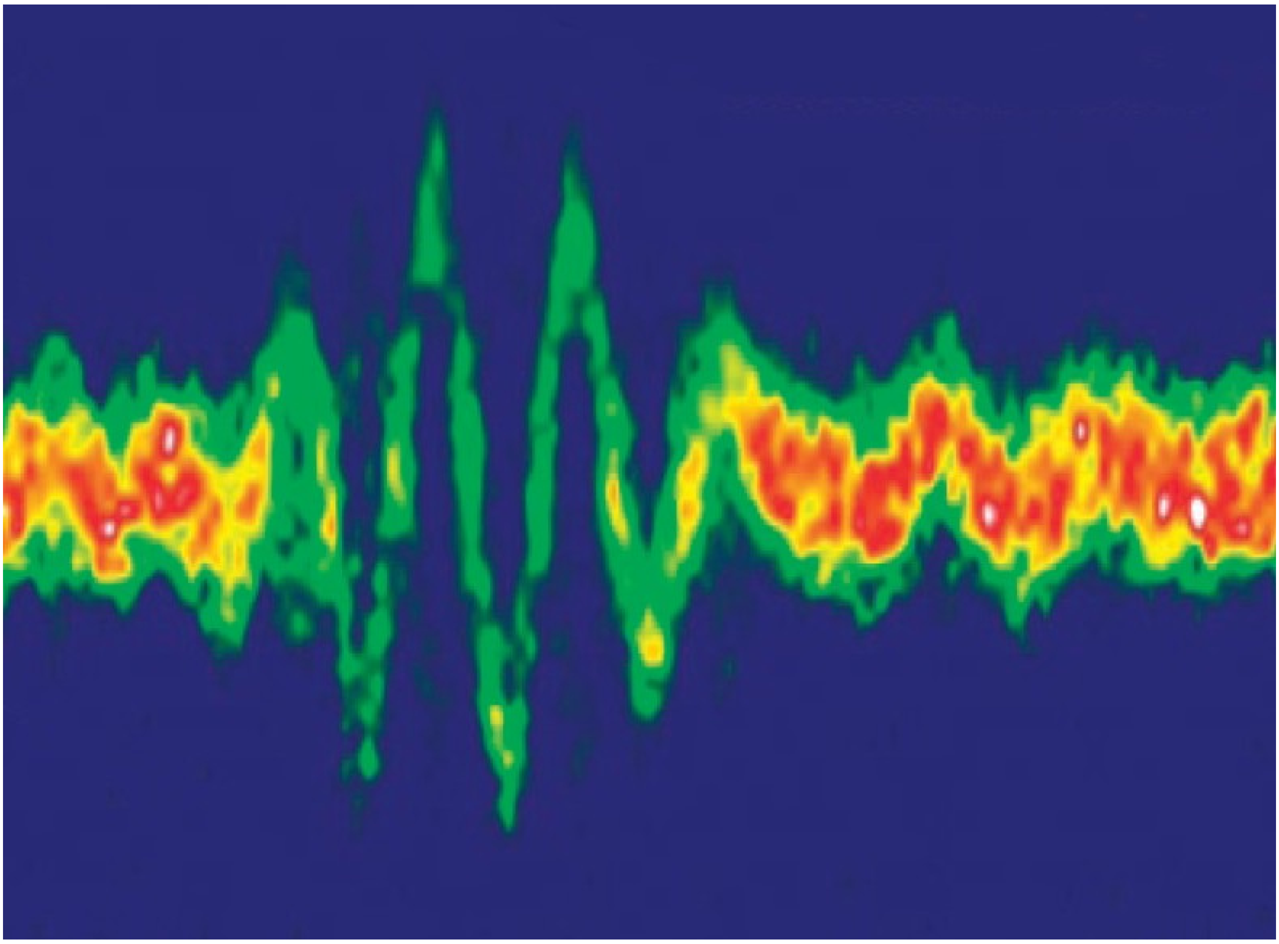

Fig. VIII-10

Temporal image of a 4.3-fs pulse of red laser light (wavelength ~ 750 nm, wave period ~ 2500 as) recorded with 250-attosecond extreme ultraviolet pulses in an apparatus that may be considered as an optical oscilloscope with attosecond temporal resolution (*Science* 305, p. 1267, 2004; *Physics Today*, p. 21, October 2004, see attached; *New Scientist*, April 9, 2005). Direct measurement of light waves was pursued shortly after the invention of the electronic oscilloscope (“… *I had repeatedly, though in vain, attempted to obtain direct current from oscillations of light”,* Ferdinand Brown, Nobel Lecture, 1909) but became only feasible with the advent of attosecond metrology (*Nature* Vol. 414, P. 509, 2001). The measurement constitutes the first direct and complete measurement of a light wave and provides clear evidence for ultrafast optics having entered the attosecond time domain, opening the way to controlling and tracing electronic motion within atoms, molecules and nanostructures.

This few-cycle light pulse if amplified to petawatt power levels, will allow generating a super-relativistic ultrahigh-density electron bunch, which may permit the realisation of the kilometre-scale X-ray free electron lasers pursued currently at Stanford (Fig. VIII-11) and Hamburg within a small laboratory.

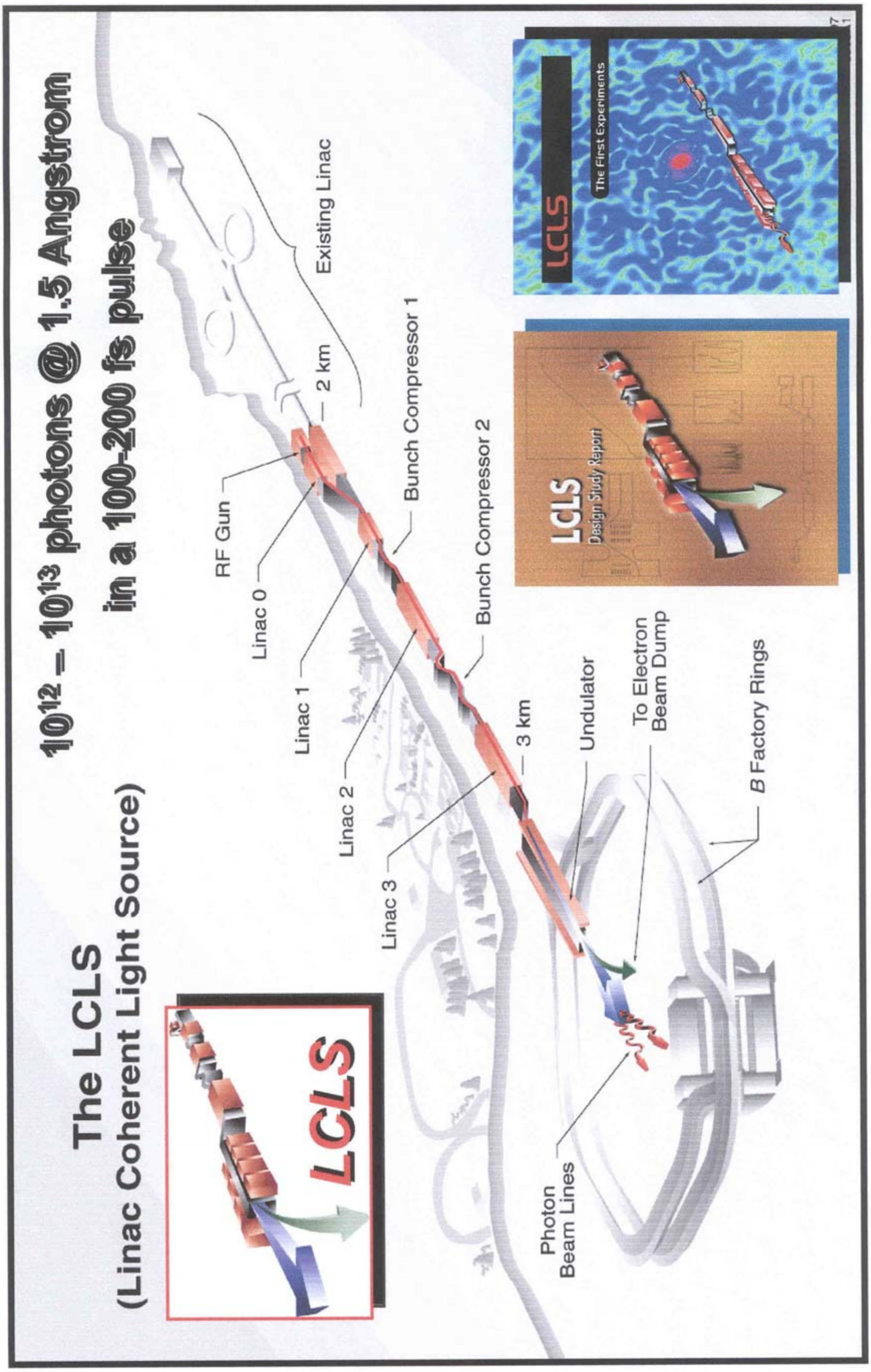
The LCLS
(Linac Coherent Light Source)
10¹² – 10¹³ photons @ 1.5 Angstrom
in a 100-200 fs pulse
LCLS
RF Gun
Linac 0
Linac 1
Linac 2
Linac 3
Bunch Compressor 1
Bunch Compressor 2
2 km
3 km
Existing Linac
Undulator
To Electron Beam Dump
B Factory Rings
Photon Beam Lines
LCLS Design Study Report
LCLS The First Experiments

Fig. VIII-11