Introduction[a]

In 1947, for the first time in history, Floyd Haber, a young staff member in the laboratory of Professor Pollock, observed radiation emitted by electrons as they moved circularly in the magnetic field of the chamber of an accelerator. This occurred during the adjustment of a cyclic accelerator — a synchrotron which accelerated electrons up to 70 MeV [2] (see also Ref.[2]). The radiation was observed as a bright luminous patch on the background of the chamber of the synchrotron. It was clearly visible in the daylight. In this way, 'electronic light' was experimentally seen for the first time as radiation emitted by relativistic electrons having a large centripetal acceleration. The radiation was called synchrotron radiation (SR)[b]since it was observed for the first time in a synchrotron.

It is hard to overestimate the importance of SR in our days, and the interest is growing incessantly since the radiation features a rare combination of fundamental properties and offers important scientific and technical applications.

It was sheer accident that the SR was observed: the opaque metallized cover of the chamber was removed to perform an adjustment and this allowed the light to be seen outside the chamber.

The discovery and first observations of synchrotron radiation were unexpected; its properties seemed mysterious and unusual at the initial stage of investigations. However, a number of theoretical studies on the emission of a relativistic accelerating electron had been carried out long before the experiment described above.

The first steps in this direction were taken by A. Liénard (1898) and O. Heaviside (1902)[4]. They extended the familiar Larmor formula for the plane power of a nonrelativistic electron,

$$W = -\frac{\partial E}{\partial t} = \frac{2e^2\dot{\boldsymbol{v}}^2}{3c^3}, \tag{0.1}$$

to a high-velocity particle. In modern notation it takes the form

$$W = \frac{2}{3}\,\frac{e^2}{m^2c^3}\left(\frac{dp_\mu}{d\tau}\,\frac{dp_\mu}{d\tau}\right) = \frac{2}{3}\,\frac{e^2\gamma^6}{c}\left[\dot{\boldsymbol{\beta}}^2 - [\boldsymbol{\beta}\dot{\boldsymbol{\beta}}]^2\right]$$

[a]From the article of I.M. Ternov, *Synchrotron Radiation* published in *Physics - Uspekhi* **38** (1995) 409.

[b]There is another name in the literature — the magnetic bremsstrahlung. This term is common in astrophysical problems (see Ref.[3])

(p_μ is the four-dimensional impulse, $d\tau = dt/\gamma$ is the intrinsic time, $\gamma = E/mc^2$, and $\boldsymbol{\beta} = \boldsymbol{v}/c$). Liénard turned his attention to the fast growth of losses in the energy of an electron describing a circle ($\boldsymbol{\beta} \perp \dot{\boldsymbol{\beta}}$) of radius R

$$W = \frac{2}{3}\,\frac{e^2c}{R^2}\,\beta^4\gamma^4. \tag{0.2}$$

The growth was proportional to the fourth power of the energy.

Subsequently G.A. Schott (1907) made an interesting detailed study of the radiation an electron emits as it follows a circular path[5]. Schott's objective was to explain the discrete nature of atomic spectra. Based on early models of the atom and especially on the Saturnian model in which electrons in an atom move about the positive charge in circles similar to the rings of Saturn, G.A. Schott made an attempt to calculate the spectrum and the distribution of spatial radiation of electrons in an atom by the strict methods of classical electrodynamics. He reckoned the spectral theory to be the most important issue of the theory of matter since he believed it to be the way to the working model of the atom.

The consistency and elegance of the Schott theory are admirable. However, his attempts to explain the atomic radiation within the scope of classical physics failed and for this reason Schott's work had been only of academic interest for 40 years and was actually forgotten. Their relevance was discovered in new circumstances 40 years later when the issue of an emitting charge moving in a macroscopic trajectory arose.

Of primary interest was the emission of accelerating electrons in a magnetic field. In 1939 I.Ya. Pomeranchuk established the radiative 'ceiling' for the energy of electrons in his attempt to determine the maximal energy the cosmic charged particles could possess at the Earth's surface due to radiative losses in the Earth's magnetic field[6]. By means of this estimation, the maximal energy was then predicted for a betatron — an induction accelerator in which electrons move in a magnetic field which builds up in time and is virtually homogeneous along the trajectory of the particle (D.D. lvanenko and I.Ya. Pomeranchuk)[7]. The existence of radiative losses in the energy of an electron in the magnetic field of an accelerator was soon verified in experiments conducted by J.P. Blewett (1946, Ref.[8]). He found that electrons moved in decreasing orbits as their energies increased: the particles moved in a converging spiral and ceased to accelerate because of a loss in energy to radiation (note that the energy, radius of the orbit, and magnetic field strength are related by the equation $\beta E = eHR$, see Ref.[22]).

Blewett's experiments could be considered to be a proof of the actual existence of radiation from relativistic charges and this radiation could even be called betatron radiation. However, attempts to visually observe this radiation were not a success: the search for radiation in the microwave range (dipole radiation) was a total failure. This exceptional situation when the energy losses of electrons were clearly observed while the radiation itself was elusive showed that large radiative losses alone did not explain the fundamental features of this extraordinary phenomenon.

Having studied theoretically the spectral distribution of the radiation power emitted by a circularly moving relativistic electron, L.A. Artsimovich and I.Ya. Pomeranchuk (1945, Ref.[9]; see also Ref.[10]) found out that the maximal power fell not on the fundamental frequency (as would be the case for dipole radiation), but on its higher harmonics: $\omega \sim \omega_0 \gamma^3$. For electrons of an energy of $80 - 100\ MeV$, the radiation ought to be observed not in the microwave range but in the radiation range of higher multifields, i.e., in the visible range. This was revealed in an experiment on the synchrotron in the USA[2,1].

It was shown in Ref.[9] that the angular distribution of the power of synchrotron radiation is highly anisotropic, i.e. it is concentrated in a slender cone of an angle $\delta\psi \sim 1/\gamma$ in the orbital plane of revolution of the electron and is directed forward in parallel to its motion. The theoretical study of the coherence of radiation [9] (this is of special interest for the radiation of a cluster of electrons in a betatron, when they fill almost the whole orbit) showed that the coherence could manifest itself at the lowest frequencies only because of fluctuations of the current density in a beam for $\gamma \gg 1$ — far from the maximum of the spectral distribution of power.

Thus, the qualitative description of the properties of synchrotron radiation were known before it was observed for the first time. However, as it is noted above, it was discovered by sheer accident.

The discovery of electronic light in the synchrotron stimulated further investigations of the SR properties and, first of all, analysis of the spectral and angular distribution of the radiation power. This was a complicated problem since Schott's formulas [5] were inconvenient for describing the radiation spectrum of a relativistic electron when it involved higher harmonics of the frequency of the circular revolution of the electron. The conventional approach of expanding the series in terms of multifields was not applicable to the analysis of the radiation. Then the asymptotic problem in the radiation spectrum of a relativistic electron arose for a large relativistic factor of $\gamma \gg 1$.

V.V. Vladimirskii [11] successfully applied the Airy functions, which had been studied thoroughly by V.A. Fock, to describe the radiation spectrum of an electron moving in a magnetic field. The asymptotical formulas for the spectral composition of synchrotron radiation were independently determined in several theoretical studies [11–15]. They opened a possibility of experimental verification. The experiments demonstrated good agreement with the theory in the visible range[16], the vacuum ultraviolet range[17], and the X-ray range[18].

The classical theory of SR was then contributed to by investigations of the polarization features of SR[19]. It was established, for example, that SR is elliptically polarized in general and it is linearly polarized when observed in the direction close to the orbital plane of revolution. The first observations of linear polarization were made in the initial studies [1] but the polarization features of SR were investigated in detail by the staff of the Physical Department of the MSU (Moscow State University) on the synchrotron in the FIAN (Physical Institute of the Academy of Sciences) and showed definite agreement with the theory [20] (see also Ref.[21]).

Numerous investigations shaped the classical theory of synchrotron radiation to perfection, and the theory was included in a variety of monographs [3,22–25] and courses[14,26]. Synchrotron radiation became important for astrophysics, in the analysis of nonthermal cosmic radiation. The Swedish scientists H. Alfven and M. Herlofson suggested in 1950 [27] that the nonthermal radiation of our galaxy could be explained through the mechanism of SR. In Russia this problem was addressed at the same time by V.L. Ginzburg[28] and I.S. Shklovskii[29]. The recognition of the importance of synchrotron radiation, the development of its theory, and experiments stipulated the outstanding advances in radioastronomy.

During the last few years the problem has acquired a new and important feature — synchrotron radiation is used extensively in scientific research. In parallel with our widening knowledge of the nature of the phenomenon, the objective of accelerators and storage units of electrons has recently changed — they have become a major source of synchrotron radiation which has taken up an independent position in experimental physics.

The physics of undulator radiation, i.e. the radiation of relativistic electrons as they move in a periodic outer field, is of utmost importance in experimental applications of SR. Undulator radiation, which V.L. Ginzburg predicted in 1947 [30], has the same origin as SR and is similar to it in many aspects. It has attracted considerable attention lately.

Although the theory of SR seemed to be complete, it turned out that the electronic light possessed a variety of fine and interesting properties which the classical theory of an accelerating charge did not describe: the physical nature of SR turned out to be richer and the quantum theory had to be applied for its comprehensive description[22,24,25].

* * *

It proved worthwhile to develop the quantum theory of synchrotron radiation on the basis of quantum relativistic mechanics and quantum electrodynamics, applying the so-called 'method of exact solutions'[24,25]. In this case the wave function which describes the quantum state of an electron obeys the Dirac equation:

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[c(\boldsymbol{\alpha}\hat{\boldsymbol{P}}) + \rho_3 mc^2\right]\Psi,$$

where

$$\hat{\boldsymbol{P}} = -i\hbar\nabla - \frac{e}{c}(\boldsymbol{A}^{\rm ext} + \boldsymbol{A}^{\rm qu}),$$

refers to the outer magnetic field which is considered exactly, and $\boldsymbol{A}^{\rm qu}$ to the quantum transverse radiation field. Here $\boldsymbol{\alpha}$ and ρ_3 are the Dirac matrices of four rows, and the wave function Ψ has four components (for details see Ref.[24]). Processes in which an electron in the bound state is involved when it interacts with the radiation field are considered by using the perturbation theory. In the perturbation theory, all expansions are made in terms of the full system of the exact solutions to the Dirac equation with an outer field (the Furry representation[31]).

Such an approach made it possible to predict and reveal a variety of new physical features of SR: quantum fluctuations of the trajectory of an electron when it moves in a cyclic accelerator and storage rings, the radiative polarization effect for electrons and positrons, the peculiar features of synchrotron radiation in strong and very strong magnetic fields, and a number of others (see Refs [24,25,32]).

Omitting the details of solving the Dirac equation (it is described in detail in Refs [24,25]) I want only to emphasize that the quantum state of an electron in a magnetic field $\boldsymbol{H} = (0,\ 0,\ H)$ is specified by the set of four quantum numbers: n is the energy number, s is the radial number, k_3 is the projection of the impulse onto the direction of the field , and ζ is the projection of the spin onto the direction of the field. In this case, the energy of an electron takes the form:

$$E = (m^2c^2 + c^2\hbar^2k_3^2 + 2e_0Hc\hbar n)^{1/2}. \tag{0.3}$$

If an electron executes a macroscopic motion, then the energy number s takes a very large value and the energy spectrum is continuous. In the nonrelativistic approximation, Eq. (0.3) describes the familiar Landau levels and also involves the kinetic energy of the motion of an electron along the field. Note that the energy spectrum given by Eq. (0.3) is degenerate with respect to the spin and to the radial number s. Taking into consideration the anomalous magnetic moment eliminates the spin degeneration and the energy spectrum takes the form (see Ref.[33])

$$E = mc^2\left(\left(\frac{\hbar k_3}{mc}\right)^2 + \left\{\left[1 + \frac{H}{H_0}(2n+\zeta+1)\right]^{1/2} + \zeta\frac{H}{H_0}\frac{\mu-\mu_0}{2\mu_0}\right\}^2\right)^{1/2},$$

where

$$\mu = -\mu_0\left(1 + \frac{e^2}{2\pi\hbar c}\right), \quad \mu_0 = \frac{e_0\hbar}{2mc}, \quad H_0 = \frac{m^2c^3}{e_0\hbar}.$$

Here H_0 is the Schwinger magnetic field. The ground state (n=0, k_3=0) [see Eq. (0.3)] corresponds to the spin oriented in the opposite direction of the magnetic field ($\zeta = -1$). The quantum numbers n and s are related to the radius of the orbit of an electron and the quadratic fluctuation of the radius:

$$\langle r^2\rangle = \frac{n+s+1/2}{\gamma_0}, \quad \langle r^2\rangle - \langle r\rangle^2 = \frac{s+1/2}{2\gamma_0}, \quad \gamma_0 = \frac{e_0H}{2c\hbar}.$$

The electrons are localized near the orbital plane of revolution for an extremely strong magnetic field since

$$R = \sqrt{\frac{n}{\gamma_0}} = \frac{\hbar}{mc}\sqrt{\frac{nH_0}{H}},$$

and the radius of the orbit is of the order of the Compton wavelength in weakly excited states as $H \to H_0$.

Restricting myself to the above remarks I move on to discuss synchrotron radiation. By the use of rather conventional methods [24,34], the expression for the synchrotron radiation power can be obtained in the form

$$W = \frac{e^2 c}{2\pi} \sum_{\nu, s', \zeta'} \int d^3k \; \delta(k - k_{nn'}) \Phi I^2_{ss'}(x), \tag{0.4}$$

where

$$ck_{nn'} = \frac{E_n - E_{n'}}{\hbar}, \quad x = \frac{k^2 \sin^2\theta}{4\gamma_0}, \quad \nu = n - n'.$$

It is taken into consideration in summing over k'_3 that the component of the impulse parallel to the field is preserved. The radial factor $I^2_{ss'}(x)$ appearing in the formula for the radiation power is a Laguerre function, which is related to the Laguerre polinomials $Q^{s-s'}_{s'}(x)$ by the equation

$$I_{ss'} = \frac{1}{\sqrt{s!s'!}} \exp\left(-\frac{x}{2}\right) x^{(s-s')/2} Q^{s-s'}_{s'}(x). \tag{0.5}$$

The function Φ depends on the elements of the Dirac matrix and is expressed in terms of the Laguerre functions $I_{nn'}$, which are approximated by McDonald functions $K_{1/3}$ by analogy with the classical theory of SR (see Refs[24,25]). Thus, the integral under the summation sign in Eq. (0.4) is the power of radiation electron emit in transitions $n \to n'$, $s \to s'$ with the spin flip $\zeta \to \zeta'$.

Making necessary manipulations, integrating with respect to angles and summing over the polarization states of the radiation field, we find the following expression for the spectral distribution of the synchrotron radiation power[24]

$$W = W^{cl} \frac{9\sqrt{3}}{16\pi} \sum_{s'} \int_0^\infty \frac{y\,dy}{(1+\xi y)^4} \, I^2_{ss'}(x) F(y), \tag{0.6}$$

where

$$\begin{aligned} F &= \frac{1+\zeta\zeta'}{2} \left[2(1+\xi y) \int_y^\infty K_{5/3}(x)dx + \frac{1}{2}\,\xi^2 y^2 K_{2/3}(y) \right. \\ &- \left. \zeta(2+\xi y)\xi y K_{1/3}(y) \right] + \frac{1-\zeta\zeta'}{2}\,\xi^2 y^2 \left[K_{2/3}(y) + \zeta K_{1/3}(y) \right]. \end{aligned}$$

Here the argument x of the function $I^2_{ss'}$ takes the form $\nu = n - n'$ upon changing the summation over y for integration with respect to the variable

$$x = \frac{\xi_1 y^2}{(1+\xi y)^2}.$$

It follows from Eq. (0.6) that the probability of spontaneous transitions of an electron is a function of two parameters:[c]

$$\xi = \frac{3}{2}\frac{H}{H_0}\frac{E}{mc^2} = \frac{3}{2}\chi = \frac{3}{2}\left(\frac{E}{E_{1/2}}\right)^2, \quad E_{1/2} = mc^2\left(\frac{mcR}{\hbar}\right)^{1/2},$$
$$\xi_1 = \frac{9}{8}\frac{H}{H_0}\left(\frac{E}{mc^2}\right)^4 = \frac{9}{8}\left(\frac{E}{E_{1/5}}\right)^2, \quad E_{1/5} = mc^2\left(\frac{mcR}{\hbar}\right)^{1/5}.$$

Now I want only to note that the SR power depends solely on one invariant parameter χ since the sum over the radial quantum number

$$\sum_{s'} I^2_{ss'}(x) = 1$$

is equal to unity. Thus, the limits in which the classical theory was predicted to be applicable[11] were strictly borne out by the quantum theory. Note that this refers, however, to the SR power only.

Expression Eq. (0.6) is exact: it allows any values of the parameter $\xi = 3\chi/2$, including $\chi \gg 1$, which are realizable in the physics of neutron stars where the magnetic field strength is close to the critical H_0. In addition, the formula for the radiation power involves the contribution of radiation which is accompanied by the flip of the spin (spin-flip transitions) when $\zeta' = -\zeta$. As follows from Eq. (0.6), the probabilities of such transitions are proportional to the square of the Plank constant $\hbar^2$.

Since the SR power depends explicitly on the orientation of the spin of an electron, the radiation accompanied by the flip of a spin affects the orientation of the spin and stimulates the directed process of polarization of the electron beam. In addition, there is a spin dependence in the formula for the SR power, which enters the terms which are independent of the flip of a spin. This is not only of theoretical interest. In fact, given a small invariant parameter ξ it follows from Eq. (0.6) that the spectral distribution of the SR power of a polarized electron beam takes the form

$$W^{\rm pol} = W^{\rm cl}\,\frac{9\sqrt{3}}{8\pi}\int\limits_0^\infty \left[(1 - 3\xi y)\int\limits_y^\infty K_{5/3}(x)dx - \zeta\xi y K_{1/3}(y)\right] y dy. \qquad (0.7)$$

Note that V.A. Bordovitsyn[35] made a large advance in interpreting quantum corrections to the classical expression for the SR power. He showed, in particular, that the quantum correction in Eq. (0.7) involves contributions from the interference of the radiation from electron, charge, and the spin magnetic moment of electron.

Thus, this offers a new possibility for visual observation of the polarization characteristics of an electron beam by determining the SR power at a fixed spectral

[c]The probability of spontaneous transitions can be found by dividing the integrand in Eq. (0.6) by the energy of the quantum of the electromagnetic field $\hbar\omega$

frequency[36]. The experiment which was performed in the Institute of Nuclear Physics, Siberian Branch of USSR Academy of Science[36], can be considered as a first visual observation of radiation which is directly associated with electron spin.

Further, the expression for the SR power can be found by summing up over the polarization states of an electron

$$W = W^{\rm cl}\,\frac{9\sqrt{3}}{8\pi}\int\limits_0^\infty \frac{y\,dy}{(1+\xi y)^3}\left[\int\limits_y^\infty K_{5/3}(x)dx + \frac{\xi^2 y^2}{1+\xi y}\,K_{2/3}(y)\right]. \tag{0.8}$$

The SR power which is uniformly applicable for any values of the parameter ξ was calculated exactly by V.G. Bagrov[37]. Here I cite two limiting cases in the form of asymptotic expansions. First, let us consider the case of small invariant parameter of $\xi \ll 1$, i.e., the quantum corrections to the classical radiation formula are

$$W = W^{\rm cl}\left[1 - \frac{55\sqrt{3}}{24}\,\xi + \frac{64}{3}\,\xi^2 + \ldots\right]. \tag{0.9}$$

This correction was found up to a linear term in Ref.[38] and was corroborated by J. Schwinger for spinless particles[39].

In the second limiting case of $\xi \gg 1$ (high energies, extremely large magnetic fields), the formula for the SR power differs drastically from the classical one (the ultraquantum limit)[24,40]

$$W^{\rm uq} = W^{\rm cl}\left[\frac{2^{8/3}}{9}\,\Gamma\left(\frac{2}{3}\right)\right]\xi^{-4/3}, \quad \xi \gg 1. \tag{0.10}$$

In the ultraquantum limit the principal term of the radiation power is of quantum nature. Therefore transition to the classical approximation is impossible.

It is characteristic that in the ultrarelativistic limit the spectrum is terminated at the frequency $\omega^{\rm uq}_{max} = E/\hbar \ll \omega^{\rm cl}_{max}$, and does not reach the classical critical frequency

$$\omega^{\rm cl}_{max} = \frac{c}{R}\left(\frac{E}{mc^2}\right)^3. \tag{0.11}$$

This follows immediately from the formula for the classical frequency of radiation (see Ref.[34]):

$$\omega_{max} = \frac{3}{2}\omega_0\gamma^3\frac{y_{max}}{1+\xi\; y_{max}}, \; y_{max} \sim 1$$

Of some interest is the radiation of weakly excited electrons (low-energy levels) in a strong magnetic field. It is peculiar for such a problem that the energy spectrum of an electron is discrete ('quantising' magnetic field). If electrons move perpendicularly to the field ($k_3 = 0$), the energy

$$E = mc^2\left(1 + 2n\,\frac{H}{H_0}\right)^{1/2}$$

takes essentially discrete values for $n \sim 1, 2, \ldots$

In this case, only numerical methods are applicable. It turns out that the probability of spontaneous transitions depends no longer on the orientation of the spin of an electron and the probability of a transition with a change in the spin orientation is the same as that with no change of polarization.

The radiation powers of the σ and π components of the linear polarization take the forms $W_\sigma = 0.742\ W$ and $W_\pi = 0.258\ W$, where

$$W = 0.453 \left(\frac{H_0}{H}\right)^2 W^{cl}$$

(see Ref.[41]). Thus, the expression for the radiation power W differs from the classical formula by the invariant factor

$$f = \frac{1}{4}\,\frac{1}{H_0^2}\,H_{\mu\nu}H^{\mu\nu} = \left(\frac{H}{H_0}\right)^2.$$

This result does not coincide with those obtained not only in the classical theory, but also in the ultraquantum case of an excited electron moving in a very strong field.

* * *

The quantum theory of SR [22,24] helps to explain the discrete nature of the radiation and its influence on the trajectory of the particle (the recoil effect). As the theory shows[42,43], this influence manifests itself in the quantum widening of the trajectory of an electron — the particle is involved in a peculiar Brownian movement and quantum fluctuations of the trajectory are macroscopic in nature. The latter fact proved to be important in the engineering of accelerator design and storage of electrons.

The quantum theory also made it possible to investigate the SR emitted by a polarized electron and the contribution of the spin of a particle to the radiation power. The analysis of the spin evolution during synchrotron radiation revealed the effect of the polarization of radiation of electrons and positrons in storage rings[44]. This effect is of special interest in connection with the problem of how to create a beam of relativistic particles with an oriented spin.

The effect is that the spins of particles are oriented in the same way under the influence of synchrotron radiation when they circulate in storage rings for a long time. This effect of radiative polarization was predicted by the author [45] and strictly established together with A.A. Sokolov with the use of the exact solutions to the Dirac equations [46] (see also Refs [34,47]).

The probability of quantum transitions accompanied by spin flips can be calculated with Eq. (0.6). The calculation shows that the probability still depends on the spin orientation and upon integration with respect to angles and to the spectrum:

$$w^{\uparrow\downarrow} = \frac{1}{2\tau}\left(1 + \zeta\,\frac{8\sqrt{3}}{15}\right), \tag{0.12}$$

where the polarization time τ has the form

$$\tau = \frac{8\sqrt{3}}{15}\,\frac{\hbar^2}{mce^2}\left(\frac{mc^2}{E}\right)^2\left(\frac{H_0}{H}\right)^3. \qquad (0.13)$$

It follows that radiation induces electrons to transit predominantly in states with a spin oriented in the direction opposite to that of the magnetic field [45]. Positrons have the opposite spin orientation. States with a predominant spin orientation match the minimal potential energy of particles, the magnetic moment of which is $\boldsymbol{\mu} = -(e_0\hbar/2mc)\boldsymbol{\zeta}$ in the magnetic field $U = (-e/\mid e\mid)\boldsymbol{\mu H}$.

Omitting the details of the kinetics of the polarization process (see Refs [46,34] and turning our attention to an ensemble of particles, we can characterize the polarization of a beam of particles by the average value $\zeta(t) = \rangle\zeta\langle$, bearing in mind that the electron goes into the combined state as a result of interaction with the electromagnetic field. Then

$$\frac{d}{dt}\,\zeta(t) = \sum_{\zeta'}(\zeta' - \zeta)\,w^{\uparrow\downarrow} = -2\sum_{\zeta}\zeta w^{\uparrow\downarrow},$$

whence it follows that[d]

$$\zeta(t) = -\frac{8\sqrt{3}}{15}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right]. \qquad (0.14)$$

The extreme degree of polarization is $P(\infty) = 8\sqrt{3}/15 = 0.924$ (for $t \gg \tau$).

The estimate for the polarization time shows that the effect of radiative polarization is accessible for observation in magnetic fields which are typical of accelerators only if the particles circulate in the magnetic field for a long time (about 1 hour). Storage rings provide a means for this possibility. Although there are effects depolarizing the beam in an actual storage ring, the effect of radiative polarization exists and provides a unique capability for creating polarization beams of high-energy electrons and positrons. The effect of radiative polarization was experimentally observed in the USSR, France, Germany, USA, Japan, and Switzerland in storage rings with electrons of energy 1–50 GeV (see Ref. [47]).

It should be noted that storage rings, in which there was a possibility of compensating for radiative energy losses, became a unique laboratory for studying quantum effects, since electrons could circulate for tens of hours under such conditions, with the average energy remaining constant. The quantum effects in synchrotrons were also verified experimentally. Thus, now both classical and quantum theories of SR are complete and reliable.

* * *

For a long time, synchrotron radiation was considered to be a nuisance in the operation of a cyclic accelerator. The reason was that it set a radiative 'ceiling' to the operation of a betatron[7]. Radiative losses of energy imposed a fundamental

[d]This result was later obtained by V.N. Baier and V.M. Katkov[48] and by J. Schwinger[49].

restriction on the inductive method of acceleration of electrons. Therefore, a new acceleration technique was adopted upon the discovery of automatic phase stabilization (Wecksler, McMillan), i.e. a synchrotron in which energy losses were compensated for. However, even early studies of the properties of SR [1,16–18] attracted the attention of experimentalists and soon aroused an interest in SR as a new source of radiation.

In the 1960s the first laboratories of synchrotron radiation appeared with the object of finding an application for SR in the physical experiment. This special attention to the new source of radiation was due to its peculiar properties: a wide spectral range of electromagnetic waves from the infrared radiation to the X-ray radiation; sharp collimination because of which the brightness of radiation was very high; high power; and natural polarization typical of this source. Of great importance was the fact that all the properties of SR were fully described theoretically. This made it possible to calculate its characteristics with a high degree of precision.

The 1980s were marked by a vigorous growth of a number of investigations in which SR was used, and by advances in new types of specialized sources of radiation. During those years there appeared scientific research centers of synchrotron radiation. They were equipped with sources of SR, free electron lasers (FELs), wigglers, systems of undulators, and auxiliary facilities built in the chamber of a storage ring. In Russia, centers of synchrotron radiation were established in the Institute of Nuclear Physics in Novosibirsk, in Lebedev Physical Institute (FIAN), and in Kurchatov Institute of Atomic Energy. Today scientists in many countries of the world such as the USA, FRG, Italy, Japan, the United Kingdom, France, Switzerland and others are engaged in research using synchrotron radiation.

The successful application of SR in the physical experiment has had a pronounced effect on the progress of physics of atoms and molecules and also on solid state physics. It is impossible to cover all these issues in our review in any detail since they constitute a vast problem, which is in itself of interest. Fortunately, there is no need for it since the issues related to applications of SR in the physical experiment are considered in detail in special literature. So, for example, the review of Gurdling was devoted in particular to the application of SR in atomic spectroscopy (see Ref.[50]). E.E. Koch and B. Sonntag reviewed applications of SR in molecular spectroscopy, D. Ling reviewed the spectroscopy of solid bodies (see Ref.[50]). Applications of SR in studies of the luminescence of crystals were considered in the monograph [25] and, finally, the review of R. Haensel is devoted to applications of SR in studies of optical properties of alkali halide compounds (see Ref.[51] and also Refs [52–55]).

Note that SR is virtually a unique source of high-intensity radiation in the range of $200 - 500$ A. In the short-wavelength range of the vacuum ultraviolet radiation and in the soft X-ray range, the power of the radiation emitted by electrons of the energy of several GeV exceeds the power of radiation available from X-ray tubes by several orders of magnitude[25].

Of special importance is the application of SR in experiments in the soft X-ray range of radiation, in which its power exceeds several times that of all other sources of X-ray radiation. It should be added that SR has an advantage over other sources since it allows for continuous adjustment of the wavelength of radiation, especially for application of long-wavelength X-ray radiation.

This peculiar feature of SR opened a possibility for its application in biology, in the study of structures of biopolymers. The reduction of the exposure time, and the prevention of the object of investigation from being destroyed because of a much smaller radiative load make SR indispensable in studies of biological structures (see Ref.[25]).

The recent years have witnessed successful application of SR in medicine, particularly in angiography by X-ray techniques. There is a possibility of obtaining more information when a smaller radiative load is applied to a patient. In 1986 H. Winick conducted angiographic inspection of a man the Stanford Laboratory of SR (earlier such inspections were conducted on animals only) (see Refs [25,56,57]).

SR has been applied in microlithograpy for obtaining elements of microschemes used in modern semiconductor devices. The unique properties of SR, e.g. sharp directivity and large power in the X-ray range, make it possible to improve the quality of elements of microschemes and obtain new elements in microelectronics (see Refs [25,58]).

I will now draw the reader's attention to new possibilities of experiments centered around the direct visual observation of 'electronic light' [25,59], when one observes an electron beam passing through an accelerating cycle or moving in a storage ring. As noted above, an outstanding success was the experimental examination of the dynamics of betatron oscillations of electrons in the presence of forces of radiative damping and quantum fluctuations[60,61].

The basis for visual observation of the dynamics of an electron beam is the high-speed photography of synchrotron radiation emitted by an electron beam followed by the processing of photographs. High-speed photography of an electron beam for the purposes of analysis of its dynamics was first performed by Pollock's group on the synchrotron 'General Electric-70 MeV' [1], and then this technique was developed by Ado [62] and also in a series of studies performed under the supervision of F.A. Korolev on the synchrotrons 'FIAN-280 MeV' and 'FIAN-680 MeV' [63].

The analysis of photographs obtained in the experiments mentioned above restored the full history of evolution of betatron oscillations under the action of forces of radiative damping and quantum fluctuations[60,63]. I would like to emphasize that the source of information on the motion of an electron was the particle itself through emitted electromagnetic waves — 'luminous electron' (for details, see Ref.[25]).

In conclusion, I shall describe briefly ways in which SR sources can be improved. One of the crucial problems is how the brightness of a source can be increased. The term brightness is understood to refer to the number of photons which are emitted in one second from a unit area of an extended source into a unit solid angle. One way of increasing the brightness is to create a storage ring of small emittance which is a characteristic of a beam of particles, and is given by $\varepsilon = \pi\sigma\theta$, where σ is the Gaussian size of the beam in meters, and θ is the angle of the cone of radiation in radians. In advanced modern sources, small emittance is achieved through strong focusing of a beam of particles, combined with systems of permanent magnets of multiperiodic undulators (note that the angular size of the cone of radiation is the quantity $\delta\theta \sim 1/(\gamma\sqrt{N})$ for an undulator made up of N sections of magnets).

Further, it is clear that the brightness of a source depends primarily on the radiation power. Of interest in this context are coherent bunches of electrons clustered at distances less than the wavelength of their radiation. As noted in the early work [10], in this case, coherence would make it possible to increase the radiation drastically since the bunch of electrons behaves like an effective charge $e_{\text{eff}} = N_e e$ (N_e is the number of electrons in the bunch).

The creation of such coherent bunches is a very complicated problem, even in the microwave range. So far as the possibility of clustering electrons in bunches of the size of the order of the optical wavelength was concerned, the difficulties seemed to be insurmountable.

At present it is established that in the theory of free electron lasers, which considers the interaction of an electron beam in an undulator with an electromagnetic wave, there is a mechanism of self-modulation of an electron beam. Electrons are clustered in the longitudinal direction and form coherent bunches of length of the order of the optical wavelength.

The mechanism of self-modulation of an electron beam is similar to some extent to the clustering of electrons in a synchrotron under the combined action of the leading magnetic field of the accelerator and the vortical high-frequency field accelerating the particles (the self-modulation principle of Wecksler and McMillan). As a result of their action, the electron beam is divided into bunches the length of which is a function of parameters of the high-frequency electric field.

It is interesting that particles are clustered in the free electron laser even if an outer electromagnetic wave is absent, with the 'trigger' wave of spontaneous radiation playing its role. The self-amplification of spontaneous radiation is one of the important properties of the undulator. When electrons pass through a large-length undulator, there is no interference initially and the total radiation power is proportional to the number of particles $W^{\text{total}} = N_e W$. Then the clustering mechanism comes into play, and the radiation of a cluster of electrons becomes coherent. The spontaneous radiation amplifies itself and the radiation power is now proportional to N_e^2 because of the interference: $W^{\text{total}} = N_e^2 W$. This self-amplification phenomenon provides the grounds for a special 'strong' source of radiation — a large-length undulator.

The coherence problems of synchrotron radiation have recently attracted the attention not only of theoreticians but also of experimentalists[64–67].

I would like to say that synchrotron radiation has not only won recognition in physical experiments of the present time but will still be an experimental tool in the future.

In *The Thousand and One Nights*, there is a story about a boy named Aladdin and a magic lamp. The boy found a magic lamp and, when he rubbed it slightly with a pinch of sand, there appeared an enormous genie and said, "I am at your disposal, I am your slave". The electronic light burst out of the chamber of an accelerator in

1947 and since then synchrotron radiation, like the genie in Aladdin's magic lamp, has shown the way to knowledge in various fields of science.

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