Eksperimenty po nakopleniyu elektronov v sinkhrotrone (Experiments on the Storage of Electrons in a Synchrotron) by Yu. M. Ado et al. Akademiya nauk SSSR, Fizicheskiy institut imeni P.M. Lebedeva, Laboratoriya fotomezonnykh protsessov. Moscow 1964. 9 pages. Translated from the Russian (November 1964) by T. Watt.

****
****
****

EXPERIMENTS ON THE STORAGE OF ELECTRONS IN A SYNCHROTRON

by Yu. M. Ado, Ye. G. Bessonov and P.A. Cherenkov

An experimental study of the possibility of the storage of electrons in a synchrotron by the method suggested earlier by one of us[2] has been reported[1]. In the present paper, we give the results of an experimental investigation of the effect of various factors on the lifetime of the particles. The experiments were performed on the 280 Mev synchrotron of the Physics Institute of the Academy of Sciences USSR[3]. A description of the apparatus and of the experimental technique may be found in the earlier paper[1].

The number of particles in orbit was determined by measuring the intensity of synchrotron radiation and was recorded on a loop oscillograph. An oscillogram illustrating the storage process is shown in Figure 1. The rising part of the oscillogram corresponds

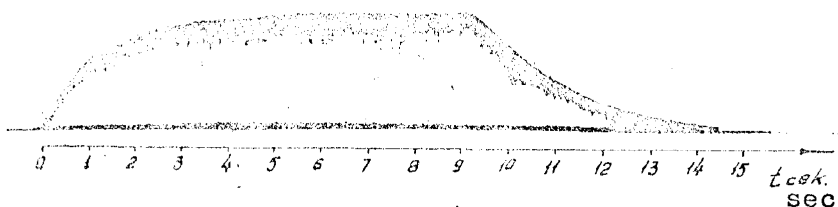

Figure 1: Oscillogram of the particle storage process

to the storage process, whilst the descending part characterizes the lifetime of the particles (microtron switched off). The lifetime of the particles was defined as the quantity τ for which $\exp(-t/\tau)$ fitted the envelope of the descending part of the oscillogram. The lifetime τ was obtained as a function of the amplitude of the high-frequency voltage V, the working pressure P, the energy of the particles, and the depth of the amplitude modulation of the high-frequency accelerating voltage, $\Delta V/V$ (cf. references 1 and 2). The lifetime τ is given in the graphs below in units of the periods of the alternating component of the guiding magnetic field or in seconds.

During the storage process, the particle energy varies in accordance with the expression

$$E = E_{=} + E_{o} \cos 2\pi \frac{t}{T}. \quad (1)$$

The particles are periodically accelerated to a maximum energy $E_{max} = E_{=} + E_{o}$, and are then decelerated to the minimum energy $E_{min} = E_{=} - E_{o}$. The frequency of the alternating component of the energy was $1/T = 50$ c/s.

a) The dependence of τ on V. This was determined with $E_{min} = 7.5$ Mev, $E_{max} = 180$ Mev, $\Delta V/V = 0.2$, $P \approx 3 \times 10^{-6}$ torr. V was varied between 1.5 and 1.0 kv. The results are shown in Figure 2.

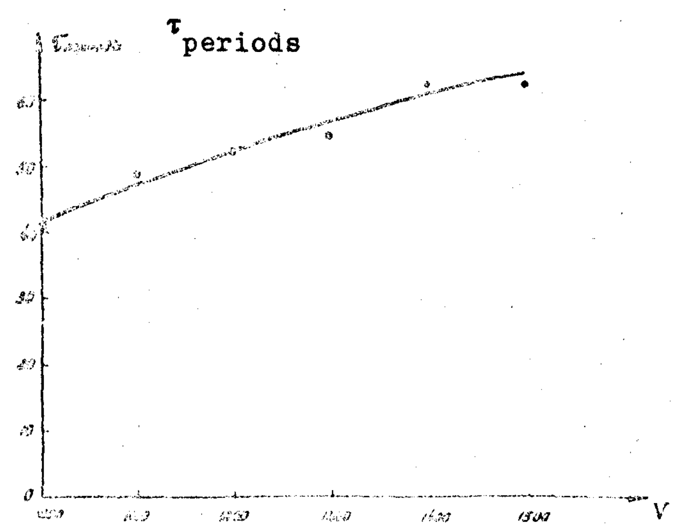

Figure 2:

Dependence of τ on the accelerating voltage V

Рис. 2

b) <u>The dependence of τ on the working pressure</u> was obtained with E_{min} = 7.5 Mev, E_{max} = 180 Mev, V = 1.5 kv, $\Delta V/V$ = 0.2. The vacuum chamber was pumped by two sets of pumps at diametrically opposite points. The change in pressure was achieved by cutting off one of the pumps. It was found that when the pressure was changed by a factor of 2, the lifetime τ changed by a similar factor.

c) <u>The dependence of τ on the particle energy.</u> These measurements were carried out with $E_{=}$ = 94 Mev, V = 1.5 kv, $\Delta V/V$ = 0.2, and $P \approx 3 \times 10^{-6}$ torr. The particle energy was varied by varying the amplitude E_o of the alternating component. Storage of the particles was carried out with E_{min} = 7.5 Mev. E_o was rapidly reduced to a value E_o' (cf. Figure 3) after the limiting number of particles had been reached, and injection of the particles was stopped. The lifetime of the particles was measured after E_o' was reached. The points in Figure 4 show the measured values of τ for different E_o' (or, what amounts to the same thing, different E_{min}). The calculated values of τ exceed the experimental values. This appears to be related to errors in the measured working pressure.

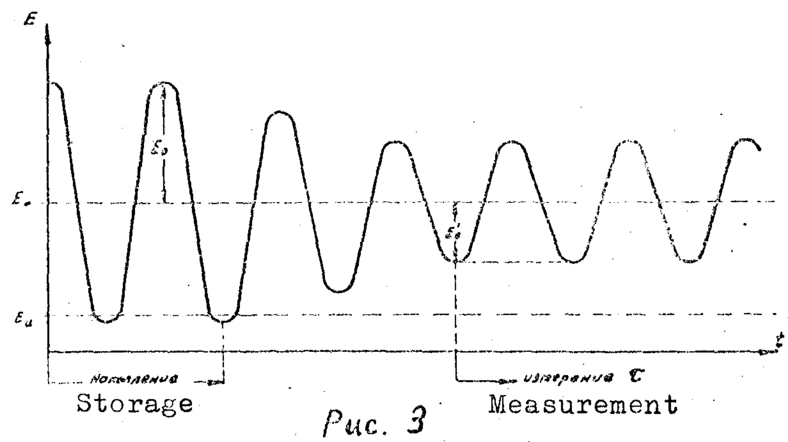

Figure 3: Measurement of τ as a function of the amplitude of the alternating component E_0' of the particle energy.

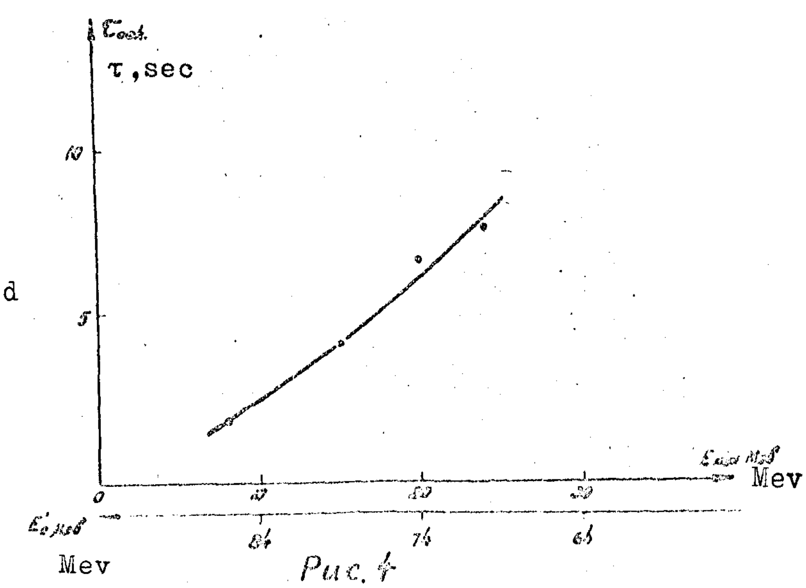

Figure 4:

Dependence of τ on the amplitude of the alternating component of the particle energy E_0'. The solid curve was calculated from equation (2) and is normalized to the experimental value of τ at $E_0' = 86$ Mev.

d) <u>The dependence of τ on $\Delta V/V$</u>. This was obtained with $E_{min} = 7.5$ Mev, $E_{max} = 180$ Mev, $P \approx 3 \times 10^{-6}$ torr, $V = 1.5$ kv. $\Delta V/V$ was varied between 0 and 0.6. The results are shown in Figure 5.

Figure 5:

Particle lifetime τ as a function of the depth of modulation of the alternating voltage $\Delta V/V$.

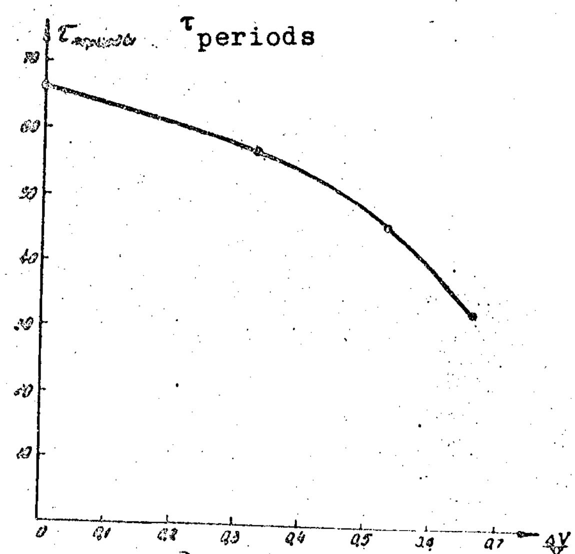

Рис. 5

A determination was also made of the number of stored electrons, N, from the intensity of the synchrotron radiation after the particle recording system had been calibrated. It was found that $N \approx 5 \times 10^{8}$ under the following working conditions: $\tau = 1.7$ sec, cyclotron current per pulse ~ 8 ma, $\Delta V/V = 0.2$, the rate of increase of the guiding magnetic field at the instant of injection 3×10^{5} oe/sec.

As in the earlier paper[1], an 0.2 mm tantalum scatterer was used instead of an inflector.

The mechanism responsible for particle loss in a storage system with an alternating guiding field exhibits the following characteristic feature. The disturbed particles are not lost immediately but only as a result of an adiabatic increase in the amplitude of the oscillations as the energy decreases.

Single processes affecting τ include Coulomb scattering and bremsstrahlung produced as a result of scattering on residual gas atoms. It may be shown that the partial lifetime determined by Coulomb scattering in the storage system with alternating energy is given by

$$\tau_p = \frac{\theta_g^2 \gamma_{min} / 2\gamma_o \gamma_{min} + \gamma^2_{min}}{4\pi r^2_e Z^2 N_o c} , \quad \left(\gamma = \frac{E}{mc^2}\right) \qquad (2)$$

where $r_e = e^2/mc^2$ is the classical radius of the electron, $Z = 7.2$ for air, and the number of atoms of the residual gas per unit volume is $N_o = 7.12 \times 10^{16}$ P, where P is in torr. For a vacuum chamber having an elliptical cross-section with semi-axes

r_k and Z_k, the permissible angle of scattering θ_g at minimum energy is given by

$$\frac{1}{\theta_g^2} = \frac{1}{8\pi^2}\left(\frac{\lambda_r^2}{r_k^2} + \frac{\lambda_z^2}{z_k^2}\right), \tag{3}$$

where λ_r and λ_z are the wavelengths of radial and axial free oscillations of the particles.

The partial lifetime for the bremsstrahlung process is practically independent of the particle energy and is given by[5]

$$\tau_B \simeq \frac{1,92 \cdot 10^{13}}{N_0}. \tag{4}$$

Multiple processes such as quantum fluctuations of synchrotron emission and multiple scattering on atoms of the residual gas are also found to lead to particle losses. Since the dimensions of the separatrix are always much smaller than the dimensions of the transverse cross-section of the vacuum chamber, it follows that particle losses are determined by the excitation of phase oscillations and this is governed by the effect of quantum fluctuations[5]. Particle losses may be described qualitatively as follows. Consider the trajectory on the phase plane which coincides with the separatrix as the energy of the particles decreases to E_{min}. When $E > E_{min}$, this phase trajectory will penetrate well into the stable region. All particles which, under the action of quantum fluctuations, will leave this phase trajectory will be lost when the energy is subsequently reduced to E_{min}. Quantum fluctuations in this system will have a more important effect than in a storage system with a constant magnetic field.

In order to find the expression for the particle loss probability in our case, we must solve the Einstein-Fokker equation[6] for the particle distribution function U in the case of an alternating guiding magnetic field:

$$\frac{\partial U}{\partial t} = \frac{d\bar{u}}{dt}\,\frac{\partial}{\partial u}\left[u\,\frac{\partial U}{\partial u} + \varkappa^2(t)\,u\,U\right], \tag{5}$$

where u is the square of the true amplitude of the oscillations;

and

$$\frac{d\bar{u}}{dt} = \frac{55\pi}{12\sqrt{3}}\,\frac{c e \Lambda}{(1-n) R^4 V \sin\varphi_s}\,\gamma^6; \quad \varkappa^2(t) = -\frac{\frac{d \ln D^2}{dt}}{\frac{d\bar{u}}{dt}};$$

$$D^2 = e^{-2\int \zeta dt}\left(\gamma V \sin\varphi_s\right)^{-0.5}$$

describes the adiabatic change in the amplitudes of phase oscillations and radiative damping with decrement ζ.

If u vanishes at ∞, the solution of (5) is

$$U(u,t) = \frac{1}{\rho^2(t)} e^{-\frac{u}{\rho^2(t)}}, \tag{6}$$

where $\rho^2(t)$ is the solution of

$$\frac{d\rho^2}{dt} = \frac{d\bar{u}}{dt} + \rho^2 \frac{d\ln D^2}{dt}. \tag{7}$$

For steady-state beam dimensions, $\rho(t+T) = \rho(t)$ and the periodic solution of (7) is of the form

$$\rho^2(t) = \frac{D^2(t)\,D^2(t+T)}{D^2(t) - D^2(t+T)} \int_t^{t+T} D^{-2}(t') \frac{d\bar{u}}{dt'} dt'.$$

We shall determine the particle losses in each period of the magnetic field by integrating the distribution (6) between u_{adm} and ∞. The particle lifetime due to the excitation of phase oscillations by quantum fluctuations of radiation will be given by

$$\tau_{quant} = Te^{u_{adm}/\rho^2} = Te^{\alpha V}$$

since $\rho^{-2} \sim V$ (because $d\bar{u}/dt \sim 1/V$). The factor α is a slowly varying function of V. The ratio u_{adm}/ρ^2 must be taken for $E \gg E_{min}$ in which case the distribution (6) fits into the region of linear phase oscillations. ρ^2 is calculated from (8) and u_{adm}

is determined by the method of adiabatic invariants using the value of u_{adm} for $E \sim E_{min}$.

Let us compare the partial lifetimes τ_p, τ_B and τ_{quant} for the selected working conditions, as specified under points (a), (b), (c) and (d) above. The orbit radius of the synchrontron was R = 81 cm, the free region of the vacuum chamber was $r_k \times Z_k \approx 4 \times 4$ cm, and $n = 0.6$. It is easy to show from equations (2) and (4) that in this case $\tau_B/\tau_p = 23$, i.e. bremsstrahlung has a much smaller effect on the lifetime than Coulomb scattering. Quantum fluctuations associated with synchrontron emission have an appreciable effect on the lifetime. This can readily be seen from Figures 2 and 5 (τ is a function of V and $\Delta V/V$). It is difficult to determine τ_p and τ_{quant} from equations (2) and (9), since the quantities p, V, E_o, and $E_=$ are not accurately known. The contribution of quantum fluctuations and Coulomb scattering to particle losses can be estimated from the experimentally determined dependence of τ on V. It follows from Figure 2 that when V = 1 kv, $\tau_1 = 0.8$ sec, whereas for V = 1.5 kv, $\tau_2 = 1.2$ sec. Using the difference $1/\tau_1 - 1/\tau_2$, we find from equation (9) that $\alpha = 4.8$. Substituting this value of α into (9), we obtain $\tau_{quant.1} = 2.4$ sec (V = 1 kv), $\tau_{quant.2} = 26$ sec (V = 1.5 kv). From the condition

$$1/\tau_{1,2} = 1/\tau_p + 1/\tau_{quant.1,2}$$

we find that $\tau_p \simeq 1.2$ sec. It may therefore be considered that when V = 1.5 kv, the lifetime τ is entirely determined by Coulomb scattering. This is also indicated by experiment (b) above, and the agreement between the experimental dependence of τ on the energy of the particles and the theoretical formula given by (2) (cf. Figure 4). We can only conclude, without discussing in detail the dependence of τ on $\Delta V/V$, that the introduction of amplitude modulation has a small effect on τ.

We note in conclusion that a reduction in the working pressure leads to an increase in the importance of quantum fluctuations. This can however be avoided by increasing V. For example, according to (9), τ_{quant} turns out to be of the order of a few hours for $\alpha = 4.8$ and V = 2.5 - 3 kv.

R e f e r e n c e s

1. Yu. M. Ado, K.A. Belovintsev, A. Ya. Belyak, Ye. G. Bessonov, O.B. Dem'yanovskiy, V.A. Skorik, P.A. Cherenkov and V.S. Shirchenko, Nakopleniye chastits v sinkhrotrone (Storage of particles in a synchrotron) (paper read to the International Conference on Charged-particle Accelerators), Dubna, 1963 (in press).

2. Yu. M. Ado, AE, 12 (I), 54 (1962).

3. A. Ya. Belyak, V.I. Veksler, V.N. Kanunnikov, P.A. Cherenkov and B.N. Yablokov, Osobennosti sinkhrotrona na 280 Mev FIAN SSSR, (280 Mev Synchrotron of the Physics Institute of the Academy of Sciences USSR), in Uskoriteli elementarnykh chastits (Charged-particle accelerators), collection of papers, Atomizdat Moscow, 1957.

4. K.A. Belovintsev, A. Ya. Belyak, A.M. Gromov, Ye. M. Morov and P.A. Cherenkov, AE, 14, (4), 359 (1963).

5. A.I. Alikhanyan, S.A. Kheyfets and S.K. Yesin, UFN, XXXI (I), 7, (1963).

6. A.A. Kolomenskiy and A.N. Lebedev, Teoriya tsiklicheskikh uskoriteley (Theory of cyclic accelerators), GIFML, 1962.

Received April 24, 1964.