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Abstract

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Experimental Investigation of Electron Oscillations in Cyclic Accelerators

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Electron accelerators have in recent years acquired very great importance in the physics of the atomic nucleus and elementary particles. Among high-energy electron accelerators, special attention is given to cyclic accelerators. In connection with the development of electron accelerators with energies above 1 Bev, the problem arises of electron oscillations in accelerators, which, at a sufficiently large amplitude, can make operation of the accelerator impossible. The possibility of quantum excitation of oscillations was first indicated in paper (^{1}), and that of radiation damping—in paper (^{2}).

The study of the excitation and damping of electron oscillations in cyclic accelerators is not only of practical interest for the operation of the accelerators themselves, but apparently will make it possible to clarify the elementary processes of interaction between electrons and photons in emission processes. It should also be borne in mind that the quantum radiation of electrons moving along macroscopic orbits will probably make it possible to establish a more direct connection between the concepts of quantum and classical electrodynamics.

In the present work an experimental investigation has been carried out of electron oscillations in the S-60 electron synchrotron of the P. N. Lebedev Physical Institute of the Academy of Sciences of the USSR, a reystrek-type machine with a maximum energy of 660 Mev (^{3}). It has the following parameters: $R = 198$ cm, $H_{\max} = 11000$ oersted, magnetic-field fall-off index $n = 0.655$, acceleration time $t = 0.6$ sec. This accelerator made it possible to verify the existence of radiation damping of oscillations, and also to estimate the magnitude of quantum excitation of oscillations, in view of the sufficiently long acceleration time and the high maximum electron energy. The investigation, as in our work (^{4}), was carried out by an optical method—by photographing with a high-speed cine camera the transverse cross section of the electron beam—the "bunch," moving along its orbit in the accelerator. Photography was carried out over the entire acceleration cycle. A special feature of this synchrotron is that the acceleration of electrons in it is performed in two stages. At first the acceleration is carried out by one resonator up to an energy of 185 Mev, and then, after $t = 0.12 \div 0.16$ sec from the moment of injection, this resonator is switched off, and after several revolutions of the bunch the latter is again captured into the synchronous

Fig. 1

Figure 1: Fig. 1

acceleration regime by a second resonator. This moment of time is called the moment of "recapture" of the electrons.

The radiation of the electrons was led out of the porcelain chamber of the accelerator through a radial pipe by means of a mirror with an external reflecting coating, 28×55 mm^2 in size, placed inside the vacuum chamber of the accelerator.* Frame-by-frame filming was carried out with an SKS-1 cine camera at a speed of about 500 frames/sec. On the film, correspondingly—

corresponding to one acceleration cycle of the electron bunch, the moment of "recapture" appears as a frame in which the image of the bunch cross section assumes a "dumbbell-like" shape with sharply increased dimensions in radius. With time this "dumbbell-like" shape disappears, gradually changing into the usual characteristic elliptical shape of the cross section. In the photographs obtained, the intensity distribution over the cross section of the electron-beam image was measured by photographic photometry methods; this corresponded to the distribution of electrons over the bunch cross section. The widths of the image were then measured both in radius and vertically, at a level of 0.3 of the maximum intensity (Fig. 1). In comparing the experimental data with theory, these widths of the electron-beam cross-sectional image were identified with twice the amplitudes of the corresponding oscillations. In view of the fact that the damping of oscillations is treated differently in different theoretical works, we made the comparison taking these differences into account.

Fig. 1

If only the adiabatic law of damping of betatron oscillations of electrons is taken into account, it is necessary to use the following formulas from work (1): a) for betatron radial oscillations, formula (28,104); b) for betatron radial oscillations caused by quantum effects, formula (28,111); c) for vertical betatron oscillations, formula (28,104); d) for vertical betatron oscillations excited by quantum fluctuations of radiation, formula (28,1476).

If, along with adiabatic damping, radiative losses are taken into account, it is necessary to use the following formulas from work (2): a) for betatron radial oscillations, formula (2.13); b) for betatron radial oscillations caused by quantum effects, formula (3.4); c) for vertical betatron oscillations, formula (2.10); d) for vertical betatron oscillations excited by quantum fluctuations of radiation, (3.6).

For synchronous radial oscillations both theories give the same formula (2.14)

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* The idea of extracting the radiation by means of a mirror through a radial pipe was proposed by K. N. Shorin, to whom the authors consider it their duty to express their gratitude.

Fig. 2

Figure 2: Fig. 2

(see (^{2})). For synchronous radial oscillations caused by quantum pumping, formula (3.5) is given in work (^{2}).

The results of the measurements and their comparison with theory are shown in Figs. 1 and 2. In Fig. 1 the results are given for measurements of the change in bunch width vertically (the Z axis) during the acceleration process. The acceleration time is plotted along the horizontal axis. The dots denote the experimental data; 1 is the experimental curve; 2 is the curve of the change with time of the energy of the accelerated electrons; 3 is the change in the doubled amplitude of the vertical oscillations, calculated in accordance with formula (28,104) from work (^{1}), and 4 is that calculated according to formula (2.10) from work (^{2}). Calculation of the amplitude

vertical betatron oscillations excited by quantum fluctuations, using formula (28,1476) from paper (^{1}) and formula (3.6) from paper (^{2}), showed that for the given accelerator it is practically equal to zero and does not change the form of curves 3 and 4.

It is evident from Fig. 1 that the actual damping of the oscillations proceeds considerably faster than according to the adiabatic law, but somewhat more slowly than according to the exponential law represented by formula (2.10) of paper (^{2}). A particularly important new phenomenon is that, beginning at an energy of 420 MeV, the oscillations cease to damp at all. From this moment a noticeable increase in the oscillations begins, which cannot be explained by existing theories.

Fig. 2

The results of analogous measurements in radius are presented in Fig. 2. Here the experimental data are also denoted by points; 1 is the corresponding curve; 2 is the change in the energy of the accelerated electrons; 3 is the change in the total doubled amplitude of electron oscillations, calculated according to a theory that takes into account only adiabatic damping. In this case the following law of addition of oscillations was assumed:

$$a^{\mathrm{ad}} = \left[(a^{\mathrm{ad}}_{\mathrm{rb}} + a^{\mathrm{ad}}_{\mathrm{rc}})^2 + (a^{\mathrm{ad}}_{\mathrm{rb}_{\mathrm{qv}}})^2\right]^{1/2}, \tag{1}$$

and 4 is the change in the total doubled amplitude, calculated by the formula

$$a = \left[(a_{\mathrm{rb}} + a_{\mathrm{rc}})^2 + (a_{\mathrm{rb}_{\mathrm{qv}}})^2 + (a_{\mathrm{rc}_{\mathrm{qv}}})^2\right]^{1/2}. \tag{2}$$

The following notation is used here: a_{rb} is the doubled amplitude of radial betatron oscillations; a_{rc} is the doubled amplitude of synchrotron radial oscillations; $a_{\mathrm{rb}_{\mathrm{qv}}}$ is the doubled amplitude of radial betatron oscillations excited by quantum fluctuations; $a_{\mathrm{rc}_{\mathrm{qv}}}$ is the doubled amplitude of synchrotron radial oscillations excited by quantum fluctuations. The superscript ad refers to calculations by the formulas of paper (^{1}).

As the initial doubled amplitude of the betatron radial oscillations, the value of the bunch width in the last frame before the moment of "recapture" was taken, since by this time the synchrotron oscillations should have completely damped. As the initial doubled amplitude of the radial synchrotron oscillations, the difference of the corresponding bunch widths before and after the moment of "recapture" was taken, since the increase in the radial dimensions of the bunch immediately after "recapture" is due only to the appearance of new synchrotron oscillations. Comparison of the experimental and theoretical data on the change in the radial beam dimensions is substantially complicated, in contrast to the change in the vertical dimensions, by the presence of synchrotron oscillations of the electrons. Comparison of the experimental and theoretical data shows that, as in the case of vertical oscillations, the best

the theory that takes radiative damping into account agrees with experiment. The presence of significant radial oscillations of the electrons toward the end of acceleration, and some increase in them, can be explained by quantum excitation.

The decrease in the amplitude of the radial oscillations at the end of acceleration, beginning at a time of 0.5 sec from the moment of injection, and the increase in the amplitude of the vertical oscillations at the end of acceleration might be explained by a transfer of energy from one kind of oscillation to another. Here, possibly, there is a coupling of the radial and vertical oscillations due to resonance at some harmonic, as is noted in Refs. (5, 6); however, this requires special theoretical consideration.

The results obtained in this work make it possible to draw the following conclusions:

1. Satisfactory agreement between experiment and theory is obtained only when radiative damping is taken into account; however, there is no complete correspondence. In particular, the experiment indicates that the actual damping occurs more slowly than is required by the theory of radiative damping.
2. In the energy region above 400 MeV in the S-60 synchrotron, there apparently occurs a significant quantum excitation of the oscillations.
3. There exist undamped oscillations in z, whose origin is unknown.
4. At the end of the acceleration cycle, there may be a coupling of the radial and vertical oscillations.

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