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Experiments on the generation of long wavelength edge radiation along directions nearly coincident with the axis of a straight section of the ”Pakhra” synchrotron

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Abstract

Generation of long wavelength edge radiation along directions nearly coincident with the axes of straight sections of storage rings and synchrotrons is discussed. The removal of destructive interference from the superimposed edge radiation patterns of a straight section on the synchrotron ”Pakhra” has been observed experimentally.

1 Introduction

The concept of long wavelength radiation was introduced in classical electrodynamics for the case of a particle emitting radiation in external fields. The spectral-angular distribution of the long wavelength electromagnetic energy emitted by the particle doesn't tend to zero when the frequency of the emitted radiation tends to zero [1, 2]. The electromagnetic wave components of long wavelength radiation have mainly one sign. The Fourier transform of their electric field strength $\vec{E}_\omega|_{\omega=0} \neq 0$ [3] - [6].

The object of this paper is to discuss the problem of generation of radiation with properties near to the long wavelength radiation by a particle or particle beams in external electromagnetic fields of synchrotrons and storage rings. Some experimental results carried out in the beginning of 1980 will be presented.

2 Selected questions of the classical electrodynamics

The electric and magnetic field strengths of a non-uniformly moving charged particle are determined by

$$\vec{E}(t) = \vec{E}^c(t) + \vec{E}^r(t), \qquad \vec{H} = [\vec{n}\vec{E}], \tag{1}$$

where

$$\vec{E}^c(t) = \frac{e(1-\beta^2)(\vec{n}-\vec{\beta})}{R^2(1-\vec{n}\vec{\beta})^3}|_{t'}, \qquad \vec{E}^r(t) = \frac{e[\vec{n}[(\vec{n}-\vec{\beta})\dot{\vec{\beta}}]]}{cR(1-\vec{n}\vec{\beta})^3}|_{t'},$$

e, c$\vec{\beta}$ and c$\dot{\vec{\beta}}$ are the charge, velocity, and acceleration of the particle; $\vec{n}$, the unit vector directed from a particle to the observation point, and R, the distance from the particle to the observation point [1],[2]. The values $\vec{\beta}$, $\dot{\vec{\beta}}$, $\vec{n}$ and R are to be evaluated at an earlier (retarded) moment $t^{'} = t - R(t^{'})/c$. The terms $\vec{E}^c(t)$, $\vec{H}^c(t)$ in Eq1 describe the sharply decreasing ($\sim 1/R^2$) Coulomb field of the particle, while $\vec{E}^r(t)$ and $\vec{H}^r(t)$ are for the free electromagnetic field radiated by the particle ($\sim 1/R$).

Usually the observation point is assumed to be far away from the region of particle acceleration, the unit vector $\vec{n}$ is sensibly constant in time [1, 2]. The region of particle acceleration and emission is assumed to have finite dimensions, and the radiation is observed from distances much larger than dimensions of the emission region (in the far-zone or wave zone). The particle emits radiation within a finite time interval determined by initial and final moments t_i, t_f of particle acceleration. The energy of the emitted radiation is finite.

The properties of the emitted radiation are defined by the Fourier transform $\vec{E}^r_\omega$ of the electric field strength vector $\vec{E}^r(t)$ of the form

$$\vec{E}^r_\omega = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \vec{E}^r(t)e^{i\omega t}dt. \tag{2}$$

For instance, the spectral-angular distribution of the energy radiated by a particle into the solid angle $do = dS/R_o^2$ or onto the area dS at the observation point is determined by

$$\frac{\partial^2\varepsilon}{\partial\omega\partial o} = R_o^2\frac{\partial^2\varepsilon}{\partial\omega\partial S} = cR_o^2|\vec{E}^r_\omega|^2. \tag{3}$$

According to Eq2 the properties of the emitted radiation are determined by the total trajectory of the particle where the particle acceleration differs from zero. This assertion is in accordance with the Fourier transform of Eq2 for the time interval $(-\infty, +\infty)$ or for the real case (t_i, t_f) [6].

Notice that the Coulomb fields have longitudinal component and $|\vec{H}^c| \neq |\vec{E}^c|$ ($|\vec{H}^r| = |\vec{E}^r|$). These are the reasons why the Fourier transform of the Coulomb and total electric and magnetic fields in near zone could not be introduced and interpreted in a simple way. Only in the ultrarelativistic case, where $|\vec{H}^c| \to |\vec{E}^c|$, the Fourier transform of the Coulomb field is interpreted as the superposition of the equivalent elementary waves corresponding to virtual quanta in the Weizsacker-Williams method. But this is the approximate method used only for the case of homogeneously moving particles in empty space. It describes well the bremsstrahlung radiation of electrons in the fields of relativistic ions [2]. In other cases the accuracy of this method is not high. For example, when the relativistic particle crosses a plane mirror it emits the transition radiation. We can say that in this case the properties of the transition radiation are defined by the properties of equivalent photons "reflected" from the mirror. However, the properties of the transition radiation are calculated precisely and they differ from those calculated by the method of equivalent photons. For instance, in the case of a perfect mirror the transition radiation fields are included in the spherical layer of the thickness $d \to 0$ (the layer contains the emitted radiation of wavelengths $\lambda \gg d$). They are emitted from one point or from a very small region [2] (equivalent photons would be reflected by the total surface of the mirror), and have a similar spectrum [7].

In some cases, the total fields (distorted Coulomb and radiation fields) of a particle must be taken into account, e.g. a distortion of scattered particles fields can change the ionizing properties of the particles [3]. At the same time, the inclusion of the Coulomb fields in the Fourier transform in some papers [8], [9], [10] is not motivated and does not change essentially properties of the emitted radiation [11]. Of course, the account of retarded Coulomb near-fields of high current beams in the storage rings [12], [13], [14], [15] and in undulators of free-electron lasers [6], [16] is necessary to obtain the correct particle trajectories and to calculate the total losses of the particle energy through coherent radiation [6].

The Fourier transform of the electric field strength at zero frequency can be presented in the form $\vec{E}^r_\omega|_{\omega=0} = (1/2\pi)\vec{I}^r$, where $\vec{I}^r = \int_{-\infty}^{+\infty}\vec{E}^r(t)dt$ is the strange parameter of the wave. Waves with this parameter $\vec{I}^r \neq 0$ were named strange waves. Strange waves have components of the electric field strength mainly of one sign. In particular, single-sign waves are the strange waves [3].

Strange waves transfer to a charged particle a momentum in the direction transverse to the wave propagation. This property of strange waves contradicts to the common opinion that light pressure is directed only in the direction of light propagation. The question appears:"Do the strange waves exist? Is it possible to generate them?" The answer is not trivial.

When they say the word "radiation" it usually means free electromagnetic waves described by a homogeneous wave equation. The solution of this equation can be the arbitrary function of argument ($\vec{n}\vec{R} - ct$) [1, 2]. The word "arbitrary" means that single-sign waves (strange waves) satisfy the homogeneous wave equation in particular case. However, the existence of such solutions is a necessary but not a sufficient condition for the existence of strange waves. What is the sufficient condition? To answer the question we must solve the nonhomogeneous wave equation.

In the case of one particle the solution of the nonhomogeneous wave equation is described by the Lienard-Wiechert fields of Eq1. Integration of the electric field strength $\vec{E}^r(t)$ determined by Eq1 leads to the strange parameter of the free field emitted by the particle

$$\vec{I}^r = \frac{e}{cR_o}[\vec{n}[\vec{n}(\frac{\vec{\beta}_2}{1-\vec{n}\vec{\beta}_2} - \frac{\vec{\beta}_1}{1-\vec{n}\vec{\beta}_1})]], \tag{4}$$

where subscripts $1, 2$ relate to initial and final electron velocities [3].

According to the Eq4 strange waves can be emitted only in the case when the initial and/or final velocities of the particle are not equal to zero and hence the particle trajectories are not limited. Unacceptable conditions for particle trajectories exist for laboratory sources of strange waves as according to these conditions the dimensions of such sources must be infinitely large. It is possible to emit strange waves in cosmos but impossible to emit them in installations of finite dimensions similar to lasers or synchrotron radiation sources [3].

3 On the laboratory sources of the long wavelength radiation based on the storage rings and accelerators

At present the high brilliance and high intensity broadband sources of both incoherent and coherent infrared radiation are absent. The long wavelength part of the synchrotron and edge radiation [3] - [6] emitted in the infrared region by particle beams in storage rings is increasingly used in different fields of science as an alternative for laboratory sources such as a mercury lamp or glowbar [17], [10]. Broadband free-electron lasers of the coherent infrared radiation are developing [18], [19], [20].

The efficiency of emission of the synchrotron radiation in the long wavelength region in storage rings and synchrotrons is increased when the value of the magnetic field strength of their bending magnets is decreased. Usually the value of the magnetic field strength of bending magnets of storage rings is high. That is why we can use special bending magnets installed in the straight sections of storage rings. The value of their magnetic field strengths have an optimum defined by the equation $e\int Hdl \simeq 2mc^2$ corresponding to the bending angle of the particle in this magnets $\simeq 2/\gamma$, where the value $2mc^2/e \simeq 3\cdot 10^3$ Gs·cm and γ is the relativistic factor of the particle. First experiments confirmed this statement [21]. The radiation from special bending magnets in such cases interferes with the edge radiation. As it turned out, at optimal conditions of generation the magnetic field introduced in the straight section must be directed opposite to the guiding magnetic field of the storage ring. In the general case, the system of bending magnets installed in the straight sections of the storage rings can produce both linear and circular polarized broadband radiation in the long wavelength region [4].

In the case of pure edge radiation (special bending magnets in the straight section of the storage ring are absent) the components of the electric field strength of each of the two wavepackets emitted in the edge fields of the storage ring at the angle $\sim 1/\gamma$ to the direction of the axis of the storage ring have mainly one sign. But signs of wavepacket components are opposite. It means that every of the wavepackets represents the strange wave radiation. Its spectrum does not tend to zero when $\omega \to 0$. However the sum of the wavepackets is not the strange radiation because of the destructive interference. The lengths of the wavepackets in this case are much less than the distance between them. The picture of the process in space is similar to the case of an instant start and instant finish of a particle at the edges of the storage ring. The edge radiation can be named "conventionally strange" or "quasiundulator" radiation [4] - [6][1].

The spectral-angular distribution of the edge radiation emitted in the long wavelength region $\lambda > d/2\gamma^2$ and under the condition when the observation point is localized at infinity (condition when we can neglect the difference between distances from edges of the synchrotron to the observation point) can be presented in the form

$$\frac{\partial^2\varepsilon}{\partial\omega\partial o} = \frac{4e^2}{\pi^2 c}\frac{\vartheta^2}{(1+\vartheta^2)^2}\sin^2\frac{\omega}{\omega_l}, \tag{5}$$

where l_{eff} is the effective length of the straight section of the storage ring, $l - l_{eff}|_{H\gg H_d} \simeq 2d\ln(H/H_d)$; l, the geometrical length of the straight section, d, the gap of the bending magnet of the storage ring, H, the value of the magnetic field of the bending magnet of the storage ring, $H_d = mc^2/ed$; m, the electron mass, $\vartheta = \gamma\theta$, $\omega_l = 4\gamma^2 c/l_{eff}(1+\vartheta^2)$, and θ, the angle between the axis of the straight section and the direction from the synchrotron edge to the observation point localized at infinity. The effective length l_{eff} and the frequency ω_l depend slightly on energy [4].

Spectrum of the edge radiation is shifted to the long wavelength region. In this case the spectral-angular distribution of the radiation emitted at $\theta \sim 1/\gamma$ is higher than that of the synchrotron radiation

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[1] When the difference between the distances from the edges to the observation points are of the order of the effective length of the straight section of the storage ring then the strange parameter $I^r = |\vec{I}^r| \neq 0$ if we neglect boundary conditions. However the windows of synchrotrons and mirrors of finite dimensions do not permit to transfer this radiation to the observation point [3].

(for the same synchrotron) [7].

According to Eq5 the main part of the edge radiation energy is emitted throughout the angles $\vartheta \sim 1$. At frequencies $\omega > \omega_l$ the spectrum oscillates with the period ω_l and at frequencies $\omega < \omega_l$ it tends to zero when the frequency tends to zero, which indicates that the wavepackets have opposite signs. This is the so-called destructive interference of the wavepackets of the opposite signs first discussed in the case of transition radiation[2][22].

4 Experimental arrangement

The experiments on generation of the long wavelength edge radiation were done on the weak-focusing race-track electron synchrotron "Pakhra". The maximum energy of the synchrotron $\varepsilon_{max} = 1200MeV$, the radius of the orbit of electrons in the bending magnets of the synchrotron $r = 4m$, the geometric length of a straight section of the synchrotron $l = 1.9m$. The frequency of the guiding magnetic field of the synchrotron $\Omega/2\pi = 50$ Hz.

The experimental setup of the "Pakhra" synchrotron used in the recent experiment [23], [24] is similar to that presented in [25]. The scheme of the experiment is shown in Fig.1, where l, l_{eff}, the geometrical and effective lengths of the synchrotron straight section, R_1 and R_2 the distances from edges of the synchrotron straight section to the observation point, θ_1, θ_2 the angles between the directions of the axis of the synchrotron straight section and vectors directed from edges of storage rings to the observation point.

The energy of electrons in the synchrotron was changed by the law $\varepsilon_e = \varepsilon_= + \varepsilon_\sim \cos(\Omega t)$, where the constant and alternating components of the energy $\varepsilon_= \simeq \varepsilon_\sim$. The electron energy changed from minimal $\varepsilon_{min} = \varepsilon_= - \varepsilon_\sim$ to a maximal $\varepsilon_{max} = \varepsilon_= + \varepsilon_\sim$. The maximal energy of the electrons in this experiment was chosen 850 MeV ($\gamma \simeq 1700$).

The scheme of selection of the wavepacket emitted from one edge of the synchrotron by a lens having the focusing distance f and located at the distance L from the right edge is shown in Fig.2. In two of produced experiments, $l_{eff} \simeq 1.25$ m and $L = 1.875$ m. The lens was installed at the window of the synchrotron, photographic plate in the first experiment and photomultiplier in the second were installed at distance $\Delta R = 1.5$ m from the lens. Filters at the wavelengths $\lambda = 8400\AA$ and $\lambda = 3850\AA$ and lenses with focusing distances $f = 1$ m and $f = 1.85$ m were used in the first and the second experiments.

The observation point in our experiments was localized at the distances $R_1 = 4.625$ m and $R_2 = 3.375$ m. The difference $R_1 - R_2 = l_{eff} = 1.25$ m was about 3 times less than R_1 and R_2 and could therefor be neglected in the experiments without the lens. In fact it could be taken into account by introducing in Eq4 unit vectors $\vec{n}_1$ $\vec{n}_2$ and distances R_1, R_2 corresponding to the edges of the bending magnets of the synchrotron [3]. The effect of using of the lens is the higher the higher the difference between R_1, R_2 and l_{eff}.

5 Discussion

According to Eq4, the condition $\beta_1 = \beta_2 = 0$ for the electron trajectories in the synchrotron, and the definition presented in the Introduction, the radiation emitted in the synchrotron is not the long wavelength one. The radiation emitted from the central part of the bending magnet of the synchrotron in the direction near to the direction of the electron velocity is a usual synchrotron radiation. In the direction of the corresponding observation point this radiation is emitted mainly from the part of the trajectory of the length $\sim l_c = 2R/\gamma$. The edge radiation is emitted from the adjoining edge regions of fringing fields of bending magnets. In this case the components of the electric field strength of the electromagnetic waves emitted in the directions defined by the angles $\theta \sim 1/\gamma$ are the two short ($l_s \ll l_{eff}/\gamma^2$) single-sign wavepackets separated by the distance $\sim l_{eff}/\gamma^2$. Spectrum of the edge radiation determined by Eq5 is shifted to the long wavelength region, as compared to synchrotron radiation spectrum.

If we could select the radiation emitted in one bending magnet from the radiation emitted in another one then we could shift the emitted radiation in a longer wavelength region. And this is not the question of the strange waves generation but the question of the spectrum shift[3].

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[2] The transition radiation emitted in the case of unlimited perfect plane mirror is the strange wave radiation.

[3] To reflect strange waves we need in perfect plane mirror of infinitely large dimensions. The mirror of finite dimensions can reflect radiation up to the wavelength $\lambda \sim a$ where a is the dimensions of the mirror. The window permit to transfer the

In the first experiment the lens was not installed. No interference fringes were observed at a photographic plate similar to those observed in [22, 26] since the picture was averaged over time (energy). When the lens was installed then the radiation emitted from the left edge was focused onto a small area at the left side of the picture. The picture of the radiation focused by the lens is presented in Fig.3. Similar picture was observed at the distance $\Delta R = 2.3$ m from the lens where the radiation emitted from the right edge of the synchrotron was focused onto a small area. So the radiation emitted in the region of one edge of the synchrotron can be focused and hence selected by diaphragms from the radiation emitted in the region of another edge. We did not observe any contribution of radiation emitted from central part of the straight section of the storage ring and defined by the Coulomb term of Eq1.

In the second experiment, the time dependence of the intensity of the emitted radiation was measured by a photomultiplier and recorded by the oscillograph. This dependence is shown in Figs. 4 and 5.

The signal of Fig.4 corresponds to the case where the radiation is not focused by lens. In accordance with the theory (see Eq5) the interference of the wavepackets emitted from edge regions of the synchrotron leads to the energy dependence of the frequency ω_l and intensity of the emitted radiation on energy and, hence, time. This observation is confirmed by Fig.4. The signal measured by the photomultiplier and recorded by the oscillograph oscillates in time.

In Fig.5, the signal is caused by the radiation which is focused by a lens. We can see again that the lens destroys the interference and selects the radiation emitted from the region of one edge of the synchrotron.

Selection of the radiation emitted in one edge of the bending magnet of the synchrotron permits one to hope that the radiation emitted at the angles $\theta \sim 1/\gamma$ to the axis of the synchrotron will be shifted to the longer wavelength region.

It is impossible to focus the radiation at all frequencies by a glass or silicon lens. Metal concave mirror can be used in optical, IR and submillimeter regions. Dimensions of windows of synchrotrons and storage rings and dimensions of mirrors restrict the spectrum from the long wavelength region.

6 Conclusion

For the first time, to our knowledge, the removal of the destructive interference in the edge radiation has been demonstrated here experimentally. We can hope that the spectrum of the radiation emitted in the angular region $\theta \sim 1/\gamma$ to the axis of the straight section of the synchrotron was shifted to the more longer wavelength region. This conclusion must be verified.

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radiation shorter then the diameter of the window [3].

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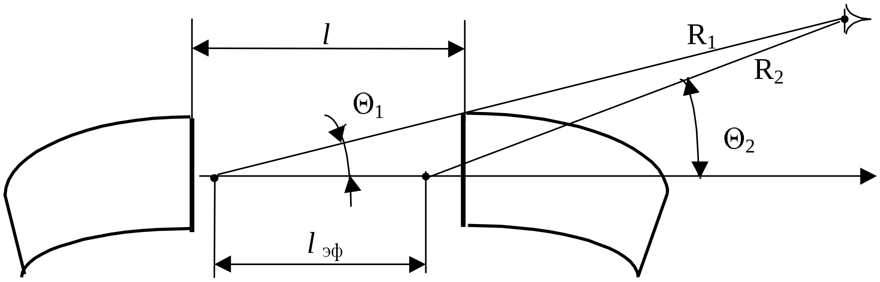

Figure 1: The scheme of the experimental setup.

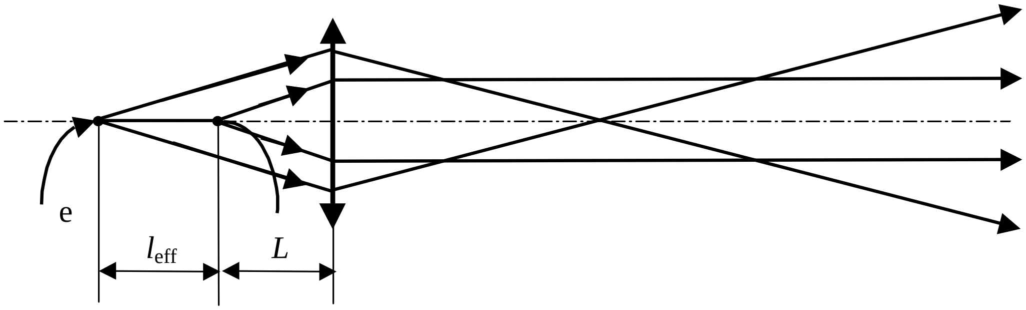

Figure 2: The scheme of selection of the wavepackets emitted from the right edge of the synchrotron.

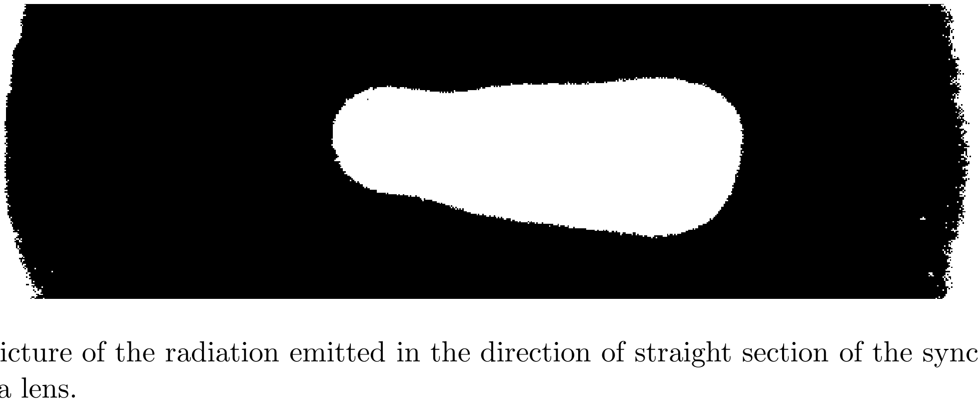

Figure 3: The picture of the radiation emitted in the direction of straight section of the synchrotron and focused by a lens.

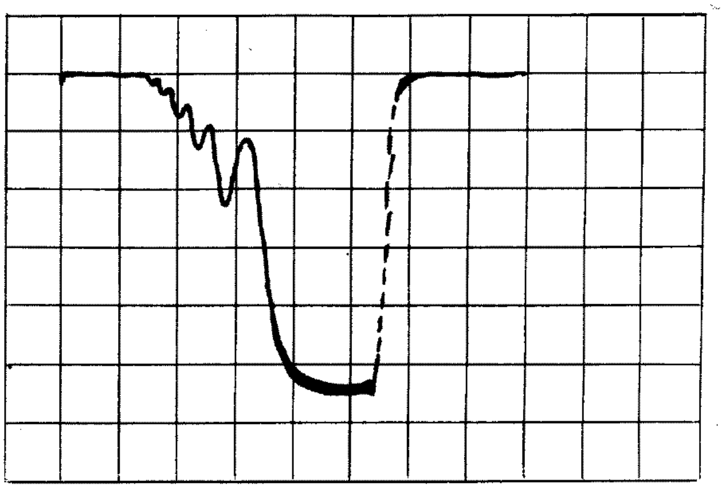

Figure 4: Time dependence of the intensity of light emitted in the direction of the axis of straight section of the synchrotron. Focusing lens is absent.

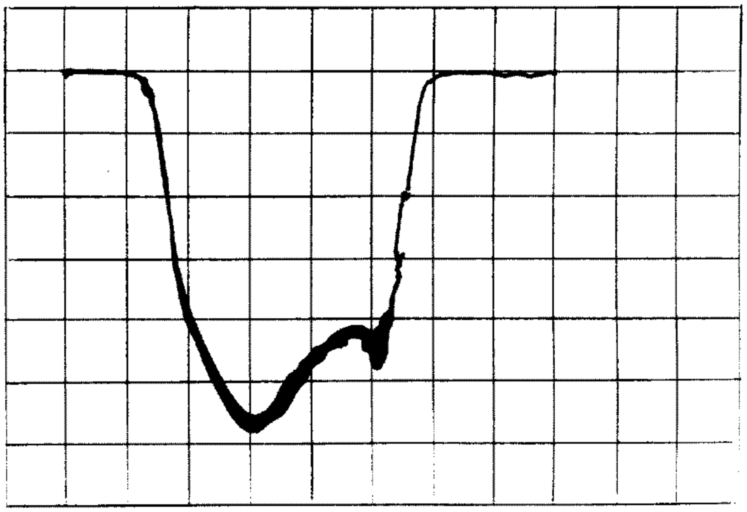

Figure 5: Time dependence of the intensity of light emitted in the direction of the axis of straight section of the synchrotron. Focusing lens is installed.