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Introduction to synchrotron radiation

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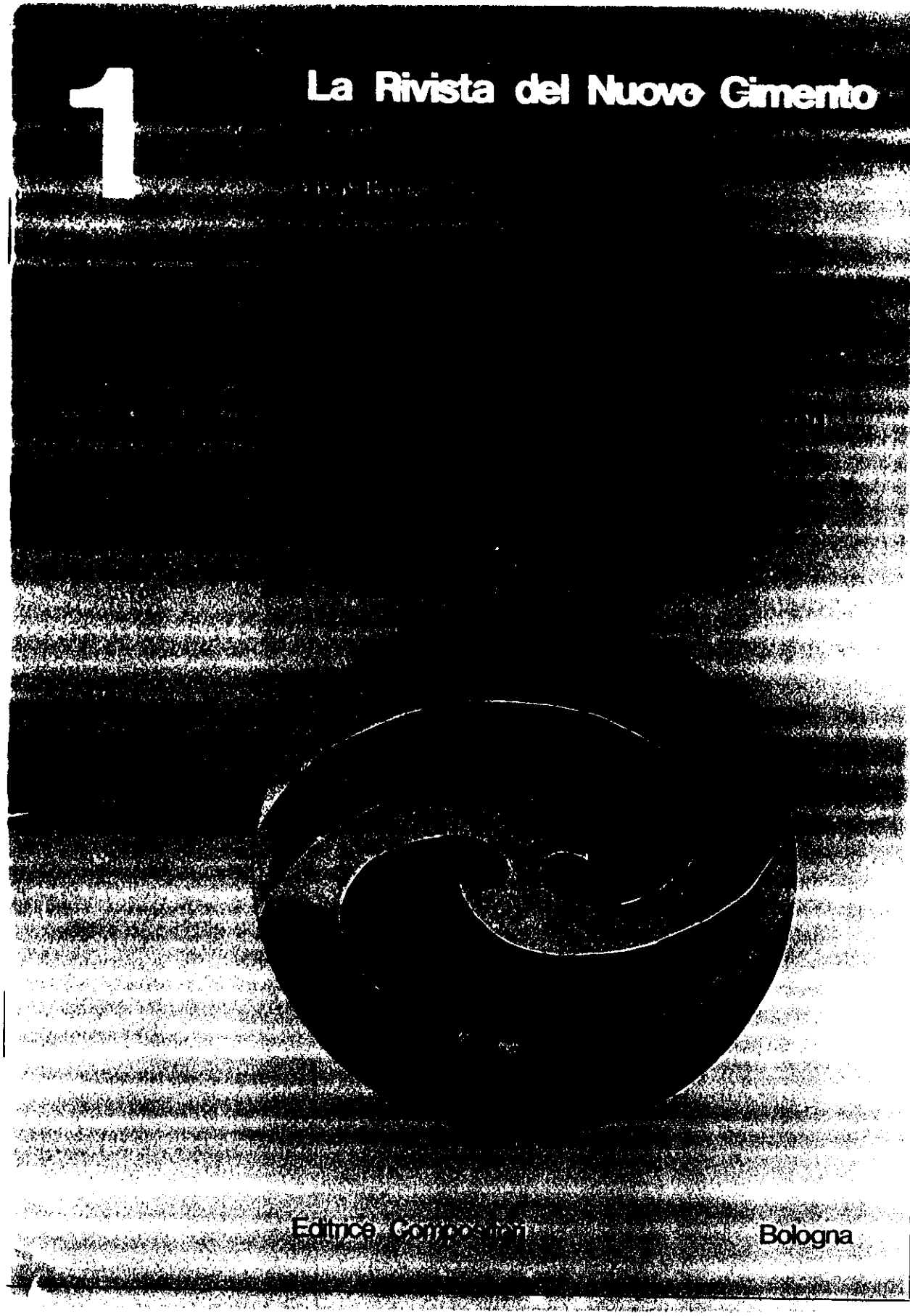

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G. MARGARITONDO

Synchrotron Light and Free-Electron Lasers.

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Synchrotron Light and Free-Electron Lasers.

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1. – Introduction: the ultimate photon sources in material physics.

Ninety years after Einstein's presentation of the concept of photon [1], Italy is opening to the international scientific community ELETTRA, the most advanced source of soft–X-ray photons in the European continent [2]. The recent commissioning of ELETTRA near Trieste marks the rebirth in Italy of a field—synchrotron light—to whose advent scientists of Italian origin had much contributed. This rebirth will have a deep impact on materials science research on a European and worldwide scale, within the general scenario created by the commissioning of similarly advanced sources in Taiwan (SRRC, Hsinchu), USA (ALS, Berkeley) and South Korea (PLS, Pohang).

This impact can be enhanced by making the Italian and European scientific community aware, at least at an elementary level, of the properties of synchrotron light, of its importance and of its fields of application. This is the main objective of the present article. My ambition is to quickly bring colleagues with little or no knowledge of synchrotron light to a basic knowledge of this field, without resorting to complicated formalism.

My presentation of synchrotron light is divided into three parts. First of all, I discuss the basic properties of synchrotron light and their physical background, using ELETTRA as a specific example. Then, I explain the scientific and technological importance of synchrotron light and its causes. Finally, I present the historical evolution of synchrotron photoemission research as a practical example of the impact of synchrotron light.

A discussion of today's status of this field, however, would not be complete without including another class of sources, whose spectral domain is complementary to that of synchrotron light: the free-electron lasers (FELs). Sections 5 and 6 will then be dedicated to the basic principles of FEL operation, and to some of the FEL applications in materials science.

The final section 7 will try to use the crystal ball, and look at the future of this field. A future in which new and exciting projects can be foreseen, such as the Swiss Light Source [3], SOLEIL in France and the grandiose plan to transform SLAC into the most powerful free-electron laser in the world [4].

2. – The basic properties of synchrotron light in a nutshell.

Forty years after the first observation of synchrotron light, and 25 after its first systematic use in research [5], most scientists are still unaware or only marginally aware of its amazing properties. These can be summarized as follows [5]:

1) Synchrotron light is emitted by charged elementary particles moving at relativistic speed in an accelerator, when their trajectory is deflected by a bending magnet.

2) Synchrotron light can be also produced by special *insertion devices* consisting of periodic arrays of magnets, which perturb electrons which would otherwise move in a straight trajectory, and force them to «undulate» with respect to such a trajectory.

3) Synchrotron light, both from bending magnets and from insertion devices, is very highly collimated.

4) The emission from bending magnets occurs in short time pulses.

5) The emission from bending magnets or from the insertion devices called «wigglers» covers a very broad spectral range from the visible to the X-rays—from which the specific photon energies required for specific applications can be extracted with filtering devices such as grating or crystal monochromators.

6) The emission from an insertion device of the «undulator» type occurs instead over a very narrow and tunable spectral band.

7) Synchrotron light is extremely intense and bright.

8) Synchrotron light is highly polarized, the polarization depending on the type of emitting device and on the direction of emission.

Before linking such properties and their physical causes we would like to anticipate one of the main conclusions of the next section, and note that the aforementioned spectral distribution is the main reason for the synchrotron light's importance in many different areas of research. In a sense, synchrotrons are the ultimate photon sources: they can either provide a broad spectral range from which

the specific desired wavelength can be extracted, or a narrow undulator band whose spectral position can be modified as required.

Synchrotron light, therefore, can solve the problem of finding high-quality photon sources for virtually every spectral region. Its role is, of course, particularly important for those parts of the electromagnetic spectrum for which other sources either do not exist or have inferior performances. The most relevant example is the spectral domain of the X-rays, which is of crucial importance in today's condensed-matter research for reasons that we discuss later.

2·1. *The physical background of synchrotron light: an elementary picture.* – A charged electron moving at speed v in a circular trajectory of radius R under the influence of a magnetic field of strength B emits light because of its (centripetal) acceleration [6]. If the motion is non-relativistic ($\beta = v/c \ll 1$), then the frequency of emission is the cyclotron frequency, $\omega = eB/m_0$. The emitted power is proportional to the square of the acceleration, $P \propto a^2$, which in turn is proportional to $(pB)^2$, where p is the electron momentum's magnitude.

As the electron's motion becomes relativistic, these conclusions must be modified in several ways. First, the cyclotron frequency in the laboratory frame must be written using the relativistic mass: $\omega = eB/\gamma m_0$, with $\gamma = E/m_0 c^2$ (E = electron's energy). Since $\omega = v/R \approx c/R$, we have

$$R = \left(\frac{m_0 c}{e}\right)\left(\frac{\gamma}{B}\right). \tag{1}$$

Second, the emitted power is still proportional to $(pB)^2$, where p is now the relativistic momentum's magnitude, thus $p \propto \gamma$. Therefore, $(pB)^2 \propto (\gamma B)^2$, and using eq. (1), $(\gamma B)^2 \propto \gamma^4/R^2$.

This, of course, is true for each electron, and the total emitted power is $P_{\text{tot}} \propto N(\gamma^4/R^2)$, where N = total number of circulating electrons. Since the circulating beam current in the ring $i = Nev/(2\pi R)$,

$$P_{\text{tot}} \propto \frac{i\gamma^4}{R}. \tag{2}$$

This equation implies that the emitted power increases very rapidly with the charged particle's energy $E \propto \gamma$, and decreases very rapidly with its (rest) mass, since $\gamma \propto 1/m_0$. This explains why only electron or positron accelerators—and not, for example, proton accelerators—are used as synchrotron light sources. Specifically, the synchrotron light used in today's research is extracted from electron (or positron) storage rings: synchrotrons, from which the term «synchrotron light» derived, have almost disappeared from the scene as photon sources.

The relativistic motion of the electrons also produces the high collimation of the emitted light. The angular-distribution pattern in the plane of the electron's orbit is proportional to $\cos^2\theta$ in the non-relativistic case (the angle θ being measured from the tangent to the orbit); in the relativistic case, this broad distribution becomes a very narrow cone, much like an extreme searchlight—see fig. 1.

A certain collimation would in fact be present for non-relativistic electrons as well. Consider a light beam emitted by a circulating electron in the plane of its orbit, at an angle θ_e with respect to the tangent to the orbit. Here θ_e is in the angle

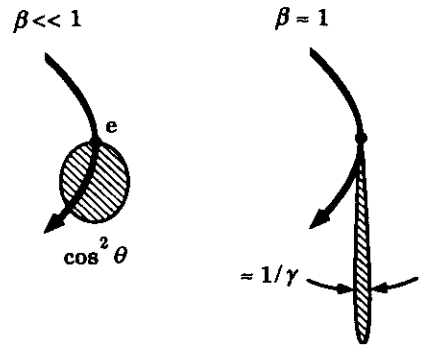


Fig. 1. – On going from the classical motion of an electron along a curved trajectory to the relativistic case, the angular distribution of the photon emission changes from the uncollimated $\cos^2\theta$ pattern to a highly collimated «searchlight» pattern whose angular amplitude is of the order of $1/\gamma$.

measured in the *inertial* reference frame (e-frame) which instantaneously coincides with the emitting electron and moves tangential to the orbit with the electron's speed. A Galileian transformation of the velocity shows that the angle θ_e corresponds in the laboratory frame to $\theta = \mathrm{tg}^{-1}(\sin\theta_e/(\cos\theta_e + \beta))$. Thus, each emission angle θ_e in the e-frame corresponds to a smaller angle θ in the laboratory frame.

For relativistic electrons, the Lorentz transformation of the velocity gives instead

$$\theta = \mathrm{tg}^{-1}\left(\frac{\sin\theta_e}{\gamma(\cos\theta_e + \beta)}\right) \approx \mathrm{tg}^{-1}\left(\frac{\sin\theta_e}{\gamma(\cos\theta_e + 1)}\right); \tag{3}$$

the γ-factor in the denominator enhances the collimation; for example, the direction of half-maximum intensity, which is $\theta_e = \cos^{-1}(\sqrt{2}/2) = \pi/4$ in the e-frame, becomes, according to eq. (3), $\theta \approx 0.41/\gamma$. Thus, the aperture of the emitted cone of synchrotron light is of the order of $\approx \gamma^{-1}$.

This extreme collimation means that a detector in the tangential direction sees a very short pulse of synchrotron light only when the electron moves approximately towards it. Assume that the detected pulse begins to be emitted at the time $t = 0$. If the detector is at a distance D, then the pulse begins to be detected at the time $t = D/c$. The emission of the pulse ends when the direction of emission (tangent to the orbit) has changed by $\approx \gamma^{-1}$, which corresponds to an electron's displacement $\approx \gamma^{-1}R$. Thus, the pulse emission ends at $t \approx (\gamma^{-1}R)/v$. The end of the detection occurs when this «end emission» reaches the detector after travelling along the distance $D - (\gamma^{-1}R)$—and therefore at the time $(\gamma^{-1}R)/v + (D - (\gamma^{-1}R))/c$.

Thus, the time duration of the pulse detection is

$$\delta t = (\gamma^{-1}R)/v + (D - (\gamma^{-1}R))/c - D/c = (\gamma^{-1}R)(1/v - 1/c) =$$

$$= (\gamma^{-1}R)(1 - \beta)/c\beta = (\gamma^{-1}R)(1 - \beta^2)/c\beta(1 + \beta) = (\gamma^{-3}R)/c\beta(1 + \beta),$$

which for $\beta \approx 1$ becomes

$$\delta t \approx \frac{R}{2c\gamma^3} . \tag{4}$$

We can now easily understand the basic properties of the spectral distribution of synchrotron light. Consider the e-frame, in which the electron's speed is zero but *its acceleration is not.* The acceleration is caused by the electrostatic force of the transverse electric field which is the Lorentz transformation of the transverse B-field in the laboratory frame. The magnitude of the electric field is γvB, which causes a centripetal acceleration of magnitude $\gamma evB/m_0$ in the e-frame, and therefore a rotation with angular frequency $\gamma eB/m_0$ in the same frame.

This is also the central emitted frequency, again in the e-frame. Its conversion to the laboratory frame implies a Doppler shift by a factor $\approx 2\gamma$, giving a central emitted photon energy:

$$\hbar\omega_c = \hbar\left(\frac{2\gamma^2 eB}{m_0}\right). \tag{5}$$

This «central» photon energy is called the *critical photon energy* of the bending-magnet synchrotron light emission. Using eq. (1), we can also write

$$\hbar\omega_c = \hbar\left(\frac{2\gamma^3 c}{R}\right), \tag{6}$$

which compared to eq. (4) enables us to realize that $\hbar\omega_c \approx \hbar(\delta t)^{-1}$. Note the rapid shift of the critical photon energy towards the hard X-rays as the electron beam energy increases.

On the other hand, the short pulse duration implies a Fourier distribution of frequencies and photon energies, which broadens the emission around the critical wavelength. The photon energy spectral width is of the order of $\hbar(\delta t)^{-1}$.

Thus, in first approximation, the bending-magnet spectrum is a band centered at $\hbar\omega_c$ and with a bandwidth also comparable to $\hbar\omega_c$. Figure 2 shows a plot

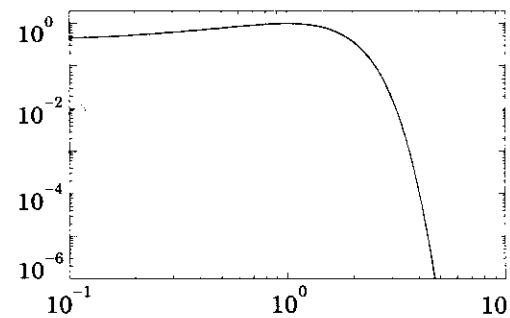


Fig. 2. – In first approximation, the spectral distribution of the synchrotron light emitted by a bending magnet is a band centered at $\hbar\omega_c$ and with bandwidth of the order of $\hbar\omega_c$. The log-log plot of the intensity as a function of $\hbar\omega/\hbar\omega_c$ does reproduce the qualitative features of the bending-magnet spectrum.

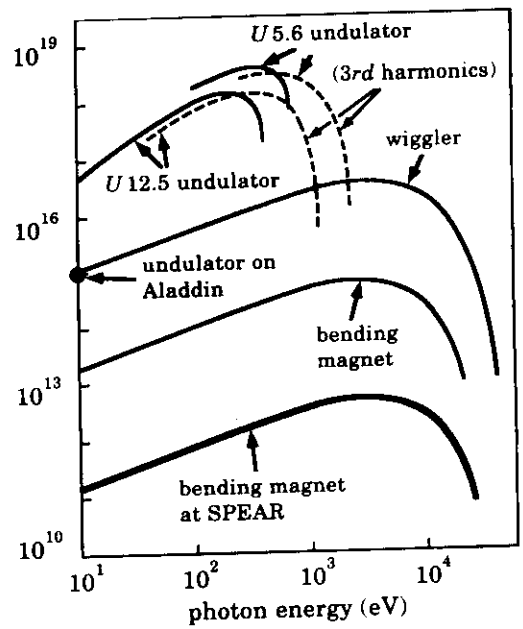


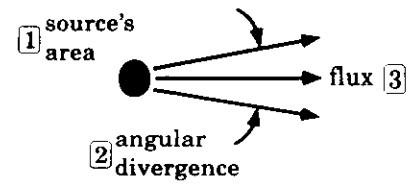
Fig. 3. – Brightness spectra from the ultrabright third-generation source ELETTRA in Trieste. The different plots refer to ELETTRA's bending magnets and undulators. These spectra of a second-generation undulator source (Aladdin) and bending magnet (SPEAR) are shown for comparison.

of this spectrum in the usual log-log scale, which indeed qualitatively reproduces the well-known appearance of the bending-magnet spectrum.

Figure 3 shows real spectra including one from the bending magnets of ELETTRA [2]. Note the main qualitative difference: the displacement of the critical photon energy with respect to the maximum point. This is due to several factors. First, the approximations of the previous derivation. Second, the fact that what is plotted in fig. 3 is not the spectrum in terms of emitted intensity, but the *brightness*, which is expressed in terms of number of photons in a constant (fractional) bandwidth ($\Delta\hbar\omega/\hbar\omega$).

In summary, a very simple analysis has enabled us to link the basic properties of bending-magnet emission—power, collimation, pulse duration and spectral distribution—to the classical emission by a rotating charge and to relativistic effects such as the Doppler shift. On the other hand, the polarization of synchrotron radiation can be qualitatively understood by imagining the motion of the electrons as seen from different points of view: it is easy to realize that the polarization is linear in the plane of the orbit and increasingly elliptical out of this plane.

2·2. *What is new in machines like* ELETTRA? *Brightness and undulators.* – The aforementioned properties already make bending magnets almost ideal sources of photons. There is, however, an additional property which is extremely important for practical applications. This property, called *brightness*, is schematically illustrated in fig. 4: in essence, it is the combination of the flux and of the source's geometrical characteristics, size and angular spread.



$$\text{brightness} = \text{constant} \times \frac{3}{1 \times 2}$$

Fig. 4. – Schematic illustration of the definition of brightness, the parameter that best characterizes the quality of a synchrotron source.

Why is brightness important? The reason is one of the many versions of the Liouville theorem, *i.e.* the volume conservation in phase space [5]. In essence, brightness is determined by the flux and by the volume in the phase space defined by the source's dimensions and angular spreads. Its Liouville-theorem conservation along an optical beamline implies that one cannot decrease the photon beam size without increasing the angular spread and *vice versa*.

The main requirement for most applications is to concentrate a large number of photons per unit time in a very small sample area at the end of the beamline, *i.e.* to decrease the beam spot size. Without a high-brightness source, this would require working with large angular divergence, therefore with large-size optical components such as mirrors—which might be technically unfeasible and are certainly very expensive and difficult to manufacture.

The conclusion, therefore, is that a source of high brightness is either preferable or needed for most applications. How can one increase the brightness of a synchrotron source? There are two ways. First, to improve the geometric characteristics of bending-magnet emission. Second, to use the insertion devices known as undulators. In a facility like ELETTRA, world-record levels of brightness are reached with the combination of both factors.

The bending-magnet brightness can be increased by decreasing the source size and the angular spread. In turn, the source size is that of the electron beam, which is caused by deviations around the nominal trajectory. The angular divergence is caused by the same deviations, combined with the natural divergence of synchrotron light emission, $\approx \gamma^{-1}$.

This latter cannot be modified, so one is forced to improve the electron beam geometry. This geometry is defined by the accelerator parameter called *emittance*: low emittance corresponds to high brightness. In the case of ELETTRA, the adoption of new solutions for the accelerator's magnet lattice has made it possible to reduce the emittance to unprecedented levels, thereby allowing equally unprecedented levels of bending-magnet emission brightness.

On the other hand, ELETTRA is equipped with several insertion devices, primarily of the type called undulators—whose brightness is much higher than that of bending magnets. In order to understand how this is possible, consider fig. 5 and imagine an electron that travels straight into the periodic array of magnets of an insertion device. Without the magnet array, the trajectory would be a straight line; the array causes instead oscillations around this straight line. The synchrotron light emission of each oscillation is in a sense equivalent to that of an individual bending

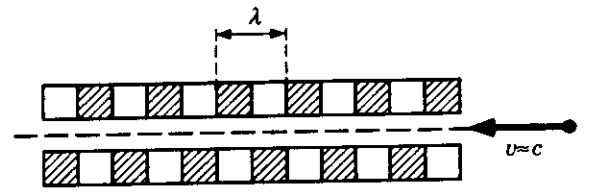


Fig. 5. – An electron subject to the action of an insertion device, consisting of a periodic array of magnets. Without the insertion device, the electron's trajectory would be the dashed straight line. The insertion device forces the electron to oscillate with respect to this straight trajectory. Depending on the magnitude of these deviations, the device works as a wiggler or as an undulator.

magnet. Therefore, the total emission is that of a series of bending magnets, with a substantial increase in flux and brightness with respect to an individual bending magnet.

This is indeed a fair description of what happens in an insertion device of the *wiggler* type, for which the emissions of subsequent electron oscillations are incoherent with respect to each other, and the intensity is just the sum of the individual oscillations' intensities.

Consider instead the case of small angular oscillations, smaller or of the order of the natural angular spread of the emission, $\approx \gamma^{-1}$. This implies that the superposition of the emissions of different oscillations is no longer incoherent, but coherent. This gives rise to a narrow-band emission rather than the broad-band emission of wigglers or bending magnets—and the corresponding insertion device is called an *undulator*.

The undulator bandwidth is trivially given, in first approximation, by the diffraction-grating theory:

$$\frac{\Delta\hbar\omega}{\hbar\omega} = n^{-1}, \tag{7}$$

where n is the total number of periods in the array of magnets.

The character of an insertion device—undulator or wiggler—is defined by the so-called undulator's K-parameter:

$$K = \frac{eB\lambda}{2\pi c m_0}, \tag{8}$$

where λ is the undulator's magnet array period. In essence, the K-parameter corresponds to the angular oscillation amplitude measured in units of γ^{-1}. The insertion is a wiggler, rather than an undulator, if $K \gg 1$.

The undulator's narrow-band emission is centered around a photon wavelength which is given, in first approximation, by the undulator's period. Note, however, that this period must be corrected for the Lorentz contraction factor γ^{-1} when seen by the moving electrons; furthermore, the wavelength emitted by the electrons is Doppler-shifted when seen from the laboratory frame.

Along the axis of the undulator, the Doppler shift factor is $\approx (2\gamma)^{-1}$, and therefore the wavelength is $\approx \lambda(\gamma)^{-1}(2\gamma)^{-1} = \lambda/2\gamma^2$. At an angle θ from the undulator's axis, the relativistic Doppler shift factor becomes $\approx (2\gamma)^{-1}(1 + \gamma^2\theta^2)$. Furthermore, one must take into account the angular deviation caused by the

magnetic field, and this further changes the Doppler factor to $\approx (2\gamma)^{-1}(1 + K^2/2 + \gamma^2\theta^2)$ [5]. Thus, the central photon energy emitted by the undulator is

$$\hbar\omega \approx \frac{\hbar 4\pi c\gamma^2}{\lambda}\left(\frac{1}{1 + (1/2)K^2 + \theta^2\gamma^2}\right). \tag{9}$$

This implies that $\hbar\omega$ can be tuned by changing either γ—the electron energy—or more realistically the B-field strength which determines K, for example by changing the magnets' gap width.

The undulator's emission is very bright because it is collimated and concentrated in a narrow band rather than in a broad band like a wiggler's or a bending magnet's emission. When combined to low emittance, the undulators produce truly superior performances: compared to typical synchrotron sources of the previous generation, machines like ELETTRA emit [2] from 3 *to* 5 *orders of magnitude* more brightness! This point can be directly appreciated in fig. 3, and constitutes one of the biggest experimental improvements of all times.

The combination of narrow bandwidth, high spatial localization and high collimation leads to a high level of coherence. A high-brightness source like one of ELETTRA's undulators is indeed also a partially coherent source. This coherence can be exploited for specialized applications such as holographic techniques.

Can one do better in the future than with the present undulators? The answer is maybe, if we are able to find solutions to some very fundamental problems. For most applications, monochromatic synchrotron light is needed, with resolving power $(\hbar\omega/\Delta\hbar\omega)$ ranging between 10^2–10^4. A typical undulator has much less than 100 periods, thus according to eq. (7) insufficiently narrow bandwidth; a monochromator can further decrease the bandwidth, but this device also reduces the brightness, sometimes by orders of magnitude.

In principle, one could increase n, the number of periods, decrease $(\Delta\hbar\omega/\hbar\omega)$, and eliminate the need for a monochromator. There, is, however, a fundamental limitation in this approach: the energy of the circulating electrons in the accelerator has a certain spread, which is primarily caused by the emission of synchrotron light. This in turn creates a spread $\delta\gamma$ in the value of γ; according to eq. (9), $\delta\gamma$ causes a spread $\delta\hbar\omega$ of the photon energy. $(\Delta\hbar\omega/\hbar\omega) = n^{-1}$ cannot be decreased by increasing n beyond the limit value $(\delta\hbar\omega/\hbar\omega)$.

From eq. (9) one has, at $K = 0$ and $\theta = 0$, $(\delta\hbar\omega/\hbar\omega) \approx 2(\delta\gamma/\gamma)$. For a machine like ELETTRA, this implies that $(\Delta\hbar\omega/\hbar\omega)$ no longer decreases after the number of periods reaches the value $n \approx 200$. The situation is even worse for $\theta \neq 0$.

There exist, at present, no solution for this problem. A way to overcome this obstacle would be very desirable indeed. Eliminating the monochromator while keeping a narrow bandwidth would amount to a huge effective increase in the brightness, something equivalent to the development of a new generation of synchrotron sources.

3. – Why is synchrotron light so universally important?

The importance of synchrotron light is not linked to a temporary fashion or to a specialized experiment: it is based instead on the very foundations of condensed-matter science. In essence, every experimental probe of condensed matter on a

microscopic scale is based on a specific type of particles, such as electrons, ions or neutrons. Photons have always been a very important—if not *the* most important—among these probes.

On the other hand, our capability to look at specific consensed-matter properties depends on the «size» of the particles used as probes—both the «spatial» size and the «energy» size. For example, one cannot easily detect morphologies on a scale much smaller than the wavelength of the probe particles.

By far the most important «sizes» in condensed matter are those of *chemical bonds*, which are the foundation of most physical properties of condensed systems—in particular, properties of practical and technological interest. The typical spatial size of chemical bonds is a few angstroms. The «energy» size ranges from tenths to tens of electronvolts.

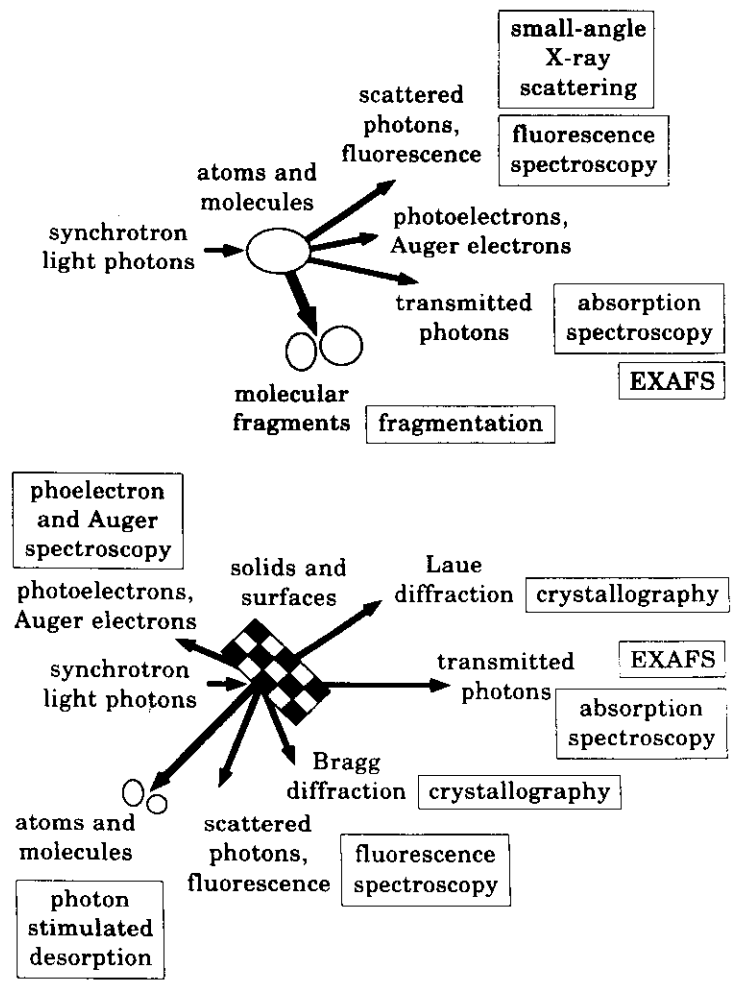


Fig. 6. – Each of the different types of interations between synchrotron light and atomic, molecular or solid-state systems can be exploited in one or several experimental techniques.

Therefore, the best photons to study chemical bonds have wavelengths ranging from 0.1–100 Å and/or energies ranging from 1 to 1000 eV. Except for its lowest-energy (visible-infrared) portion, this spectral range is dominated by ultraviolet and X-ray radiation, for which synchrotrons are truly superior sources.

One can then say that synchrotron sources are fundamentally important because they are the best sources of photons with the right «size» to study chemical bonds and other fundamental properties of nature. This is a radical departure from the original role of particle accelerators, which were used for highly specialized experiments in elementary-particle research. Synchrotron sources, on the contrary, are the essential ingredient of a huge variety of experimental techniques, whose applications touch many parts of physics and, beyond physics, disciplines as diverse as medical research and materials engineering.

Virtually every kind of interaction between a condensed-matter system and synchrotron photons can provide the basis for one or several synchrotron-based experimental techniques. For example, photon absorption is exploited in absorption spectroscopy, photoelectron yield spectroscopy and EXAFS (extended X-ray absorption fine structure) [5]. Figure 6 schematically illustrates this point, both for solid-state applications and for research on atoms and molecules.

One can easily imagine how much, prior to the advent of synchrotron light, the absence of good photon sources for ultraviolet and X-ray photons negatively affected the scientific and technological progress. In that situation, any source would have been better than no source at all. But a synchrotron is certainly not «any source»: it is a truly superior instrument, with virtually all of the characteristics of an ideal photon emitter. Each of these characteristic—high brightness and flux, linear and circular polarization, spectral distribution, time structure—has been extensively exploited for different types of experimental techniques [5].

For example, the time structure of bending-magnet emission—which reflects the bunch structure of the electron beam and consists of short pulses separated by larger intervals—is useful in time-dependent experiments. In the future, one can envision an increasing exploitation of this property, with two-particle techniques such as the pump-and-probe experiments. One can, for example, use a photon of a given energy to stimulate a certain process at a given time and then a photon of a different energy to study its characteristics after a certain delay: the applications of this approach are virtually unlimited.

4. – A fundamental example: photoemission, from spectroscopy to spectromicroscopy.

We cannot, of course, discuss all of the applications of synchrotron light, which would occupy several volumes. We will try to give a more specific idea of the past, present and future impact of synchrotron light on research by selecting a specific area and following its evolution. The area that we selected, because it is familiar to us, is photoemission.

Photoemission research initiated with Hertz's discovery of the photoelectric effect [7]. The early research with photoelectrons produced one of the most important physics results of all times: the confirmation in the 1910's of the 1905 Einstein's proposal of the concept of photons [1]. However, photoemission as a basic tool in materials science, as we know it today, arrived much later, in the 1950's [8].

The main cause of this delay were instrumental limitations, primarily in three areas: the electron analyzers, the photon sources and the vacuum systems. The first break through such limitations was Kai Siegbahn's realization [8] of the need for ultraclean surfaces, which originates from the extreme surface sensitivity [5] of photoemission experiments—and requires the use of ultrahigh vacuum.

Even after this breakthrough, the progress towards full exploitation of the potential information carried by photoelectrons was quite slow—until the advent of synchrotron light. In order to understand how much information is stored in the photoelectric effect, imagine an «ultimate» photoemission experiment (which cannot yet be performed).

This «ultimate» experiment would require complete control and full tunability of all of the relevant parameters in the photoemission process, plus excellent resolution in the broadest possible sense. This means controlling the photon energy, direction and polarization and the photoelectron energy, direction of emission and spin polarization, with high photon and electron energy resolution, photon collimation and photoelectron angular resolution, and space and time resolution.

The main problem in even partially achieving this objective is the signal level: even now, with the best possible instrumentation and in particular the brightest photon sources, we are quite far from it. But substantial progress has been made, and synchrotron light has been a major factor [5].

Before the advent of synchrotron light, photoemission experiments were typically [5] scans of the photoelectron energy with no possibility to change the photon energy, no angular resolution, no photon collimation, no photon or spin

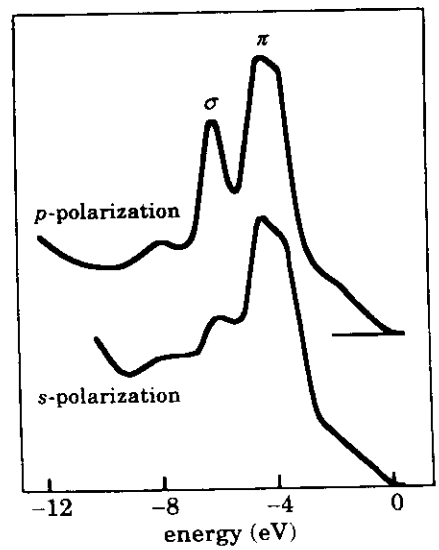


Fig. 7. – Early study of photon polarization effects in photoemission spectra, made possible by the advent of synchrotron light with its high degree of polarization. The spectra were taken on Cl chemisorbed on Si(111). The spectral changes ongoing from s-polarization to p-polarization made it possible to distinguish the spectral features originating from σ-states and π-states. Data from Schluter *et al.*, ref. [9].

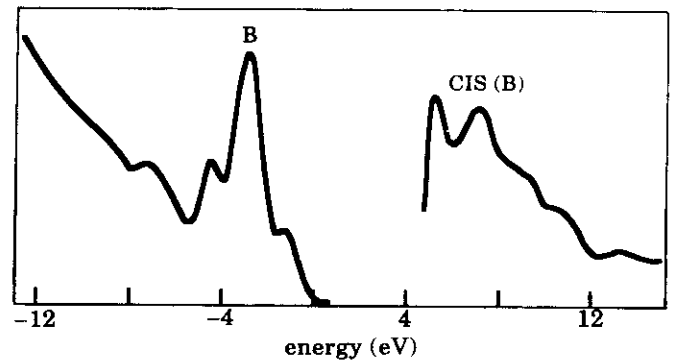


Fig. 8. – The combination of different synchrotron photoemission techniques made it possible in this early exploitation of the synchrotron photon energy tunability to explore both the occupied and unoccupied valence electronic states of GaSe. The left-hand side spectrum is a photoelectron «energy distribution curve» (EDC) taken at a constant photon energy of 28 eV: this spectrum reflects the valence band density of states. The right-hand curve is a «constant initial state» (CIS) spectrum obtained by monitoring the photoelectron intensity while simultaneously scanning the photoelectron energy and the photon energy, and keeping their difference constant. This corresponds to keeping the initial-state energy constant, so that the CIS curve primarily reflects the conduction-band density of states above the vacuum level. The right-hand side CIS curve corresponds in this case to the initial-state energy of peak *B* in the EDC. Data from Margaritondo *et al.*, ref. [12].

polarization control, no spatial or time resolution. With the first storage ring sources of synchrotron light—such as ADONE at Frascati or TANTALUS at Wisconsin—this primitive situation started to improve [5].

Figures 7 and 8 show early examples (from the mid 1970's) of experiment as a function of photon polarization [9]. Figure 9 illustrate some of the first examples (same period) of band mapping by angle-resolved photoemission [10] and of experiments involving the scanning of the photon energy [11]. Quite important in this last development was the introduction of specialized techniques like constant-initial-state (CIS) spectroscopy [12] and partial-yield (PY) spectroscopy [13]. At the same time, substantial progress was being made in the detection of spin polarization [14].

The advent of angle-resolved photoemission was conceptually quite important in solid-state physics. The knowledge of the energy and direction of propagation of a photoelectron is equivalent—except for the spin—to a full knowledge of its quantum state. Several methods have been developed [5] to derive from the photoelectron's state the corresponding unperturbed quantum state of the electron in the solid. This capability to study condensed-matter electronic states as if they were independent of each other was a huge improvement with respect to the previous optical experiments —which «mixed» initial- and final-state properties measuring, for example, the joint density of states.

Photoemission, of course, does not really measure independent states: final-state and collective phenomena always play a very important role in the photoelectric effect [5]. Nevertheless, the first angle-resolved experiments allowed the physicists to almost «touch» individual-state properties such has the band structure, which had been previously confined to the realm of theory. This had an important conceptual and even psychological impact on the history of condensed-matter physics.

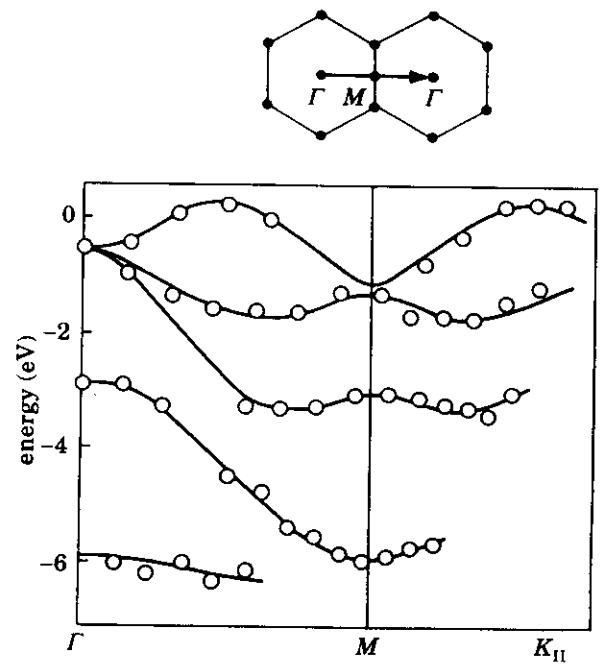


Fig. 9. – Early example of band structure mapping by angle-resolved photoemission with synchrotron light: the experimental band structure of GaSe along the Γ-M-Γ line of the two-dimensional Brillouin zone (top). The bands were mapped by deriving the k-vectors from measurements of the energy and direction of emission of the photoelectrons. Data from ref. [10].

The next synchrotron-allowed breakthroughs in photoemission occurred in the late 1980's. First of all, the discovery of high-temperature superconductors suddenly made «almost» possible to directly measure with photoemission the properties of the superconducting gap [15-17]. «Almost» because the typical energy resolution in the late 1980's—a few tenths of meV—was still quite far from the high-temperature superconductor gap values.

But the discovery of high-temperature superconductors stimulated a rapid development in this field, and resolutions of 10–20 meV were not uncommon at the beginning of the 1990's. Figures 10 and 11 illustrate this rapid evolution, with an early detection of the opening of a superconductivity gap [15] and with one of today's much better results [16].

The other breakthrough of the late 1980's was the advent of spatial resolution [18-23]. Until then, photoemission experiments typically averaged over areas of the order of 1 mm^2 or not much less, completely missing the microstructure and nanostructure properties of the sample. This made it impossible, for example, to investigate life-science systems, whose spatial features are in the scale of one micron or less [19, 20].

One of the major factors allowing high spatial resolution in photoemission was the advent of the first undulators [5], which increased the available photon brightness and signal level, and in turn made it possible to reduce the probed area to one micron or less.

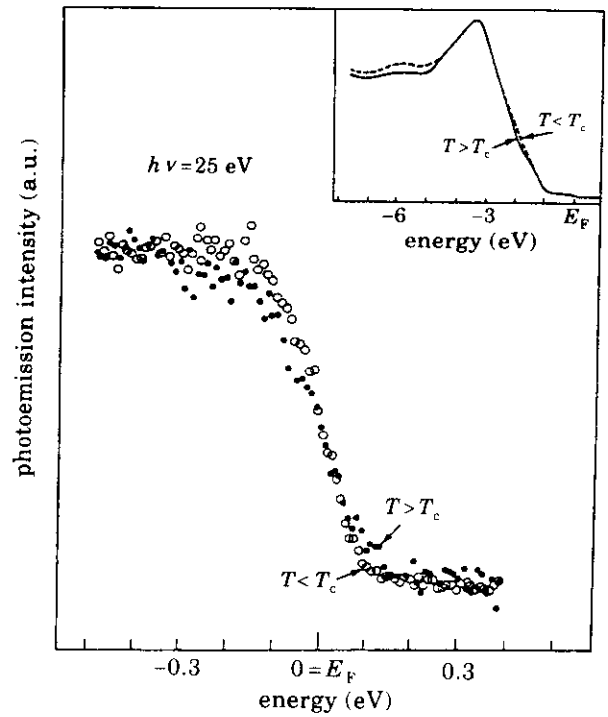


Fig. 10. – The first hints of the opening of the superconductivity gap in photoemission spectra from Bi-Ca-Sr-Cu-O: the insufficient resolution makes it difficult to clearly see the phenomenon (data from ref. [15]).

This boost in brightness was exploited by Cerrina *et al.* [18,21] for the development of their photoelectron spectromicroscope MAXIMUM, a scanning instrument whose lateral resolution is primarily based on the X-ray focusing action of a multilayer-coated Schwarzschild objective. Figure 12 shows some recent examples of result obtained with this instruments [22]. These data clearly show that photoemission has reached the submicron domain, and can deliver two new types of information: chemical composition and properties over very small areas, and micropictures in which the image formation process includes both topological and chemical mechanisms [18].

As for other types of electron microscopy, photoemission at high lateral resolution can be implemented in two complementary ways: the scanning mode, of which MAXIMUM is an excellent example, and the mode based on electron optics. One nice example of this last approach is the XSEM (X-ray secondary-electron (emission) microscope), developed in Wisconsin by Brian Tonner and his coworkers [23]. The main spectroscopic performance of this instrument is the delivery of the surface X-ray absorption coefficient for micron-size areas of the specimen. This is measured, using the Kunz-Gudat technique [13], by detecting the yield of secondary photoelectrons as a function of the photon energy.

The XSEM has been extensively used to investigate biological specimens [19,20]. Figure 13 shows a nice example of this approach: the microchemical analysis of neuron cell cultures, which reveals the spatial distribution of the toxic element

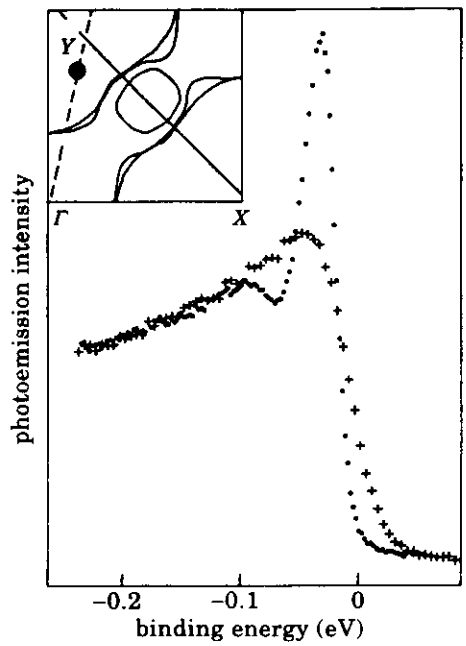


Fig. 11. – A very rapid evolution from the previous figure: in these data from Hwu *et al.* (ref. [16]) the differences between normal and superconducting state of Bi-Ca-Sr-Cu-O are evident, and so is the opening of the gap.

aluminium, to which the culture had been artificially exposed. Results of this kind illustrate how the submicron lateral resolution—made possible by the brightness of synchrotron light—allows photoemission to contribute to life sciences.

This short historical overview has shown the intimate interconnection between the development of synchrotron light and that of a basic instrument of modern science

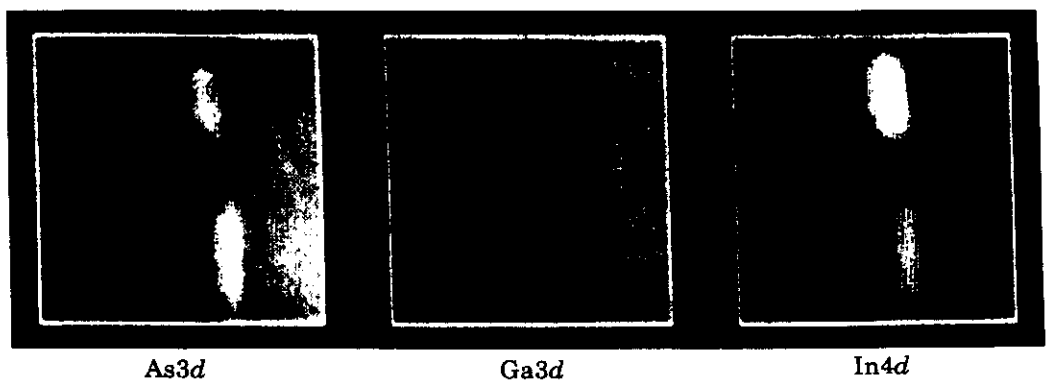


Fig. 12. – Recent results from the scanning photoemission spectromicroscope MAXIMUM (20×20) μm^2 images of patterned InGaAs overlayer (on the left) over a GaAs substrate. By selecting the energy of the detected photoelectron to coincide with one of the core levels of the substrate and/or of the overlayer, one can detect the spatial distribution of the corresponding element. Data from Ng *et al.*, ref. [22].

Fig. 13. – With high lateral resolution, photoemission spectromicroscopy has reached the domain of life sciences. On the left: test image (ref. [20]) obtained at the Taiwan Synchrotron Radiation Research Center (SRRC) on neuron network specimens by De Stasio *et al.* (ref. [19,20]). On the right: analysis of the aluminum content of a similar specimen, artificially exposed to this toxic element; right top: photoelectron image of the analyzed area; right bottom: digital subtraction of images taken at photon energies above and below the Al $2p$ X-ray absorption edge. The dark spot reveals the localization of the toxic element. The Al analysis data were obtained by De Stasio *et al.* (ref. [19]) on Tonner's spectromicroscope (ref. [23]) at the Wisconsin Synchrotron Radiation Center.

such as photoemission. Similar interconnections can be found in other areas, which explain why synchrotron light has become a pivotal ingredient of today's research.

5. – The free-electron laser: basic properties.

Synchrotrons and storage rings are not the only type of accelerator-based photon sources. Specifically, accelerators have made possible the implementation of another, truly superior class of sources, primarily used for the infrared domain: the FELs [4, 24].

The FEL operation can be qualitatively understood in the following way. The undulator operation described in subsect. 2·1 can be also described by saying that, from the point of view of the circulating electrons, the undulator is equivalent to an electromagnetic wave of Lorentz-contracted wavelength λ/γ (note that the Lorentz transformation of the undulator's B-field produces both a transverse B-field and a transverse electric field, as required for a wave). This wave is Thomson-scattered by the circulating electrons, producing a scattered wave with wavelength λ/γ (in the electrons' e-frame). This wave is Doppler-shifted, producing in the laboratory frame the wave described by eq. (9).

The basic mechanism of undulator operation is, therefore, Thomson scattering. Besides this mechanism, the interaction between wave and electron can also occur in a *stimulated* way, in the sense that an existing wave can be amplified by the electrons while they are subject to the action of the undulator. The result is somewhat similar to the mechanism of a laser: however, the active (amplifying) medium is not a solid, a liquid or a gas, but the electron beam interacting with the undulator.

If this system is coupled to an optical cavity, and if the optical gain is sufficient to overcome the losses, one has the lasing action of an FEL. An FEL essentially consists, therefore, of an electron accelerator, which produces the electron beam of the required energy, of an optical cavity, and of an insertion device such as for example an undulator. In the extreme case of very high optical gain, one can also have a super-radiant FEL with no optical cavity [4, 24].

The emitted photon energy along the axis of the FEL is given by eq. (9); for $\theta = 0$,

$$\hbar\omega \approx \frac{\hbar 4\pi c\gamma^2}{\lambda}\left(\frac{1}{1+(1/2)K^2}\right). \tag{10}$$

The small-signal gain G_0 is given by Pellegrini's derivation [25], which leads to

$$G_0 \propto (\hbar\omega)^{-3/2}\,; \tag{11}$$

the implication of eq. (11) is quite clear: the gain decreases for large photon energies. Therefore, the FEL operation is quite simple in the case of infrared emission, but it becomes progressively more difficult for shorter wavelengths. At the present time, no FEL exists beyond the visible and very near ultraviolet.

What is the practical interest of FELs? The answer is, of course, related to the superior properties of its emission, specifically the high intensity, flux and brightness, the continuous tunability and the time structure. Note, in particular,

TABLE I. – *Tentative parameters of the* FERMI FEL *facility in Trieste.*

Accelerator	ELETTRA's LINAC
Overall wavelength range	0.5–100 μm
FEL-1 undulator	minimum magnet gap: 36 mm magnet period: 85 mm $K = 3.8$ spectral range: 10–100 μm
FEL-2 undulator	minimum magnet gap: 20 mm magnet period: 50 mm $K = 2.5$ spectral range: 2–30 μm
FEL-3 undulator	minimum magnet gap: 11 mm magnet period: 30 mm $K = 1.68$ spectral range: 0.5–10 μm

that according to eq. (10) the photon energy can be tuned by modifying the electron energy and therefore γ.

At the present time, the FELs are providing for the infrared performances similar or even better than those of synchrotrons in the ultraviolet and X-ray ranges, and of conventional lasers in the visible. Table I shows, for example, the predicted spectral performances of the recently proposed FEL faclity by scientists from ELETTRA, from the ENEA-Frascati and from the INFN in the framework of the FERMI project [25]. This infrared device is based on ELETTRA's LINAC injector. In the future, one hopes to see FELs operating in the ultraviolet and X-ray domains.

Note, however, that FELs (and other conceivable X-ray lasers) will never replace synchrotron light sources, because they can only serve one or at most a very few users simultaneously. Their development and operation costs are not, therefore, spread over as many parallel utilizations as synchrotron light, and will remain relatively high. The FELs are likely to be reserved for superior applications which specifically require them.

6. – The free-electron laser: examples of applications.

What are, then, the applications of the FELs? Similar to synchrotron applications at shorter wavelengths, any interaction between infrared electromagnetic radiation and atomic or condensed-matter systems can be exploited for a variety of FEL-based experimental techniques. In the infrared spectral domain we find many fundamental «sizes» of nature: vibrational energies, forbidden gaps of semiconductors, gaps of superconductors, binding energies of impurities in solids, etc. Each of them can be explored with the FEL light.

Once again, it is impossible to present here a complete picture of all possible applications, therefore we will only discuss a few examples. One of the first practical applications of FELs in condensed-matter research was the study of interface energy barriers [26]. This is an old and fundamental problem in solid-state science: for decades, theorists have tried to develop models of Schottky barriers, heterojunction band discontinuities and other interface barriers [27]. Each of these problems appeared simple at first, its complication becoming evident only later.

One crucial missing ingredient for further progress in this domain is a good data base of reliable and accurate berrier measurements. FEL may provide the solution: recently, Coluzza *et al.* of the EPF-Lausanne and McKinley, Tolk *et al.* of the Vanderbilt University have collaborated [26] in the development of a highly accurate and reliable method to measure interface energy barriers.

Figure 14 shows a scheme of this approach, code-named FELIPE (FEL-Internal PhotoEmission). Note that the interface barrier (a band discontinuity in this case) can be directly derived from the corresponding threshold in the photocurrent *vs.* FEL photon energy plot. Figure 15 shows an example of application: it is quite evident that the measurements can easily reach an accuracy of a few meV.

Why is the FEL used for these measurements? In principle, conventional sources could be used—and are in fact used—for similar approaches, like the one illustrated in fig. 14*b*). The problem is that the barrier measurements are no longer direct and require the accurate knowledge of other parameters such as—in the case of fig. 14*b*)—the local gap. The FEL provides a tunable and very intense source in the

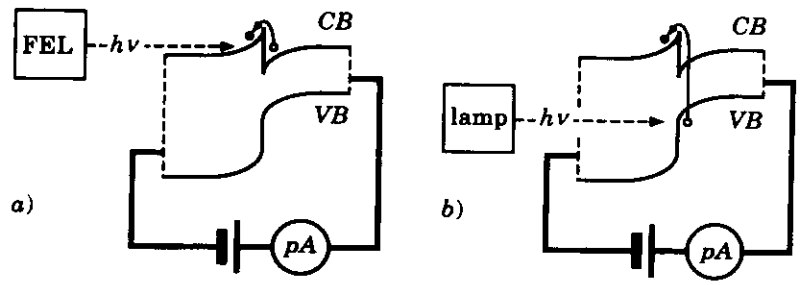


Fig. 14. – *a*) Scheme of the Free-Electron Laser Internal Photoemission (FELIPE) approach [26] to measure interface energy barriers—in this case, a conduction band discontinuity ΔE_c at a semiconductor heterojunction: ΔE_c is directly given by the corresponding photocurrent threshold; *b*) a less direct version of this approach, using a conventional source rather than the FEL.

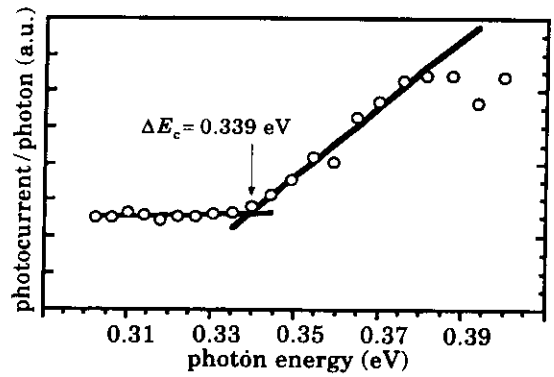


Fig. 15. – Some of the first results of FELIPE: the conduction band discontinuity of the interface between amorphous Ge and GaAs. Data from ref. [26].

spectral domain directly corresponding to many of the interesting interface energy barriers; therefore, FELIPE provides more direct, hence more reliable, results than conventional-source measurements.

The applications of FELs are certainly not limited to materials science. Recently, medical scientists at the Vanderbilt University have found [28] that laser surgery at tunable photon energies results in very limited secondary cell damage. One can already envision extensive applications of FELs to cancer and implant surgery. The FEL beam can be transported to the relevant part of the patient's body with optics fibers, using an acupuncture-like technique. Its photons can not only provide a very powerful and selective surgical tool, but also be used for a simultaneous spectroscopic characterization of the surgery's results.

The FEL applications in materials science are also quite extensive and exciting. Besides FELIPE the Vanderbilt program has revisited the relatively old domain of two-photon absorption spectroscopy. The FEL has immediately eliminated the long-standing problem in this research, such as the detection of the two-photon indirect absorption edge of germanium [29].

7. – Towards a brighter and brighter future.

How will synchrotron light and FEL research evolve in the future? Some guidelines are provided by the recent trends, by technical considerations and by the data of surveys, notably the Megascience Forum report recently published by the OECD [30].

The OECD projects a continuation of the fast increase in the use of synchrotron light at least until the beginning of the next century: for example, the number of users in Europe is expected to double between 1994 and 2000. This means that, contrary to a popular misconception, the critical shortage of synchrotron beamtime has not disappeared and in fact is worsening in spite of the several new sources that have been recently commissioned.

The main causes of this rapid increase are the following. First of all, synchrotron light is expanding from its traditional domains—physics and chemistry—into new areas such as medical applications, life sciences and industrial fabrication, reaching very large numbers of new potential users. Second, the most advanced applications of synchrotron light increasingly require long periods of beamtime: photoemission spectroscopy of the superconducting gap is a typical example of this trend [15-17]. This trend substantially increases the demand for beamtime.

The resulting beamtime shortage is particularly dramatic for the top-level facilities. The characteristics of new sources like ELETTRA are so superior that they tend to attract the users' demand much more than conventional sources. The OECD-projected beamtime shortage, already serious for synchrotron radiation in general, is truly dramatic for superior sources. This situation negatively affects the development of this field.

On the positive side, the rapid improvements in the source performances are opening new and completely unforeseen research opportunities. With the third-generation sources like ELETTRA, it is now possible to simultaneously optimize several aspects of synchrotron experiments—whereas with previous sources one could optimize only one or two of them.

Photoemission again provides a good exemplification: in the past, it has been possible to optimize spatial resolution, *or* energy and angular resolution, *or* spin detection, *or* time-dependence detection. In the future, with sources like ELETTRA and its successors, one hopes to optimize several of these performances at the same time. This possibility could be enhanced by a possible advent of FELs in the ultraviolet and X-ray domains.

One of the most rapidly growing applications of synchrotron light is industrial fabrication. Synchrotron light is the main ingredient of two industrial fabrication techniques: shallow X-ray lithography for production of submicron-resolution integrated circuits, and deep lithographic fabrication of micromechanical devices with techniques such as LIGA (*Lithographie, Galvanoformung und Abformung*). The corresponding photon sources have very different characteristics with respect to the synchrotrons used for spectroscopy of crystallography. Reliability, easy operation, low cost, small size are more important than brightness. In fact, brightness is not used for lithographic applications which require instead high flux over extended areas.

Another domain of industrial use for which one foresees a rapid expansion is industrial crystallography. This technique is a necessary ingredient for modern drug engineering in the pharmaceutical industry. Until now, the use of synchrotron light

has been sporadic and not directly linked to production problems. Many experts in the pharmaceutical industry believe that this situation will radically change in the next ten years. This will pose huge new problems of non-technical nature, such as confidentiality and cost control for extensive exploitation.

The industrial use of synchrotron light could also be boosted by photochemical applications. The unprecedented energy density of the new synchrotrons begins to be exploited to stimulate novel processes in photochemistry [5]. This is a relatively unexplored field; new discoveries could be exploited for better fabrication and processing techniques.

The final question is of course: what lies beyond ELETTRA and the other facilities of its generation? Has the push for higher brightness reached its natural limits? The answer is negative: two new projects, the Swiss Light Source (SLS) [3] and SOLEIL-2 in France envision an increase in brightness by almost one order of magnitude with respect to ELETTRA. And even these machines could be surpassed by the possible development of ultraviolet and X-ray FELs. A brute-force solution of this last problem has in fact already been proposed by the SSRL in Stanford: the conversion of the linear accelerator SLAC into a gamma-ray FEL [4].

We believe, therefore, that the future of this domain will be dominated by three simultaneous trends: first, the push for more sophisticated, higher-brightness sources that will open up new research opportunities. Second, the completion of an extensive world-wide network of synchrotron and FEL facilities, that will make these sources available to all interested users in all possible domains. Third, the development of sources specifically optimized for industrial-fabrication applications.

We must cease to consider these synchrotron light and FEL facilities as exotic tools reserved for a small group of «rich» investigators. With a wise policy of source and beamline development, their cost can be contained and become reasonable for all investigators. With such a policy, the sky is the limit for the future of synchrotron light and FEL activities—and it is a very bright sky indeed!

* * *

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INDUSTRIAL USE OF SYNCHROTRON RADIATION

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1. General Background: Overview of Synchrotron Radiation and Industry

Industrial applications have been a prime factor in the development of synchrotron radiation from the very beginning of its history. For example, IBM and Bell scientists were among the pioneers of the first dedicated source of synchrotron radiation, Tantalus in Wisconsin. In some of the American synchrotron centers, industry-related programs constitute more than 50% of the overall activities. There are even example of centers entirely developed by industry, in the USA (IBM), and in Korea (Pohang Iron and Steel Co.).

Synchrotron radiation, therefore, is not a scientific activity in search of practical applications: such applications have already been for decades an essential stimulating factor of the explosive growth of this field.

The main objective of this short overview is to explain in simple terms what are the causes of the interest of industry for synchrotron radiation, in the hope to stimulate additional industrial uses – in particular by small industries. We will not try to be exhaustive, since this would be impossible within the limits of this paper. On the other hand, we assume no previous knowledge of synchrotron radiation by the reader, so that the presentation meets the requirements for a tutorial introduction.

The overview, therefore, begins with a simple introduction to the basic properties of synchrotron radiation. Second, we discuss the present and potential applications of synchrotron x-rays to fabrication techniques in microelectronics and micromechanics. We then move to a broad spectrum of applications in the characterization of materials, beginning with industrial crystallography and then continuing with spectroscopy, microscopy, and spectromicroscopy.

We conclude our presentation by briefly discussing the potential applications of synchrotron radiation in medicine and other areas, such as photochemistry. The last part of the discussion concerns a different type of source: the free-electron lasers (FELs). We specifically discuss FEL's practial applications in surgery and materials science.

The final section summarizes our conclusions, and tries to foresee the future development in this field, in which we believe that industrial applications will play a leading role.

Before beginning our discussion we would like to emphasize two points. First, we aimed for an elementary and concise presentation, therefore we left out the formalism: the interested reader is referred to more specialized technical presentation for the formal aspects.[1,2] Second, we tried to avoid advertisement, and to base our conclusions on solid facts. We believe, in fact, that the industrial interest in synchrotron radiation is not a hypothesis, but a present

and expanding reality. We also believe that this interest is based on solid and fundamental reasons, as we will discuss later.

Therefore, synchrotron radiation is not an exotic product that requires hard selling, but a basic commodity for industry. It is in the best interest of potential industrial users to become aware of this commodity, and helping them to know is the prime objective of our overview.

2. What is Synchrotron Radiation?

Synchrotron radiation is the electromagnetic radiation emitted by electrons that circulate at a speed close to the speed of light in an electron accelerator, most commonly a storage ring. Such electrons emit radiation of excellent quality over a broad spectral range of wavelengths, extended from the visible to the hard x-rays. In principle, they could provide the required radiation for basic and industrial applications in any part of this broad spectral range.

In practice, synchrotron radiation is used to fill the gaps in the spectrum where either no other sources exist or only inferior-quality sources are available. This is particularly true for the spectral range of the ultraviolet and soft x-rays (although in some cases infrared synchrotron radiation has also been used).[1]

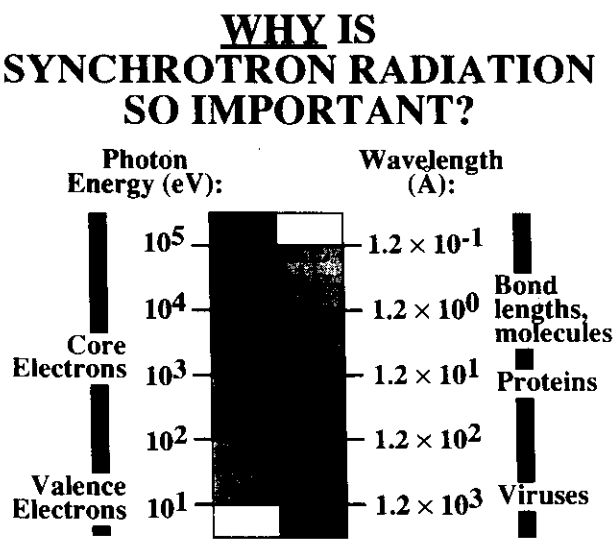


Fig. 1. The wavelengths and photon energies produced by a synchrotron source match some of the most fundamental magnitudes in nature and technology, and in particular, the length and energy of chemical bonds.

Why are ultraviolet and x-ray photons important for basic and industrial applications? The answer is based on four very fundamental facts (see Fig. 1).

(i) The wavelengths of these photons, from 0.1 Å to 1,000 Å, are close in magnitude to the interatomic distances of molecules and solids. They are, therefore, ideal to study chemical bonds, which are the common denominator of most basic and industrial problems in modern technology.

(ii) Such wavelengths are also ideal for lithographic fabrication techniques in a scale from microns to nanometers.[11] These techniques are an essential ingredient of today's industry.

(iii) The same wavelengths correspond to photon energies ranging from a few electronvolts to a few kiloelectronvolts; such energies are close in magnitude to those of electrons engaged in chemical bonds or indirectly affected by their formation. Therefore, these photon energies are also ideal for the study of chemical bonds and in general of the electronic structure of molecules and materials.

(iv) The same photon energies can also break chemical bonds and stimulate a variety of photochemical processes that can be used for industrial applications.

One point should be very clear: synchrotron radiation is not a specialized tool for a specialized class of applications. It is, instead, the general ingredient for any technique, in research and fabrication, that requires ultraviolet radiation or x-rays. Think about visible radiation: we use it in a huge variety of ways, from merely "seeing" things to showing movies or television, to laser machining and laser surgery, for compact-disk readers, for interferometry, and for a very long list of other applications. Likewise, as seen in Fig. 2, every conceivable way in which ultraviolet and x-ray photons interact with condensed matter can be exploited[1] for characterization and fabrication techniques, most of which are used by industry.

2.1. *Historically, a fortunate accident*

Synchrotron radiation was, in a sense the result of a lucky historical accident.[1] The accelerators that

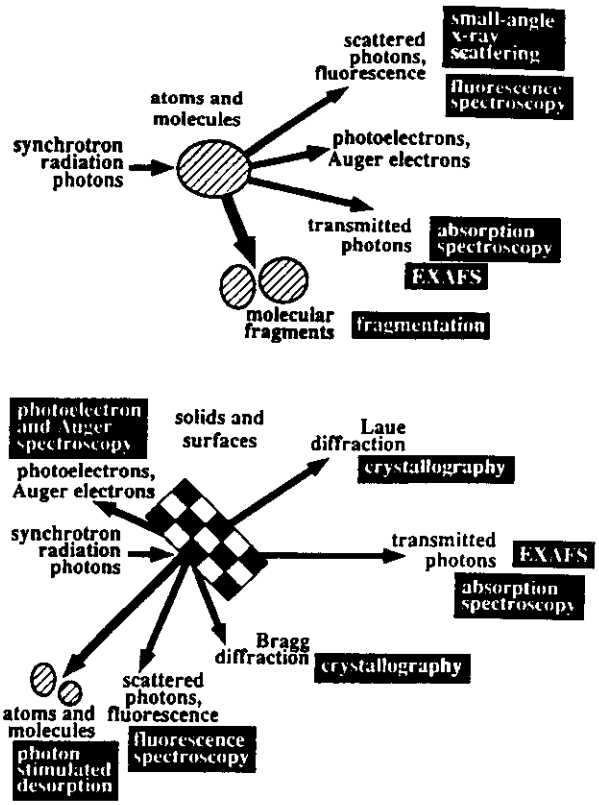


Fig. 2. Each of the many types of interactions between synchrotron radiation and atoms, molecules, or solids can be exploited for a variety of techniques. Hence, synchrotron radiation is not a single experimental technique, but the required ingredient for many different techniques.

first delivered synchrotron radiation had not been developed for its production, but for research in elementary particle physics. There was a long delay between the discovery of synchrotron radiation and its first practical applications.[1] Afterwards, the importance of such applications grew so rapidly that synchrotron radiation eventually became the leading reason for building electron accelerators, with a worldwide financial impact of several billion dollars.

Basically, synchrotron radiation opened up for practical use the entire spectral range of ultraviolet and x-ray radiation. In a sense, even an inferior source in this range would have had an important impact: *any* source is better than no source at all. Quite amazingly, however, a synchrotron is not "any source", but one of the best photon sources in any spectral range: the "historical accident" produced a superior tool for today's technology.

The superiority of synchrotron sources is primarily caused by their characteristics:[1,2] (i) first of all, as we already discussed, their spectral range; (ii) their high power; (iii) their polarization; (iv) their time structure; (v) their concentration in space and their angular collimation, which produces high brightness (or billance); and (vi) their high degree of coherence.

The primary causes of these characteristics are two well-known relativistic effects: the Lorenz contraction of the length from one inertial reference frame to another, and the Doppler shift of the electromagnetic radiation wavelength. Without resorting to complicated formalism,[2] we remind the reader that:

(a) An object whose length is L in its own (rest) reference frame appears contracted to a length L/γ in a reference frame in which the object moves at a speed v in the direction of its length. Here the relativistic factor γ is defined as $\gamma = 1/\sqrt{1-(v-c)^2}$.

(b) If a source emits radiation of wavelength λ in its own (rest) reference frame in the direction of a detector, and the source moves at the speed v (close to c) towards the detector, then the detector sees the wavelength which contracted by the Doppler effect to approximately $\lambda/2\gamma$.

It should be noted that if the source is an electron in an accelerator, the relativistic γ-factor is also equal to $\gamma = E/m_0c^2$, where E is the electron (relativistic) energy and m_0 is the electron (rest) mass. Practically speaking, $m_0c^2 \approx 0.5$ MeV, so γ is approximately the electron energy in units of one-half megaelectronvolt.

Imagine now an electron circulating in a storage ring. In order to keep it from moving away from the orbit in a tangential direction, one uses the deflecting action of a series of dipole magnets, one of which is schematically shown in Fig. 3. The magnetic B-field acts with a Lorentz force of strength $f = evB$ on the electron, where e is the electron charge. This force deflects the electron with a centripetal acceleration.

Elementary physics tells us that any accelerated charge is compelled to emit electromagnetic radiation. Centripetal acceleration is indeed the cause of the emission of synchrotron radiation by the deflected electrons in a storage ring. The centripetal acceleration corresponds to a circular motion with angular speed $\omega = v/r$, where r is the trajectory radius

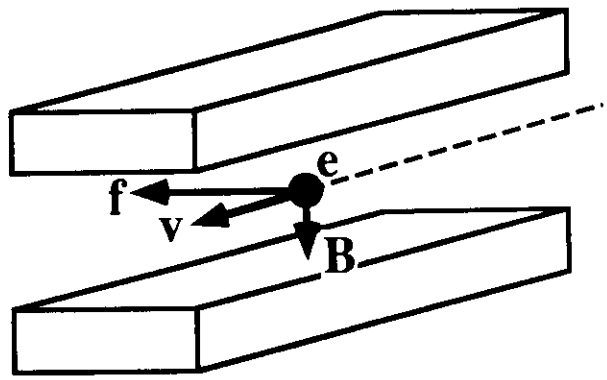
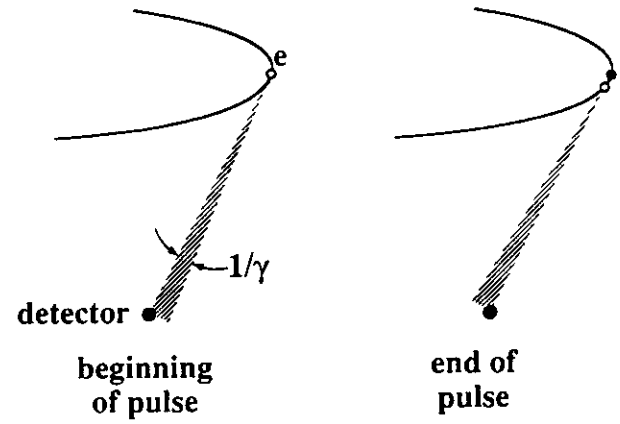


Fig. 3. Scheme of one of the bending magnets of a storage ring, which deviates the electron trajectory with the Lorenz force.



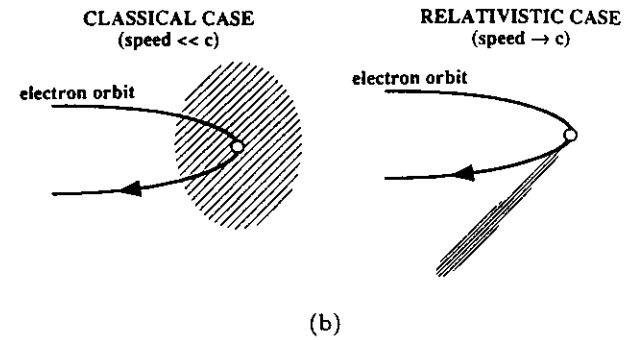


Fig. 4. (a) The "searchlight" effect: because of the angular collimation of each electron emission, the corresponding signal at the detector is a short pulse; this gives a broad spectrum of frequencies and wavelengths. (b) The angular collimation is a relativistic effect.

of curvature. The value of ω also gives the central frequency of the emitted synchrotron radiation, and the corresponding central wavelength $\lambda_c = 2\pi c/\omega$.

If the electron did not move at relativistic speed ($v \to c$), there would be no difference between the emitted wavelength in the electron reference frame and the frequency detected in the laboratory frame. The high speed of the electron, however, requires a specific analysis of the phenomenon including relativity. This analysis[2] shows that, *in the electron reference frame*, $\omega = v/r = \gamma eB/m_0$, thus the central emitted wavelength is $2\pi cm_0/\gamma eB$. Seen from the laboratory frame, this wavelength is Doppler-shifted by approximately 2γ, giving $\lambda_c = \pi cm_0/\gamma^2 eB$. What is the typical magnitude of this wavelength? Consider a typical storage ring with energy $E = 1$ GeV, corresponding to $\gamma = 2{,}000$ in units of 0.5 MeV, and a typical B-field strength of 1 T; since $c \approx 3 \times 10^8$ m/s, $e \approx 1.6 \times 10^{-19}$ C, and $m_0 \approx 9 \times 10^{-31}$ kg, we obtain in this case $\lambda_c \approx 1.3 \times 10^{-9}$ m $= 19$ Å. This is indeed a typical wavelength in the range of soft x-rays.

We have mentioned, however, that the emitted synchrotron radiation is not confined to a narrow band of wavelengths, but covers instead a very broad spectrum. The cause of this broad bandwidth is illustrated in Fig. 4(a): the radiation emitted by each deflected electron is confined to a narrow cone, like an extremely collimated searchlight. This searchlight illuminates the detector for a very short period of time, and produces therefore a short pulse of light. The pulse has a broad spectrum of Fourier components, i.e., of frequencies which corresponds indeed to a broad spectrum of wavelengths.

The extreme collimation of the emitted radiation is a relativistic effect.[2] In a nonrelativistic case, the electron would emit radiation like an oscillating dipole, as shown in Fig. 4(b). In the relativistic case, the emission is confined[2] to an angle of the order of $1/\gamma$. One can show[2] that this narrow "searchlight" illuminates the detector for a time of the order of $\delta t \approx m_0/2\gamma^2 eB$, corresponding to a frequency bandwidth $\approx 1/\delta t$ and to a wavelength bandwidth of the order of $\Delta\lambda \approx \pi cm_0/\gamma^2 eB$. Note that the bandwidth has the same order of magnitude as the central wavelength λ_c. Therefore, in first approximation the synchrotron radiation produced by a dipole bending magnet is centered at $\lambda_c \approx \pi cm_0/\gamma^2 eB$, and has a

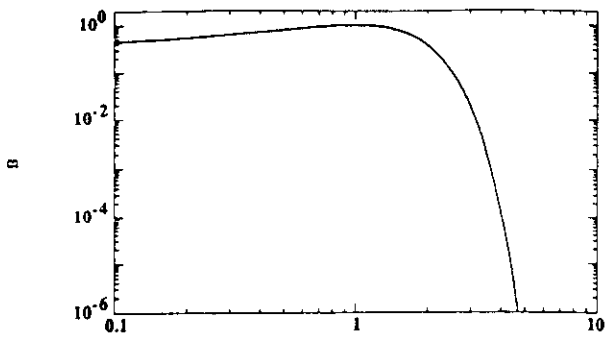


Fig. 5. The spectral distribution of bending-magnet synchrotron radiation is fairly well described by the approximate approach discussed in the text. Here the plot is as a function of the photon energy normalized to the value corresponding to the central emitted wavelength.

bandwidth of the order of $\Delta\lambda \approx \lambda_c$. Figure 5 shows that this is a fair description of the emission spectrum produced by a bending magnet.[2]

2.2. *High power, polarization, and time structure*

The high level of emitted synchrotron radiation power is also a relativistic phenomenon. Elementary (nonrelativistic) physics tells us that the emitted power is proportional to the square of the acceleration. In turn, for a dipole bending magnet the acceleration magnitude is proportional to that of the Lorentz force, therefore to vB and to pB, where p is the magnitude of the electron momentum. In summary, the emitted power is proportional to $(pB)^2$.

This is also true in relativity, only that p is the relativistic momentum, given by the product of the "relativistic mass" γm_0 times the speed $v \approx c$, thus the emitted power is proportional to $(\gamma B)^2$. One can also show[2] that B is proportional to γ/r, therefore the emitted power is proportional to γ^4, i.e., to the fourth power of the electron energy. This means that the power increases rapidly with the energy of the storage ring. On one hand, this makes it possible for synchrotron radiation to be very powerful and intense. On the other hand, in most applications only a small portion of this power is used, since each application only requires a narrow band of frequencies, and the rest of the broad emitted bandwidth is filtered out. The full emitted power, however, is still delivered to the first optical component of each of the beamlines that channel the emitted radiation to specific application chambers. This very high power causes severe stability problems for the optical components.

The general rule, therefore, is to avoid high accelerator energies if they are not strictly required. We have seen that the central emitted wavelength λ_c decreases with the square of $1/\gamma$ and therefore with the reciprocal square of the energy: applications that require short wavelengths also require high electron energies – with the consequent power-load problems for the optical components. One can, however, use smaller electron energies for larger wavelengths in the ultraviolet and soft-x ranges, thereby decreasing the impact of the power load.

These simple arguments explain the present use of two specialized classes of sources: those for medium wavelengths, down to 1–10 Å, with energies up to $\approx$ 2 GeV, and the high-energy, short-wavelength sources of "hard" x-rays at energies up to 6–8 GeV. ELETTRA in Trieste, the Advanced Light Source (ALS) in Berkeley and the sources in Pohang (Korea) and Hsinchu (Taiwan) are typical examples in the first class, whereas the European source in Grenoble is in the second class.

The polarization of synchrotron radiation is easy to understand. Imagine to observe an electron moving in a storage ring from the point of view of a detector placed tangential to the orbit and in the plane of the ring. You would "see" the electron moving in a line, like part of the motion of a linear oscillating dipole, thus you would detect linearly polarized radiation in the plane of the orbit. As the detector moves out of the plane of the orbit, it "sees" the electron moving in an elliptical trajectory, and the emitted radiation no longer has purely linear polarization. This makes it possible to obtain nonlinear polarization by moving out of the plane of the orbit. Remember, however, that the emission is mostly concentrated in a narrow angle of width $\approx 1/\gamma$; therefore, the intensity falls rapidly as one moves out of the electron orbit's plane.

The time structure of the radiation is also easy to understand. We have seen that each electron would produce a very short pulse of light. One should consider, however, that not one but many electrons circulate in the storage ring. These electrons form one or more short bunches, so the actual duration of each collective pulse is given by the transit time of a bunch

in front of the viewpoint of the detector; this is simply the bunch length l divided by $v \approx c$. In practice, therefore, the emitted radiation consists of short pulses of duration $\approx 1/c$, separated by longer intervals. This time structure is exploited in specialized applications.[1]

2.3. *Brightness and coherence: the role of undulators*

We have already seen that the emitted synchrotron radiation is intrinsically collimated. The real angular spread in the vertical direction is actually larger than $1/\gamma$, because each electron moves in a trajectory which slightly deviates from the "ideal" orbit.[1] This produces at the same time an additional angular divergence of the light emission and a finite size of the source. In modern storage ring, both the size and the angular spread of the synchrotron source are extremely small.[3]

The small size and angular spread contribute to the overall quality of the source. For most applications, the best quality factor is in fact the *brightness*, which roughly corresponds[1] to emitted power (or flux) divided by the source size and by the angular spread. The reason for choosing brightness as a quality factor is quite fundamental: optics shows that brightness is conserved along a beamline, if one neglects the losses due for example to absorption or imperfect reflection by the optical components.[1]

In many applications, one tries to concentrate as much radiation flux as possible in a small area. This requires focusing: because of the conservation of brightness, without a bright source one cannot focus on a small area without causing a relatively large angular divergence. This divergence would in turn require large optical components, that are certainly expensive and in many cases not technically feasible. If possible, one prefers to work with high-brightness sources. Note, however, that this is not an absolute criterion for all types of applications. For example, it does not apply to industrial fabrication based on lithography, for which high brightness is at best irrelevant and in many cases even counterproductive, as we will see later.

Brightness is nevertheless commonly used today as the most important factor to define the quality of a synchrotron source. And the progress in increasing the brightness has been nothing short than

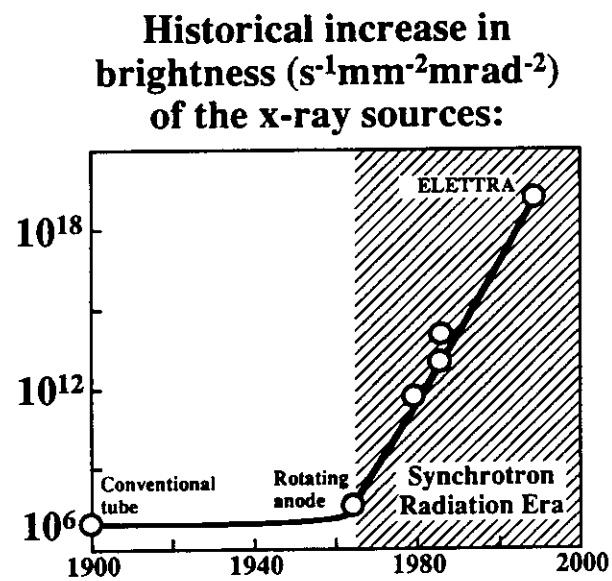


Fig. 6. The spectacular increase in brightness (note the log scale) of x-ray sources, made possible by the advent of synchrotron radiation.

spectacular, as seen in Fig. 6. We are moving at present from the second to the third generation of synchrotron sources, with a brightness increase of 2–3 orders of magnitude.[3] The opportunities that are opened up by this technical improvement are very exciting, both in basic research and in technology.

This increase in brightness is not due to an increase in the emitted radiation power or flux, but

(a) to a substantial improvement in the geometric characteristics of the electron beam in storage rings, and
(b) to the extensive use of new and advanced sources of synchrotron radiation known as *undulators*.

The basic philosophy of an undulator is illustrated in Fig. 7, and can be understood[1,2] in very simple terms. Instead of using a single bending magnet, one forces each electron, which would otherwise move in a straight line, to undulate because of the action of a periodic array of magnets. In first approximation, one could be tempted to conclude that this increases the output with respect to a single bending magnet proportionally to the number of periods, N.

This conclusion is, however, a bit naïve, and misses two important points.[1,2] First of all, we have seen that the power produced by a dipole bending

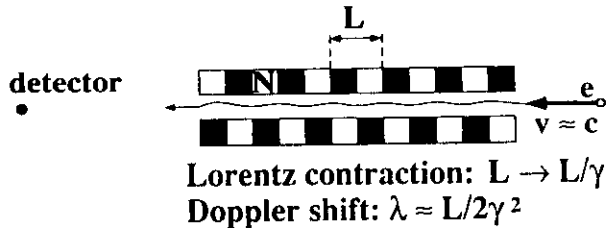


Fig. 7. The idea of an undulator: the electron enters the periodic field of the magnets array, and is forced to "undulate" around its straight trajectory. This causes emission of radiation that, because of the Lorentz contraction and of the Doppler shift, is of much shorter wavelength than the undulator period. Furthermore, it is a narrow-band emission as discussed in the text.

magnet is spread in a broad wavelength bandwidth because of the "searchlight" effect and of the consequent short duration of each electron emission pulse. Suppose now that the undulation caused by the periodic array of magnet in Fig. 7 is so gentle that the detector is continuously illuminated: the "searchlight" effect is no longer present, and the power is concentrated in a much narrower bandwidth, thus increasing the brightness.[2]

This condition of "gentle" undulation is met in the case of the undulators, which are devices with relatively weak magnetic field and therefore small undulations. This is no longer true in the case of the high-field devices known as "wigglers": a wiggler *de facto* works as a series of bending magnets.[1,2] The bandwidth of the undulator emission can be estimated by realizing that the array of magnets works like a diffraction grating: the relative bandwidth $\Delta\lambda/\lambda$ is given by $1/N$.

There exists a second effect that increases the brightness in the case of an undulator: an additional angular collimation that is caused by the array of magnets. This effect further decreases the angular divergence by approximately a factor of $\sqrt{N}$ with respect to $1/\gamma$.[2] The brightness is inversely proportional to the solid angle in which the emission occurs,[1] therefore to $(\sqrt{N})^2 = N$. Thus, the overall brightness in an undulator is proportional to N because of the concentrated bandwidth, and then again to N because of the additional collimation; this produces a quadratic $\approx N^2$ increase, as opposed to the linear-N law valid for a wiggler.

What is the wavelength emitted by an undulator? The answer can be derived with a simple relativistic approach.[2] The electron traveling in the undulator "sees" the magnet array as an electromagnetic wave, with wavelength equal to the undulator period L, corrected for the Lorentz contraction: L/γ. The electron is scattered by this wave and emits radiation of the same wavelength L/γ; this, however, is the wavelength in the electron frame. In the laboratory frame, along the undulator axis the wavelength appears Doppler-shifted by a factor $\approx 1/\gamma$, and becomes $\lambda \approx L/2\gamma^2$.

We thus find, once again, a combined relativistic factor of the order of γ^2, that "squeezes" the wavelength making it possible to emit x-rays. Note however, that the derivation leading to $L/2\gamma^2$ is only valid along the axis of the undulator; in other directions (which must still be close to the axis because of the small angular divergence) the Doppler shift is slightly different and gives a dependence of the emitted wavelength on the direction.[2]

Furthermore, one should take into account that the "wiggles" of the electron trajectory caused by the undulator magnetic B-field effectively decrease the average velocity along the axis, and therefore again slightly modify the Doppler effect. This introduces an important correction: the wavelength increases with the B-field strength.[2] It is thus possible to tune the wavelength by modifying the field, for example by changing the undulator gap.

We finally note that a source with small size and small angular divergence is not only bright but also at least partially coherent[5] (this is well known to readers familiar with lasers). One can distinguish between two types of coherence. The *longitudinal* or time coherence is related to the spectral purity of the source, i.e., to the relative bandwidth $\Delta\lambda/\lambda$, which for an undulator equals $1/N$.

On the other hand, the *transverse* or space coherence is related to the product of source size and angular divergence. For each transverse direction, one reaches a condition of *full coherence*, limited by diffraction, when this product equals the radiation wavelength.[5] Third-generation synchrotron sources like ELETTRA or the ALS do not yet reach this full-coherence limit, which is instead the objective of the planned fourth-generation facility SLS (Swiss Light Source).[4]

3. Industrial Fabrication: X-ray Lithography and Micromechanics

Historically, the initial use of synchrotron radiation by industry was for materials characterization, with the techniques which will be discussed later in Secs. 4 and 5. At the present time, however, much interest is devoted to fabrication rather than to characterization. Synchrotron radiation is a candidate for the production of the next generation of memories in the electronic industry.[6] Furthermore, the new technique[7] known as LIGA (the German acronym for Lithography, Electroforming, and Plastic Molding) is stimulating developments that could very well lead to a new industrial revolution.

The principles of radiation-based microlithography for memories and other integrated circuits are schematically shown in Fig. 8(a). This is basically a photographic technique, in which structures are produced by exposing a photoresist to radiation that changes its chemical properties. The exposure is made with a mask, with the desired pattern. In an actual fabrication sequence, one finds a combination of several exposure, etching, deposition, and annealing steps.

One of the important factors which limit the lateral resolution of microlithography is diffraction. The most direct remedy for diffraction is, of course, the use of short wavelengths: ultraviolet radiation has indeed replaced visible light for the majority of microlithography fabrication procedures.

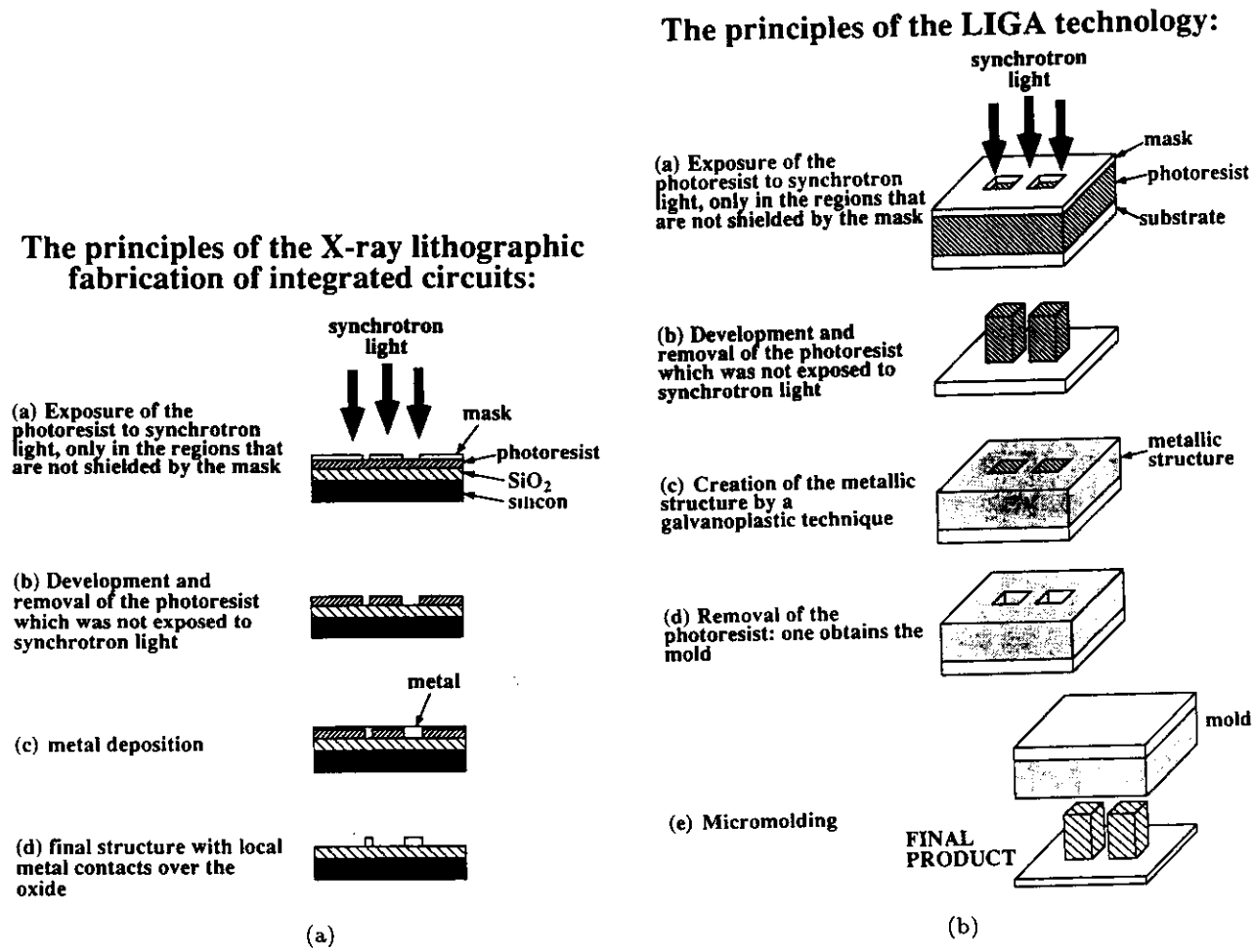


Fig. 8. The principles of x-ray lithography with synchrotron radiation, illustrated by two simplified examples: (a) a fabrication sequence for a metal–oxide–semiconductor structure, of the type used in integrated circuits; (b) microfabrication sequence with the LIGA technique.

Why, then, not use x-rays, which have even shorter wavelengths than ultraviolet radiation? There is, in fact, a general consensus that x-ray lithography will be needed sooner or later to replace ultraviolet lithography. Ultraviolet lithography has been able to stretch its domain of applications much beyond the micron-level resolution, and this improvement has pushed further in the future the advent of x-rays. But x-rays will eventually arrive, because ultraviolet-based fabrication is becoming somewhat stretched to the limit.

The x-rays required for microlithography must be produced with a synchrotron source.[6] The reason is that one cannot simply use very short wavelengths, which correspond to high photon energies. In fact, high-energy photons can produce a cascade of electrons in the photoresists, and this causes blurring. The interplay of this effect with diffraction and with some other factors[6] determines the optimum range of wavelengths and photon energies, which for integrated circuit fabrication falls between 1–2 keV.

Photons of this spectral range are not easily produced with conventional sources, and synchrotron sources are much superior. Thus, x-synchrotron lithography has become a synonym of x-ray lithography. Synchrotron radiation is also absolutely required for the second variety x-ray lithography: microfabrication and more specifically LIGA.[7] The basic idea of LIGA is illustrated in Fig. 8(b). The final product of this technique is not an integrated circuit, but a small mechanical part, such as an orifice, a gear, or something more complicated.

The basic difference between x-ray lithography for electronics and x-ray microfabrication by LIGA is that the latter is a three-dimensional technique, which requires not only a high lateral resolution, but also high accuracy in defining the structure in the perpendicular direction. In other words, the products require a high *aspect ratio*. This, in turn, requires a photon source with specific characteristics. First, a very good collimation. Second, a high penetration depth in the photoresist: this brings the optimum wavelength to slightly shorter values than those suitable for the fabrication of integrated circuits. Both characteristics require the use of synchrotron radiation.

LIGA has been invented and developed several years ago,[7] and some private companies are already active in the field, such as the Microparts and IMM companies in Germany, and Micromore in Italy (connected to the ELETTRA source in Trieste). These companies often show for advertisement of the LIGA process rather sophisticated products such as electric motors of the size of a few microns. The most likely candidates for widespread marketing, however, are much simpler: orifices or micromeshes for chemical filtering and for the car industry, micromechanical parts for the weapon industry, etc.

In the long range, this new technology is likely to stimulate an industrial and technological revolution comparable to that of integrated circuits. Today, we are living in a technological paradox: microelectronics has reduced the size and the cost of electronic components to almost unthinkable levels, but at the same time the mechanical parts that are controlled by electronics are still quite large and expensive.

The objective of LIGA is to reduce the size of mechanical actuators, which could conceivably reach the same level of integration as the microelectronics devices. One can thus envision an overall mechanical–electronic integration, with devices including sensors that feed information to a microprocessor, and microactuators to act under the control of the microprocessor.

The applications of these superintegrated microsystems are virtually limitless: smart pharmaceutical pills, local controls in engines and energy converters, local microdetectors of pollution, are but a few examples of such devices. Only the future can tell us the extent of this potential revolution.

4. Industrial Crystallography

X-ray crystallography has been for decades the main tool for the determination of the structure of solids and molecules.[1,8] Conventional sources of x-rays have been used for most of its history, but synchrotron radiation is increasingly becoming the preferred tool for many different reasons. The simplest is that synchrotron sources are very intense, bright, and collimated, so that crystallographers can find structures of much smaller single crystals than with conventional sources.

Synchrotron radiation is also used for more specialized x-ray crystallography approaches. For example, it is a key tool in the crystallography of surfaces.[1] It is also essential for magnetic scattering,[1]

a technique which would otherwise be reserved to neutrons.

One of the most exciting ways to use synchrotron sources in crystallography is the solution of the phase problem.[1] Roughly speaking, the phase problems arise from the fact that in a diffractogram one obtains intensities and not phases, and the solution of a structure requires more specific information in order to identify the atomic positions in the unit cell. Rather sophisticated solutions have been developed for the phase problem, for example, those based on the substitutions of atoms in the crystals.[1]

The wavelength tunability of synchrotron radiation can offer alternate and very elegant solution to this problem, based on anomalous scattering, i.e., on the rapid change of the x-ray scattering parameters with the photon energy.[1] This technique reduces the need for replacing specific atoms in the structure that must be determined.

Novel crystallographic approaches made possible by synchrotron radiation are used by scientists working for industry. We believe, however, that the key factor in the use of synchrotron radiation for industrial crystallography is the high brightness and the aforementioned, consequent possibility to solve structures using very small crystals.

This is a very important element for the use of crystallography in the pharmaceutical industry.[8] Structural information about viruses and about possible candidates for drugs is increasingly becoming an important element in the development of new pharmaceutical products – the so-called designer's drugs. One should not, however, create the illusion that synchrotron crystallography is the magic tool to solve pharmaceutical problems. The process of drug design, production, and marketing is an extremely complex and lengthy one. For every drug that reaches the market, some 10^4 structures may have to be solved. Therefore, the use of synchrotrons to solve one specific structure cannot be presented as "the" solution of a given pharmaceutical problem. Nevertheless, the role of synchrotron sources is truly fundamental in this process. Eliminating delays is a crucial factor to maintain profitability when facing tough competititon. The transition from solving structures to marketing a drug is a long one, and includes the identification of drug candidates for which profitable mass production is feasible, laboratory tests, tests on animals, and finally test on humans. Every measure that shortens this transition is crucial to profitability.

Synchrotron radiation, as we have seen, can decrease the required size of crystals for solving structures. This can lead, in most cases, to a time saving of several months, which could be crucial for profit. In this sense, and on a realistic basis, synchrotron radiation is likely to become an essential tool of the pharmaceutical industry.[8]

5. Materials Characterization

We will now comment on the oldest and most established area of industrial use of synchrotron radiation: the advanced characterization of materials. Industrial researchers have been active as pioneers in this area from the very beginning of synchrotron-radiation activities. We note, for example,[1] the outstanding contributions of Dean Eastman of IBM and his co-workers, and of Neville Smith, Mort Traum, Jack Rowe, Brian Kincaid, and Peter Eisenberger of Bell Labs and EXXON.

As we have seen in Fig. 2, every interaction of synchrotron photons with materials can be exploited for characterization. A complete review of the corresponding techniques is well beyond the scope of this article,[1] therefore we will focus our attention on some of the latest developments in the subfield of spectroscopy.

There are in fact different types of synchrotron-based spectroscopies,[1] such as EXAFS (Extended X-ray Absorption Fine Structure) (which is used as a structural technique), NEXAFS (Near-Edge X-ray Absorption Fine Structure), x-ray absorption in general, ultraviolet reflectivity, stimulated desorption and photoemission. EXAFS and NEXAFS[1] have for primary objective to investigate the atomic structure in the neighborhood of the atom in which the photon absorption takes place. Stimulated desorption[1] investigates the emission of particles upon photon bombardment of a solid surface, trying to elucidate the static and dynamic properties of the particle bond to the surface.

All other spectroscopies[1] have for primary objective the determination of the electronic structure of the system. Specifically, they try to determine the status of the valence electrons that are directly participating to the formation of chemical bonds. On

the other hand, the valence charge distribution affects the energies of core electrons, even if these do not directly participate to the formation of bonds. Therefore, core-level energies carry indirect information on the formation of chemical bonds. These are the principles upon which well-established spectroscopies[1] like ESCA (electron spectroscopy for chemical analysis) are based. The synchrotron versions of such spectroscopies have contributed to materials research for three decades.

The present trends towards higher source brightness are stimulating an important evolution in this domain: the implementation of synchrotron materials-science spectroscopies in the microscopic domain, with lateral resolutions at the micron and submicron levels.[9] This means that very advanced chemical and physical characterization of materials is now possible at the same level.

Figures 9–12 provide some examples of the sophistication level reached by today's synchrotron spectroscopies.[9–13] Figure 9 shows[11] one example of photoemission spectroscopy performed at the micron

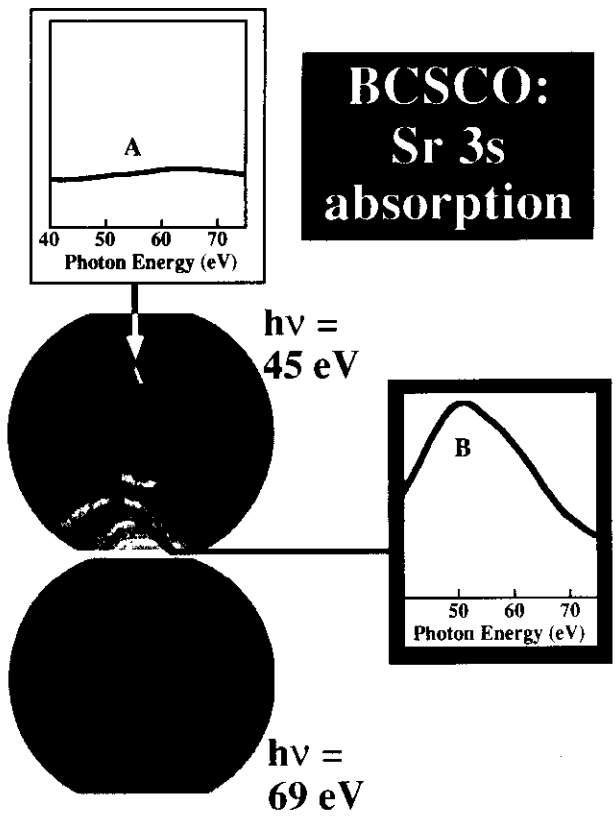


Fig. 9. A photoelectron spectromicroscopy quality test of single crystals of the high-temperature superconductor BCSCO-2212. In point B, the photoelectron yield as a function of the photon energy $h\nu$ reveals absorption in the region of the Sr-3s x-ray edge, whereas no Sr absorption is seen in point A. This explains the difference in signal intensity between the images taken at $h\nu = 45$ and 69 eV: the clear area of point B in the upper image corresponds to a strontium microprecipitate. Data from Ref. 11.

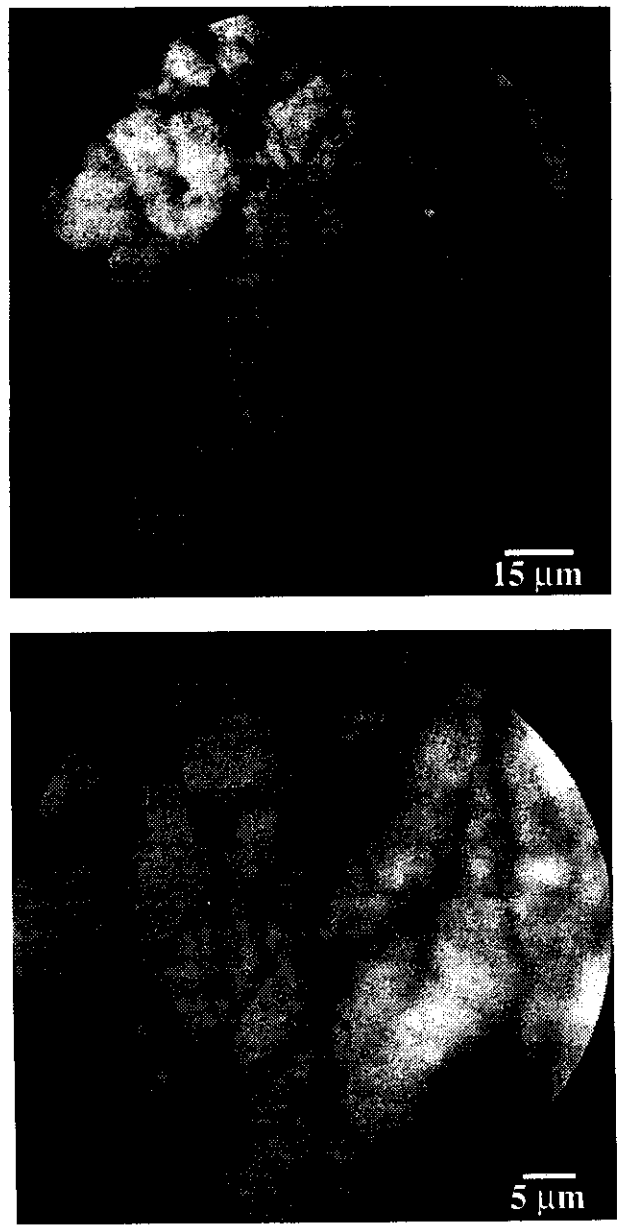


Fig. 10. Photoelectron micrographs of a neuron culture on a metallic substrate (data from Ref. 11).

level. The technique consisted of taking images by detecting the emitted photoelectron intensity, while bombarding the specimen with two different photon energies. The photon energies correspond to high or low absorption of photons by a given element–strontium in this particular example. The comparison of the two images makes it possible to discriminate between features of topological origin and those that correspond to chemical differences related to the element. In the particular example of Fig. 9, this spectromicroscopic photoemission technique was used for quality assessment of the production of advanced single crystals of high-temperature superconductors in the BCSCO-2212 family. The tests demonstrated that almost all specimens in the batch were indeed of high quality, but they also identified sporadic problems due to Sr microprecipitates, like the ones seen in Fig. 9.

Figure 10 shows how this approach can be extended to the life science.[10] When synchrotron spectroscopy can be performed with a lateral resolution

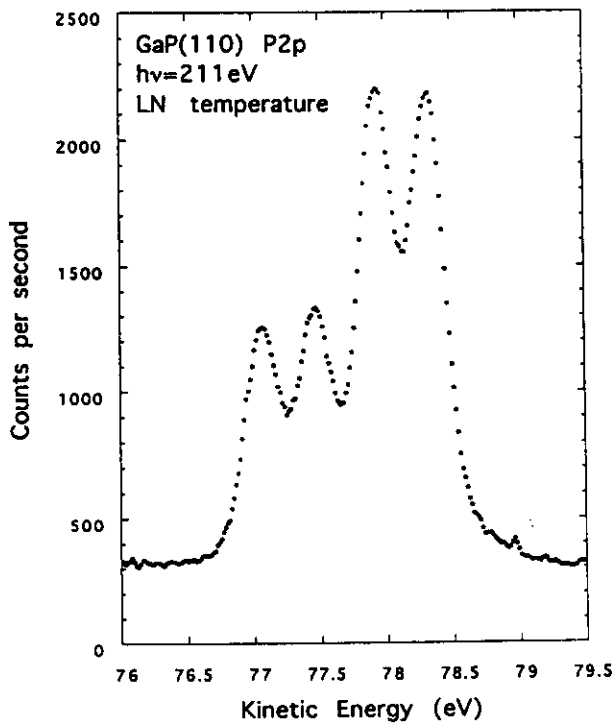


Fig. 11. Extremely high-resolution core-level photoemission data recently taken on ELETTRA-Trieste by C. Ottaviani *et al.*[12] Note the excellent resolution of the spin–orbit components and the clear separation of the bulk components from the surface components.

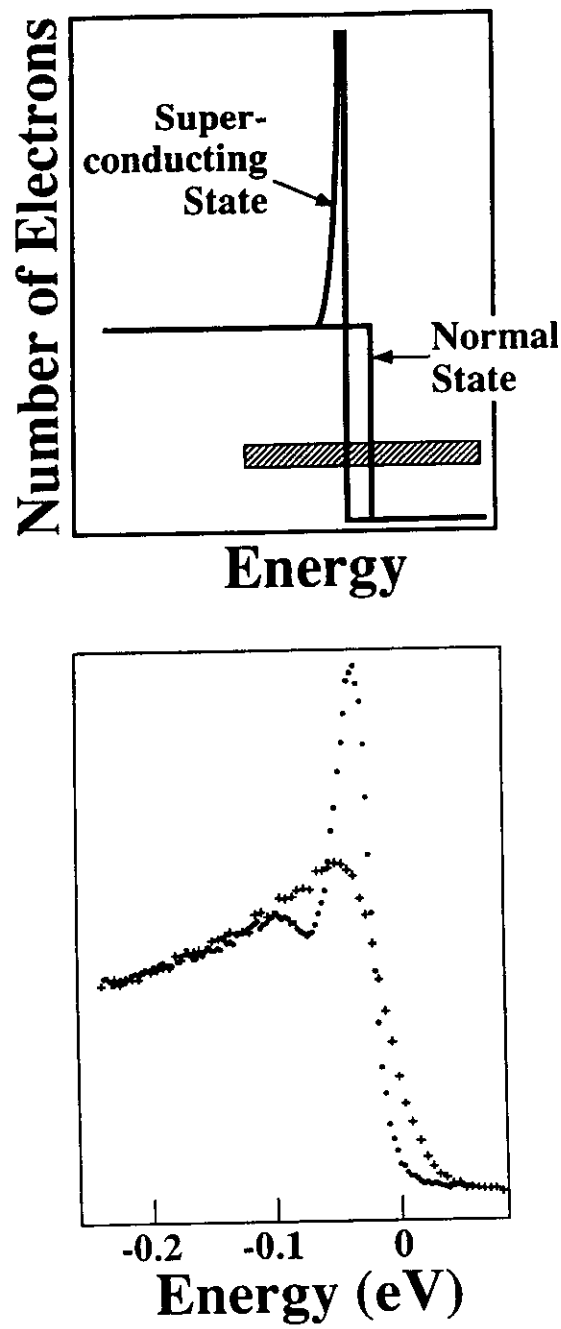


Fig. 12. High-resolution photoemission data reveal the opening of the superconductivity gap in BCSCO-2212. The upper part shows the theoretical comparison between the electron distribution in energy for the normal (metallic) state and for the superconducting state. The shift of the leading edge corresponds to the opening of the gap. Until recently, the typical resolution of photoemission spectroscopy (shaded area) was not sufficient to observe the phenomenon. The bottom part shows experimental data revealing the gap opening and demonstrating the rapid progress in resolution. Data from Ref. 13.

better than one micron, it becomes useful for chemical analysis of biological specimens, whose microstructure size is of the order of magnitude of individual cells or parts of cells. This particular figure shows photoelectron micrographs of interconnected neuron cells in a culture grown on a metal substrate. Experiments of this type have been used[10] to identify the distribution of toxic metals in neuron systems.

Figure 11 shows the excellent level of energy resolution that can now be reached[12] in the photoelectron spectroscopy analysis of materials, thanks to the high brightness of the new photon sources. We see an example[12] of a core-level peak spectrum for the surface of a semiconductor. Not only the spin–orbit components are well resolved, but one can also clearly distinguish between surface and bulk spin–orbit doublets.[1] Those who, like this author, remember the first elusive evidence for surface core-level peaks, will surely appreciate the extremely high quality of results like those of Perfetti *et al.* in Fig. 11.

Figure 12 shows equally spectacular results[13] concerning the opening of the superconductivity gap for the high-temperature superconductor BCSCO-2212. The gap opening is clearly visible while comparing spectra taken above and below the transition temperature. Experimental results of this kind have been extensively used to investigate, e.g., the symmetry properties of the superconducting gap, and to rule out for example the hypothesis of symmetric s-wave superconductivity.[13]

The few examples shown here carry a common message: today's materials characterization with synchrotron radiation has reached performance levels that were simply unthinkable a few years ago. This traditional domain of applications of synchrotron radiation to industry continues, therefore, to be in full bloom.

6. Medical Applications

X-rays have been a leading diagnostic tool in medicine since their discovery by Röngten. Not surprisingly, the possibility to use synchrotron x-rays has stimulated much attention, although the corresponding techniques still are at a developmental stage rather than at the stage of practical use.[1]

One domain in which synchrotrons could play an important diagnostic role is that of coronary angiography.[1] This is normally a highly invasive technique, with unacceptable high rates for mortality and morbidity. As a consequence, x-ray diagnosis of coronary diseases is not used for large-scale screening, even if such diseases are the most important killer in today's industrialized world.

The invasive character of the technique is linked[1] to the need to inject a high dose of iodine to enhance contrast, and to do that in a very short time because of the frequency of the heartbeat. This requires the use of a catheterism, to inject an iodine compound rapidly in the very region of the heart. On the other hand, synchrotron radiation makes it possible to take images at two different photon energies, one below and one above the K-absorption edge of iodine.[1] The pixel-by-pixel subtraction of the two image intensity creates a third image with high sensitivity to iodine. It becomes thus possible to decrease the dose of iodine, and to replace the invasive catheterism with a noninvasive peripheral injection.

This technique has already been tested,[1] first in the USA and then in other countries. The radiographs are not yet at the level of conventional angiography, but much progress has been made in recent years. The final impact of synchrotron angiography will depend on the competition with other possible approaches such as those based on NMR. On the other hand, much interest is now devoted[14] to the use of synchrotron radiation for mammography; once again, the wavelength tunability enhances the performances of the technique. The objective of this technique is the early detection of cancer symptoms, which in turn requires the detection of small microprecipitates. A leading program in this field, SYRMEP, is under development at the Trieste ELETTRA facility by the Trieste University and by the INFN.[14]

7. Other Applications: Photochemistry, Innovative Technologies, etc.

The domains discussed in the previous sections do not exhaust the possibilities of use of synchrotron radiation in industry. For example, the ultrahigh brightness of the new sources makes it possible to concentrate an unprecedented intensity of ultraviolet and x-ray radiation into a small area. This radiation can stimulate chemical reactions: for example, that is how photoresists work.

Several classes of synchrotron-radiation-stimulated reactions have been discovered, but the field is largely unexplored. In particular, we do not know much about chemical stimulation at very high intensities. It is quite likely that some of the newly discovered reactions will be used by industry. We note, for example, that synchrotron radiation has been used to stimulate chemical reactions on semiconductor surfaces.[15] Such reactions could conceivably lead to new "cold" procedures for passivation.

Should synchrotron-radiation-stimulated reactions become part of industrial fabrication processes, one could then envision entirely new approaches, in which the synchrotron sources are used both for the fabrication of products and for testing them. This possibility is not as remote as it could appear, since for example synchrotron x-ray lithography and LIGA are already in use, and synchrotron-based microcharacterization is also an independent reality. The integrated approach would only require combining together its two already existing components.

8. Free-Electron Lasers in Medicine and Industry

Electron accelerators are used for the production of synchrotron radiation not only as synchrotron sources, but also in the more recent devices known as free-electron laser (FEL).[9,16] The conceptual background of an FEL is primarily provided[1,17] by the theory of undulators and wigglers. We have seen in Sec. 2.3 that an insertion device of this kind results in the emission of synchrotron radiation of wavelength $\lambda \approx L/2\gamma^2$.

This is the equivalent of spontaneous emission in a conventional medium. One could also have, however, stimulated emission at the same wavelength, caused by the interaction between the radiation and the "medium" consisting of the electron beam interacting with the insertion device. With an optical cavity and sufficient optical gain, this can produce a lasing action.[1,17]

The corresponding device, the FEL, consists then of an electron accelerator, of an insertion device, and of an optical cavity. The gain decreases with the wavelength,[17] so that lasing is much easier in the infrared (the main spectral domain of FELs) than in the ultraviolet or in the x-ray region. Furthermore, optical cavities do not exist for x-rays, so that one should work in a super-radiant regime.

FELs have been providing for several years broadly tunable infrared radiation, in a range spanning from the visible to $\approx$ 100 micron. This region includes natural sizes of crucial interest for technology, such as the semiconductor gaps, impurity binding energies in semiconductors, high-temperature superconducting gaps and vibrational energies. In principle, therefore, FELs could be advantageously used in science and in technology.

The practical applications of FELs, however, are still quite scarce.[9,16] This is due in part to the "serial" character of these devices: they can accommodate only one or a very few experiments in parallel, whereas a synchrotron can support hundreds of simultaneous experiments.

In the past three years, FELs have started to become practical devices for applications.[9,16] We note, for example, their use to measure semiconductor energy barriers with very high accuracy – a technique that is used for gap engineering tests of direct interest to industry. Furthermore, the wavelength tunability has been used by Vanderbilt researchers[18] to identify highly effective spectral regions for laser surgery. This approach has made it possible to selectively destroy tissue with very limited collateral damage. Furthermore, the FEL is used to precisely cut pieces for bone transplants.

The FEL uses are still too limited to make a final assessment of their industrial impact. We note, however, that FELs can concentrate an extremely high and tunable radiation intensity in the infrared. This may again lead to new photon-stimulated phenomena, and to chemical processes of interest to industry.

9. Conclusions: A Look at the Future

The basic messages of short review are the following:

(a) Electromagnetic radiation has been for centuries a leading ingredient of industrial fabrication, quality control and research. X-rays and ultraviolet are among the most important parts of the spectrum for such applicatons. Synchrotron sources reach unprecedented quality in producing radiation in these parts.

(b) Not surprising, there is a huge variety of uses of synchrotron radiation by industry. Industry

has been for a long time a major player in synchrotron radiation, not a promise for the future.

(c) Synchrotron sources have reached not only an extremely high level of performance, but also a very high level of reliability as required for industrial applications.

We have reviewed several different ways in which synchrotron radiation is used by industry. What is in the future? Future is always difficult to predict in areas that are linked to the economy, but we feel that it is safe to make the following projections.

(i) Materials characterization, the traditional area of synchrotron radiation use by industry, will remain strong and in fact expand further.

(ii) In particular, industrial crystallography for the pharmaceutical industry is likely to become the tool of preference in the chain of development of new designer's drugs.

(iii) Industrial fabrication based on synchrotron x-ray is likely to reach its window of utilization in the next three years. Furthermore, we will witness a rapid growth of the use of LIGA and micromechanics in general. The corresponding products will create an expanding market in the next five years.

Beyond this, we can reasonably hope that the applications in medicine and in photochemistry will finally arrive in the market, and that FELs will find widespread industrial applications.

In a more futuristic approach, we note that the technical developments in synchrotron radiation have not yet been exhausted. The next push[4] will further increase brightness, and most likely bring us to full coherence. The applications of the new sources, including industrial applications, are still mostly undiscovered. Extrapolating from the past experience, we believe that we will be surprised by their impact, including the industrial impact.

When synchrotron radiation was initiated, we were dealing with budgets at the hundred thousand dollars level, but we already had with us our industrial colleagues fighting for its development. We are now dealing with budgets of hundreds of millions of dollars, with multinational facilities and with extremely sophisticated instruments. The industrial presence has grown together with the rest of the field, in a partnership that is likely to expand in the future into new areas and new opportunities.

Acknowledgments

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