High-power ultraviolet and x-ray sources[1)]

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The review is devoted to the problem of using cyclic electron accelerators and storage rings as sources of high-power ultraviolet radiation and x rays. A brief description is given of the properties of synchrotron radiation and also of the undulatory radiation which can be generated in such installations. Particular cases of use of these radiations are discussed. The parameters of Soviet accelerators and storage rings and the intensities of the synchrotron radiation beams from these installations in the far ultraviolet and x-ray regions of the spectrum are given. These characteristics are compared with the corresponding data for the DESY synchrotron at Hamburg, whose radiation is extensively used for x-ray structural analysis of biological polymers, investigation of the electronic structure of solids and gases, surface phenomena, and many other purposes.

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1. INTRODUCTION

In widely different fields of science there has recently been an increase in interest in investigations in the field of far ultraviolet and x-ray radiation. This has occurred first of all in solid-state physics, including the physics of semiconductors and dielectrics, the physics of surface phenomena, photochemistry, and x-ray structural analysis, particularly of biological objects. This class of electromagnetic radiation also has practical application, in particular, in connection with space programs. Almost all of the studies in these fields are carried on in cyclic electron accelerators (synchrotrons and electron storage rings), which are high-power sources of vacuum-ultraviolet (VU) and x-ray radiation. In addition, the high intensity and continuous spectrum in synchrotrons permit investigations which cannot be carried out with other sources.

To give an idea of the intensity we indicate that the average intensity of ultraviolet radiation of the comparatively small 680-MeV accelerator at FIAN is several times higher than the intensity of ultraviolet radiation of the Sun at the Earth's orbit (outside the atmosphere) and only several times less than the total flux density of radiant energy of the Sun. The integrated radiation flux of such contemporary accelerators as ARUS in Erevan or DESY in Hamburg is many times greater.

In this article we report briefly the properties of the synchrotron radiation of accelerators and storage rings, we discuss the undulatory radiation, which is a variety of synchrotron radiation, and also transition cases, which are interesting from the point of view of practical application. At the end of the review we present the comparative characteristics of Soviet accelerators and storage rings which can be used as sources of ultraviolet radiation and x rays. We will not discuss pulsed sources of x rays, which have been described in detail in a previous review,[1] or arc sources of VU radiation (see for example ref. 2).

We will consider two regions of the spectrum: the broad range 50–2500 Å (250–5 eV) and the region of wavelengths of the order of 1 Å (~ 10 keV), which are used in classical x-ray structural studies.

The first region is of interest primarily for solid-state physics, particularly for the study of band structure, luminescence, the inert gases, photochemistry, and practical application.

The second region, which is usually used for x-ray structural analysis, is of interest for molecular biology, where it is necessary, in obtaining new information on the structure of biological polymers, particularly proteins, and also on the kinetics of this structure, to have intensities many times higher than those of ordinary x-ray sources.

2. PROPERTIES OF SYNCHROTRON RADIATION

The theory of synchrotron radiation has been highly developed[3] and has been confirmed in numerous experiments.[4,5] The data obtained have been systematized in a number of reviews.[6-10] The questions of the effect of synchrotron radiation on the operation of an accelerator have been analyzed in detail.[11] We will dwell below on the main properties of this radiation which are necessary for the discussion which follows.

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In cyclic electron accelerators and storage rings the electrons rotating in a circular orbit radiate. The synchrotron radiation (magnetic bremsstrahlung) produced is extraordinarily intense and has a number of interesting properties.

As the result of relativistic effects the synchrotron radiation is sharply directional. It is concentrated in the plane of the accelerator orbit and at any instant is confined to a cone with opening angle $\theta \approx 1/\gamma$ about the tangent, where $\gamma = E/m_0c^2$ is the relativistic factor of the radiating electron. As a result of the Doppler effect the maximum power is not radiated at the rotational frequency ω_0 but is shifted to the region of higher frequencies $\sim\gamma^3\omega_0$.

The loss of energy by radiation of one electron having an energy E per revolution in an orbit with radius R is

$$\Delta E = \frac{88.5E^4}{R}; \quad (1)$$

here and subsequently ΔE is in keV, E is in GeV, and R is in meters.

At the FIAN 680-MeV synchrotron [12] this quantity is as high as 9.5 keV, and in the 1.3-GeV synchrotron under construction at FIAN [13] it is 63 keV.

The spectrum of radiation of isolated electrons consists of a set of harmonics of the rotational frequency ($\sim 10^6 - 10^7$ Hz). However, since the maximum power occurs in harmonics with numbers $10^9 - 10^{12}$, as a result of the spread in the parameters in the beam of a real accelerator a smearing of the individual maxima occurs, and even in the optical region their width becomes several orders of magnitude greater than the distance between them. For this region the line structure of the spectrum can be observed only for small harmonic numbers in the radiofrequency region; in this same region it is possible to observe coherent effects. In the remaining region, which presents the greatest interest, the distribution can be considered continuous with high accuracy.

The spectral distribution of the radiation is described [4b] by the formula

$$I(\lambda) = N(E, R)\, G(y), \quad (2)$$

where

$$N(E, R) = \frac{3^{5/2}}{16\pi^2}\left(\frac{e^2 c}{R^3}\right)\gamma^7, \quad (3)$$

$$G(y) = y^3 \int_y^\infty K_{5/3}(\eta)\, d\eta; \quad (4)$$

$K_{5/3}(\eta)$ is the Macdonald function, $y = \lambda_c/\lambda = \omega/\omega_c$,

$$\lambda_c = \frac{4\pi}{3} R\gamma^{-3} \quad (5)$$

is the so-called characteristic wavelength. A universal curve of the spectral distribution of the radiation of monoenergetic electrons is shown in Fig. 1. The maximum radiation occurs at a wavelength

$$\lambda_m = 0.42\,\lambda_c. \quad (6)$$

The spectral distribution curve of synchrotron radiation has a shape reminiscent of the Planck curve for the radiation of a black body, for which

$$\lambda_m T = 0.2897 \text{ cm-deg}, \quad (7)$$

where T is the temperature of the body. Combining Eqs. (6) and (7), we find that the dependence of the effective temperature of synchrotron radiation (SR) on the accelerator parameters has the form

$$T_{SR} = 6.89\cdot 10^7 \lambda_c^{-1} = 1.23\cdot 10^7 E^3 R^{-1}; \quad (8)$$

here and below in formulas with numerical coefficients, λ is expressed in Å.

For the DESY and ARUS synchrotrons, T_{SR} reaches several tens of millions of degrees, and for the 680-MeV FIAN synchrotron—about 1.5×10^6 degrees.

The spectral intensity of the radiation near the peak of the curve is

$$I(\lambda) \approx 9\cdot 10^{-24}\,\gamma^7 R^{-3}, \quad (9)$$

where I is in erg/sec-Å-electron. For the long-wavelength part of the spectrum ($\lambda \gg \lambda_c$) the radiation density is practically independent of the electron energy:

$$I(\lambda) \approx 90\, R^{-2/3}\lambda^{-7/3}. \quad (10)$$

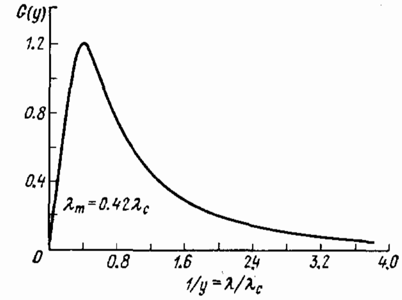

FIG. 1. Universal curve for synchrotron radiation. To obtain the spectrum of an accelerator it is necessary to multiply the ordinate by the quantity A from Table I. The abscissa represents the quantity $1/y = \lambda/\lambda_c$ (λ_c is also given in Table I).

For $\lambda \ll \lambda_c$ the intensity drops rapidly according to a law

$$I(\lambda) \sim \sqrt{y}\, e^{-y}. \quad (11)$$

The formulas given above give the spectral density of radiation per unit wavelength interval. The spectral density of radiation calculated per unit frequency interval has the form [7]

$$I(\omega) = \frac{\sqrt{3}}{2\pi}\frac{e^2}{R}\gamma y \int_y^\infty K_{5/3}(\eta)\, d\eta. \quad (12)$$

The maximum of this distribution occurs at a frequency

$$\omega_m = 0.29\,\omega_c,\ \lambda(\omega_m) = 3.45\,\lambda_c = 8.2\,\lambda_m.$$

For $\omega \ll \omega_c$ the number of photons per unit photon-energy interval can be estimated from the following formula

$$N(\hbar\omega) = 2.07\cdot 10^8 R^{-2/3} (\hbar\omega)^{2/3}, \quad (13)$$

where $\hbar\omega$ is in eV and $N(\hbar\omega)$ is in photons/eV-sec.

Synchrotron radiation is elliptically polarized. [5] The degree of polarization depends on the angle of the radiation and the wavelength. Directly in the orbit plane the radiation is completely linearly polarized and the electric vector lies in this plane. The degree of linear polarization, averaged over all angles and wavelengths, is 75%. Figure 2 shows the angular distributions of the two components of synchrotron radiation. An important fact is that the polarization, like the other properties of synchrotron radiation, can easily be calculated for any specific case.

It should be noted that the formulas given above refer to a monochromatic beam of electrons. In calculation of the intensities in accelerators it is necessary to take into account the increase of the electron energy with time during each acceleration cycle, the angular and spatial spread of the electrons in the beam, and in a number of cases the instabilities in the location of the electron orbit and the intensity loss in the acceleration process. The actual experimental conditions are taken into account, for example, in ref. 4b.

In the vacuum chamber of the accelerator or storage ring which is the source of synchrotron radiation, a high vacuum is maintained (better than 10^{-6} Torr), which has definite experimental advantages and in addition imposes further requirements on the design of the experimental apparatus, since the vacuum systems of the latter communicate directly with the accelerator vacuum chamber. In particular, spectral apparatus must be pumped with oil-free pumps, since the intensity of synchrotron radiation is so great that the residual pressure of oil in the vacuum chambers of the spectral apparatus, if they are pumped by oil diffusion pumps, results in formation on the surfaces of the mirrors and diffraction gratings of a permanent film which rapidly destroys the usefulness of the apparatus.

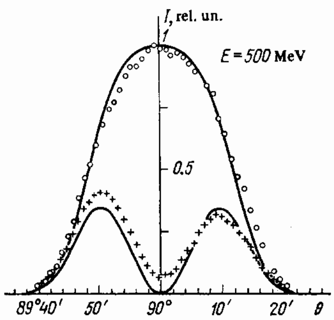

FIG. 2. Angular distribution of the two mutually perpendicular components of synchrotron radiation [5]. The upper curve corresponds to a polarization vector lying in the orbit plane.

3. UNDULATORY RADIATION

So-called undulatory radiation, [14-16] which is similar in its properties to synchrotron radiation, is generated on motion of a relativistic electron in a periodic field. Calculations [14] show that an electron moving in a static electric or magnetic field with a spatial period λ_0 will radiate at a frequency

$$\omega = \frac{c}{\lambda_0(1-\beta\cos\theta)}, \quad \omega_m = \frac{2c}{\lambda_0}\gamma^2; \tag{14}$$

ω_m is the maximum frequency, which corresponds to radiation in the direction of motion ($\theta = 0$). Equation (14) is valid if the field intensity is sufficiently small that the maximum deflection angle α of the electron in the field is less than $1/\gamma$.

This situation can be realized in practice if the undulator (radiator) is placed in a straight section of the orbit of a cyclic accelerator or storage ring.

For the case of an infinitely long radiator, where the particle undergoes harmonic oscillations, the radiation intensity per unit length can be written in the form [16]

$$i_\omega = \frac{1}{\omega_m} F\left(\frac{\omega}{\omega_m}\right), \quad \frac{1}{4\gamma^2} \leqslant \frac{\omega}{\omega_m} \leqslant 1, \tag{15}$$

where

$$F(\xi) = 3\xi(1 - 2\xi + 2\xi^2).$$

At first glance it may appear that at a given angle (for example, $\theta = 0$) it is possible by collimation to obtain monochromatic radiation; however, this is not true. Although the spectral intensity at the maximum of an ideal radiator is several times higher than the corresponding quantity for synchrotron radiation (for equal total intensities), [16] as a result of the strong directivity of the radiation (all radiation is concentrated in an angle $1/\gamma$ along the direction of motion) it is difficult to provide monochromaticity of the radiation in radiators, and in this respect undulatory radiation has no fundamental advantages over ordinary synchrotron radiation.

As the field strength in the radiator (and consequently also the angle α) are increased, the maximum frequency decreases somewhat, [16]

$$\omega'_m = \frac{2c}{\lambda_0}\gamma_\parallel^2, \quad \gamma_\parallel^2 = \frac{1}{1-\beta^2\cos^2\alpha}. \tag{16}$$

If we assume that $\alpha \ll 1$, the last equation can be written in the form

$$\omega'_m \approx \frac{2c}{\lambda_0}\gamma^2\frac{1}{1+(\alpha\gamma)^2}.$$

Here the density of radiation increases in proportion to the square of the radiator field intensity. [14] However, if the condition $\alpha \ll 1/\gamma$ is not satisfied, the radiation is no longer dipole, and higher harmonics appear. [17]

The maximum spectral density at the frequency ω'_m per unit area is obtained for the condition $\alpha \sim 1/\gamma$; on further increase of the field the increase in radiated power begins to lag behind the increase in the angle in which this radiation is concentrated. [16]

It is of interest to consider the limiting case of "undulatory" radiation with one element of periodicity and a very high field in this element, i.e., actually synchrotron radiation from a small section of orbit where the magnetic field is much higher than in the remaining orbit, and to compare the radiation produced by this radiator in a given direction with the radiation of an ordinary ring accelerator with radius R_2 at an energy E_2. If, in order to be specific, we require that the maximum of the radiation in the two cases occurs at a selected wavelength, then the radius of the radiator R_1 and the electron energy E_1 can be chosen so that

$$\lambda_c \sim R_1 E_1^{-3} = R_2 E_2^{-3}. \tag{17}$$

It is reasonable to assume also that the average magnetic field in the two cases is the same and therefore the radius of the mean orbit and the time of revolution are proportional to the electron energy.

The radiation of an electron from a radiator, per unit angle of revolution, will be no different from the radiation of an electron from a portion of a circular trajectory, but in determining the radiated power it is necessary to take into account that the number of traversals in a selected direction will be different in the two cases being compared. The energy $W(\lambda)$ radiated in rotation of an electron through unit angle, according to Eq. (9), will be

$$W(\lambda) = \frac{I(\lambda)}{2\pi f} \sim \gamma^7 R^{-2},$$

and if we take into account that the time of revolution in the mean field is proportional to the energy, we can represent the spectral power of the radiation in the form

$$I'(\lambda) \sim \gamma^6 R^{-2} H. \tag{18}$$

Comparison of the values of $I'(\lambda)$ for the two cases, with allowance for Eq. (17), gives

$$\frac{I'_1}{I'_2} = \frac{\gamma_1^6 R_1^{-2}}{\gamma_2^6 R_2^{-2}} = \frac{\lambda_{c2}^2}{\lambda_{c1}^2} = 1.$$

In spite of the fact that the intensity at the maximum is proportional to the seventh power of the energy and inversely proportional only to the square of the radius, the two means of increasing the intensity at a given wavelength by increasing the beam energy or by creating a radiator of small radius in the orbit have turned out to be equally valuable.

This fact must be taken into account in choice of the parameters of an accelerator or storage ring specially designed to produce intense synchrotron radiation at a chosen wavelength.

An interesting case of undulatory radiation has been discussed by Ginzburg, [18] who considered the radiation of an electron in the field of an intense electromagnetic wave. What we are talking about is actually the Compton scattering of light by relativistic electrons, which has been well studied at higher energies [19] and has found a field of application. [20] The point is that in scattering of laser photons by relativistic electrons the scattered radiation is sharply directed along a tangent to the electron trajectory, the energy of the radiation is concentrated near the maximum energy of the scattered photons, the radiation preferentially preserves the polarization of the incident light, and the scattering cross section and achievable intensities of the colliding beams are so large that the intensity of the scattered radiation is sufficient for carrying out a number of interesting experiments at high energies.[20]

At lower electron energies (~ 50 MeV) and for laser photon energies of 0.1 eV, the scattered photons lie in the spectral region being discussed near 1 Å. From a technical point of view this principle can already be used to produce pulsed sources of quasimonochromatic arbitrarily polarized x rays, but in average intensity they will still be greatly inferior to accelerators, which we will discuss below.

4. ELECTRON ACCELERATORS—SOURCES OF SYNCHROTRON RADIATION

We will consider first the spectral region 50—2500 Å. In this region of the spectrum, accelerators and storage rings have no competition as radiation sources, and it is not surprising that in many active installations there are extensive programs for use of synchrotron radiation. It is sufficient to mention the accelerators DESY at Hamburg, NINA at Daresbury, England,[21] and the synchrotrons at Frascati[22] and Tokyo.[23] Work has begun on use of VU radiation at Moscow and Erevan in the USSR. Projects are being discussed for creating special accelerator-storage rings intended for use of the synchrotron radiation.[24]

Several accelerator installations, having exhausted their high-energy physics program, have been converted entirely to operation as synchrotron-radiation sources.[25] One of the most intensive programs is in the synchrotron-radiation beam of the DESY accelerator[9,26] in Hamburg, West Germany. In spite of the fact that practically no time is especially devoted to these programs, the SR beam is used during the performance of other experiments in the accelerator for about 150 hours per week (out of 168 possible). Roughly a third of the entire scientific output of the accelerator occurs from the SR channel.

The experimental apparatus for work with SR is located in a bunker 40 m from the accelerator orbit. The working conditions at DESY permit an extensive research program to be carried out,[8,9,26] and on comparing various SR sources, we will compare them with the DESY synchrotron. Since the experimenter is interested in the flux of radiation incident on his apparatus, we have listed below in Tables II and III the radiation fluxes through a unit area located a distance L from the orbit suitable for performing experiments in a given specific accelerator.

In Table I we have given the main parameters of several Soviet accelerators and storage rings operating or about to begin operation; for comparison we have also given in this table the parameters of the DESY synchrotron.

The average spectral density of the flux of SR through an infinitely long vertical slit of width b = 1 cm at distance L from the orbit, produced by the beam of a given accelerator, is determined by the expression

$$P(\lambda)=N(E, R)\,G(y)\,n_e\frac{d}{2\pi L}\,\frac{t}{T}=A\left(E, R, n_e, L, \frac{t}{T}\right)G(y), \qquad (19)$$

where n_e is the number of electrons in the accelerator orbit and t/T is the reciprocal duty cycle of the accelerator. The quantity P(λ) can be found from Table I with use of the values of A given in Table I.

TABLE I. Main parameters of some accelerators

Accelerator	Energy, GeV	λ_c, Å	$\frac{t}{T}$	Number of electrons: in the orbit	Number of electrons: accelerated per second	L, m	$N(E, R)$, erg/sec-A	A, erg/sec-cm-A
DESY	7.5	0.42	0.3	10^{11}	$5\cdot10^{12}$	40	31	$3\cdot10^{7}$
ARUS [27]	6.0	0.74	0.3	$5\cdot10^{10}$	$2.5\cdot10^{12}$	45	8.7	$7.5\cdot10^{6}$
FIAN [12]	0,68	35	0.1	$2\cdot10^{10}$	$4\cdot10^{9}$	5—10	$6.3\cdot10^{-3}$	$1.6\cdot10^{3}$
FIAN [13]	1.3	10	0.3	$2\cdot10^{11}$	10^{13}	30	0.073	$1.9\cdot10^{5}$
TPI [28]	1.2	14	0.03	$2.5\cdot10^{10}$	$5\cdot10^{10}$	10	0.036	$3.2\cdot10^{3}$
VÉPP-2 [27]	0.67	23	1	$2\cdot10^{11}$		2	0.025	$1.7\cdot10^{6}$
VÉPP-3 [27]	3.0	1.3	1	$3\cdot10^{11}$		5	7.5	$3.7\cdot10^{8}$

TABLE II. Spectral density of beams of vacuum ultraviolet in various accelerators

Accelerator	λ_c, Å	L, m	I, $\frac{\text{erg/cm-sec-A}}{\text{photon/cm-sec-A}}$, λ = 100 Å	I, $\frac{\text{erg/cm-sec-A}}{\text{photon/cm-sec-A}}$, λ = 1000 Å
DESY	0.42	40	$\frac{100}{5\cdot10^{11}}$	$\frac{0.5}{2.5\cdot10^{10}}$
ARUS	0.74	45	$\frac{60}{3\cdot10^{11}}$	$\frac{0.3}{1.5\cdot10^{10}}$
FIAN, 0.68 GeV	35	10	$\frac{1.6\cdot10^{2}}{0.8\cdot10^{12}}$	$\frac{0.75}{4\cdot10^{10}}$
FIAN, 1.3 GeV	10	30	$\frac{10^{4}}{5\cdot10^{13}}$	$\frac{40}{2\cdot10^{12}}$
TPI	14	10	$\frac{30}{1.5\cdot10^{11}}$	$\frac{0.1}{5\cdot10^{9}}$
VÉPP-2	23	2	$\frac{5\cdot10^{4}}{2.5\cdot10^{14}}$	$\frac{2\cdot10^{2}}{10^{13}}$
VÉPP-3	1.3	5	$\frac{1.4\cdot10^{5}}{7\cdot10^{14}}$	$\frac{6\cdot10^{2}}{3\cdot10^{13}}$

In Table II we have given the time-averaged spectral densities of the SR fluxes at a distance L from the orbit for values λ = 100 and 1000 Å.

It can be seen from Tables I and II that the ARUS accelerator at Erevan is very close in its parameters to the DESY accelerator. A number of studies[29] have already been carried out in the SR beam of this accelerator.

In its spectral intensities the operating FIAN accelerator in the spectral region 100—1000 Å (actually this statement is valid for the broader region 50—2500 Å) is equal to the DESY synchrotron and also permits an extensive program of use of the vacuum ultraviolet to be carried on. During recent years work of this type has been carried on at the 680-MeV synchrotron jointly by groups from FIAN and Moscow State University.[30] The vacuum monochromator, sample, and detecting apparatus are located in the accelerator room 5 m from the orbit. An important deficiency of the existing experimental arrangement is the absence of shielding around the experimental area. However, it should be noted that, as a result of the fact that the accelerator operates in a quasi-storage-ring mode (0.5 sec acceleration, 0.5 sec slow beam dump at constant energy), the problem of apparatus shielding is greatly simplified in comparison with other accelerators (the average intensity of the accelerated electron is hundreds of times smaller than in other accelerators). This fact permits local shielding to be avoided in a number of experiments.

Also of interest to experimenters is the proposed mode of operation of this accelerator at reduced energy (300 MeV) with an extended flat-top (up to 100 sec),[31] which is little different from the ordinary mode of operation of storage rings. In this mode the maximum intensity will be shifted from 15 Å to a wavelength of about

150 Å, the instantaneous intensity of radiation in the region 200—2500 Å will be practically unchanged, and the average intensity will rise substantially.

The 1.3-GeV accelerator (PAKHRA) being built at FIAN will have more favorable characteristics [13] than the operating 680-MeV accelerator. In addition to the standard acceleration mode, special modes of operation are planned, in particular, installation of a radiator and conversion of the accelerator to a storage mode, which will permit more intense beams of vacuum ultraviolet to be obtained and the region of possible use of this accelerator as a VU source to be further extended.

The operating accelerator of the TPI (Tomsk Polytechnic Institute) at Tomsk, [28] which has a lower intensity, is very similar in its remaining parameters to the PAKHRA synchrotron.

The VÉPP-2M and VÉPP-3 storage rings of the Nuclear Physics Institute, Siberian Division, Academy of Sciences, USSR, will be promising SR sources after the planned intensity values have been obtained in these machines. These accelerators will also be promising sources of x rays in the wavelength region near 1 Å where, in addition to accelerators, there are intense radiation sources—x-ray tubes producing narrow lines of characteristic radiation. It is difficult to compare accurately and in general form the intensities produced by an x-ray tube and a synchrotron; a great deal depends on the specific conditions under which the radiation is used.

In choosing a source of x rays, the experimenter must take into account the following circumstances:

1) A high-power tube with a copper anode (10 kW) can produce in an angle 1 msr (1 cm^2 at a distance of 30 cm from the anode) a flux of characteristic radiation 10^{10}—10^{11} photons/sec, or 10^2—10^3 erg/sec. For comparison we have shown in Table II the characteristics of the accelerators mentioned in this region of the spectrum. It should be kept in mind that at the exit of the monochromators, the need for which arises in work with SR, the intensity is reduced by several times.

2) Although the line width of the characteristic radiation is narrower than 10^{-3} Å, in experiments with SR, as a rule, it is possible to work with a much broader interval of wavelengths up to 0.1 Å.

3) In use of x-ray tubes for x-ray structural analysis of objects of small area (~ 10^{-2} mm^2), the experimenter is interested not in the total flux of radiation in this direction, but in the brightness of the part of the anode spot on which the collimator is adjusted. The experimenter frequently prefers to work with a less powerful tube which gives a greater brightness at the center of the spot. In working with tubes, it is possible to obtain at the collimator exit a beam divergence of several milliradians. The distances from the tube anode to the irradiated object are sometimes only a few centimeters.

The situation is different in working with accelerators. In this case a divergence several times smaller is obtained naturally, and the question of source brightness plays a role only in operation at extremely small distances (~2—3 m) from the accelerator orbit. To illustrate this statement we can consider the worst case: an accelerator with weak focusing, where the electron beam has large dimensions (for example, in the FIAN 680-MeV synchrotron the beam dimensions are 2×10 mm) and consequently the beam brightness is smaller than in accelerators or storage rings with strong focusing. From design considerations it is realistic to carry out an experiment at distances from the orbit point used of the order of or greater than the orbit radius. At these distances an object placed in the center of the beam beyond a collimator of not too great length with an angular aperture greater than 10 mrad will be illuminated by the entire beam circulating in the accelerator, and the angular divergence of the beam passing through the target will be no greater than a few milliradians.

It is evident from the foregoing that the additional advantage of strong-focusing accelerators and storage rings, which have a higher beam brightness as the result of the smaller transverse dimensions, can be realized only in rare cases and only if the work is carried out practically adjacent to the accelerator vacuum chamber. We note that, in working with SR from an accelerator or storage ring with strong focusing, it is necessary to remember that the angular distribution of the SR and (more important) the angular distribution of the polarization of this radiation can be strongly distorted by the betatron oscillations of the electrons in the beam.

It can be seen from Table III that accelerators of the DESY and ARUS type and the storage ring VÉPP-3 are serious competitors to an x-ray tube. However, if the 1.3-GeV accelerator is equipped with special magnets which increase the curvature of the electron trajectory in small portions of the orbit by a factor of ten, then it is possible in certain directions to increase the intensity substantially in this region of the spectrum, as shown in the fifth line of the table. An installation consisting of more complex systems of radiators with strong poles in which, as noted above, each "cusp" will operate independently, will permit still further increase of the intensity of radiation from this synchrotron.

There is no question but that for a number of problems these intensities may turn out to be insufficient. For solution of the problems of molecular biology in the coming years, x-ray sources with maximum intensity in the 10-keV region are obviously required. There is misgiving that even the accelerator VÉPP-3 and the storage ring DORIS, with energy 3 GeV and an intensity more than ten times that of the DESY accelerator beside which it is being built, will not satisfy the growing demands of biologists. For this reason it is interesting to consider the possibilities of use of still more intense sources of ultraviolet and x radiation, in particular special storage rings. [24] Godwin [19] and the Committee of the National Academy of Sciences (USA) [32] consider that construction of an accelerator or storage ring specially for spectroscopic purposes is difficult to justify economically. However, this opinion is in no way indisputable. [9]

TABLE III. Spectral density of x-ray beams in various accelerators

Accelerator	λ_m, Å	I, erg/cm-sec-A	
		$\lambda = 1$ Å	$\lambda = 2$ Å
DESY	0.18	$5 \cdot 10^6$	10^6
ARUS	0.3	$2.5 \cdot 10^6$	10^5
FIAN, 0.68 GeV	15	0	0
FIAN, 1.3 GeV	4	$7 \cdot 10^4$	$1.5 \cdot 10^5$
FIAN' 1.3 GeV, with special magnets	0.5	10^7	10^6
TPI	5.8	10^3	$2 \cdot 10^3$
VÉPP-2	10	$4 \cdot 10^3$	$6 \cdot 10^5$
VÉPP-3	0.5	$3 \cdot 10^8$	10^8

In the review we have discussed mainly operating Soviet accelerators and storage rings. It is apparent that synchrotron radiation, which at one time was the cause of so much trouble to the builders of these installations,[11] can be used effectively as a research instrument in adjacent fields of science.

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