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Abstract

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EXPERIMENTAL STUDIES OF THE COMPRESSION OF AN ELECTRON BUNCH IN A 280 MeV SYNCHROTRON

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Recently, in connection with the development of synchrotrons with energies of several BeV, interest has increased in the experimental study of betatron and synchrotron oscillations and of their influence on electron losses in accelerators. It should be noted that experimental works devoted to testing the existing theories of electron oscillations in synchrotrons are very few in number [(1–4)].

In the present work a new method is proposed for studying the change in the transverse dimensions of an electron bunch during the process of their acceleration, and the results are given of an investigation of the compression of an electron bunch accelerated in the synchrotron of the P. N. Lebedev Physical Institute of the Academy of Sciences of the USSR to 280 MeV [(5)].

The presence of electromagnetic radiation from electrons, sufficiently powerful in the visible region of the spectrum already at energies of the order of 100 MeV, makes it possible to study the behavior of an electron bunch during acceleration by photographing the radiation with a high-speed cine camera.

Calculation of the betatron oscillations of electrons in a synchrotron according to the classical theory [(6)] shows that the amplitude of these oscillations decreases with increasing energy of the accelerated particles, according to the adiabatic law

$$a_b \sim E^{-1/2}, \tag{1}$$

where a_b is the amplitude of the betatron oscillations, and E is the energy of the accelerated electron. Taking into account the influence of the electromagnetic radiation emitted by the accelerated electrons leads to a different law for the damping of the amplitudes of vertical and radial oscillations [(7)], namely: the amplitude of vertical electron oscillations damps according to the law

$$a_z \sim E^{-1/2} \exp\left[-\frac{1}{2}\int_0^t \frac{W}{E}\,dx\right], \tag{2}$$

Figure 1

Figure 1: Figure 1

the amplitude of the betatron radial oscillations changes according to the law

$$a_{\rho b} \sim E^{-1/2} \exp\left[-\frac{n}{2(1-n)} \int_0^t \frac{W}{E}\, dx\right], \tag{3}$$

and for the amplitude of the synchrotron oscillations we have

$$a_{\rho c} \sim V^{1/4} E^{-3/4} \exp\left[-\frac{3-4n}{2(1-n)} \int_0^t \frac{W}{E}\, dx\right]. \tag{4}$$

In these formulas E is the energy of the accelerated electron; W is the power of the electromagnetic radiation emitted by it; n is the exponent of the decrease of the synchrotron magnetic field; $V = V_0 \sin\varphi$, where V_0 is the amplitude of the electric field of the accelerating gap, and φ is the phase of the electron with respect to this voltage.

In carrying out our experiments, the radiation of the accelerated electrons was observed through a window in a special branch pipe of the accelerator' s porcelain chamber and was photographed with an SKS-1 high-speed motion-picture camera. The optical system made it possible to photograph a section of the electron orbit about 25 mm long. The filming was done through a monochromatic light filter having maximum transmission at $\lambda = 5780$ Å, at a speed of about 4300 frames per second, which made it possible to obtain up to 25 photographs of the bunch during one acceleration cycle, beginning at an electron energy of about 100 MeV. For sensitometric processing of the photographs of the bunch, the same

Fig. 1. *a*—photograph of the electron bunch and the directions in which the blackening was photometered; *b*—distribution of light intensity along the radius in the image of the electron bunch and the measured width of the bunch (R_0 —equilibrium-orbit radius of the accelerator); *c*—distribution of intensity with height.
$E_s = 205$ MeV

motion-picture camera was used to photograph a step wedge illuminated by electron radiation, as well as the radiation spot projected onto the step wedge. All films were developed simultaneously in one developer. In the photographs obtained of the electron bunch, the distribution of blackening over the height and width (which correspond to the direction of the magnetic field and the radius of the accelerator) of the image was measured with an MF-4 microphotometer; the two measuring directions intersected at the point in the image with the

Fig. 2. Comparison of theoretical and experimental data. E_s is the curve of the energy increase of the accelerated electrons

Figure 2: Fig. 2. Comparison of theoretical and experimental data. E_s is the curve of the energy increase of the accelerated electrons

maximum blackening value (see Fig. 1a). The measured blackening values were recalculated, using the characteristic curve of the photographic film, into radiation intensities, and then curves of the intensity distribution over height and radius were plotted for each frame of the given acceleration cycle. The image of the bunch had the form of an ellipse with an axial ratio very close to the ratio of the vertical and radial dimensions of the cross section of the accelerator chamber. From the obtained intensity-distribution curves, the bunch width was measured at intensity values I equal to 0.3, 0.4, 0.5, and $0.6I_{\max}$, where $I_{\max}$ is the maximum intensity for the given frame, both for the vertical and for the radial dimensions of the bunch image (see Fig. 1b).

To study the law governing the change in bunch width, for any of the indicated intensity values the data obtained were used to determine the ratio of the bunch width measured at time t to the bunch width at $t = 2.76$ msec. Time was measured from the instant of injection. The times

$t = 2.76$ μs corresponded to an energy $E = 86$ MeV, at which an image of the bunch was obtained that made it possible to carry out reliable photometric measurements. In this way several different acceleration cycles were measured.

Figure 2 gives a comparison of the experimental results obtained with the theoretically calculated dependence, for this synchrotron, of the relative amplitudes of different types of oscillations on the acceleration time. Curves 1, 2, 3, and 4 are the results of the theoretical calculation according to formulas (1), (2), (3), and (4), respectively; the points are the experimental results. Comparison of the theoretical and experimental data shows that the radial dimensions of the real bunch of accelerated electrons decrease

Fig. 2. Comparison of theoretical and experimental data. E_s is the curve of the energy increase of the accelerated electrons.

faster than follows from the adiabatic law (see formula (1)). Moreover, for the radial dimensions an effect is noticeable in which the center of the bunch is compressed more rapidly than its peripheral part. This is illustrated in the graph by two curves: the curve formed by points a, corresponding to the change in the radial width of the bunch measured at $I = 0.3I_{\max}$, and the curve formed by points b, at $I = 0.6I_{\max}$. The vertical dimensions of the bunch decrease approximately according to the adiabatic law; within the accuracy of the experiment, both the center and the peripheral parts of the beam are compressed equally in height.

The short acceleration time characteristic of this accelerator does not allow the law of compression of the bunch of accelerated electrons in the vertical direction to be determined more accurately.

In addition, in the present work the influence of a gradual displacement of electrons from the equilibrium orbit during acceleration on the law of change of the bunch dimensions was specially investigated. The gradual displacement of the electrons was ensured by having, at the moment when the electrons reached an energy of 242 MeV, the amplitude of the high-frequency voltage on the accelerating gap of the synchrotron begin to decrease according to a definite law, producing a linear-in-time displacement of the electrons from the equilibrium orbit onto the target. A study, for this case, of the law of change of the vertical and radial dimensions of the bunch by the same method showed that no difference is observed in the law of compression of the bunch in comparison with the case when no deliberate displacement of the electrons from the equilibrium orbit is carried out. The root-mean-square error in measuring the relative dimensions of the bunch was $\pm 5\%$ and can be reduced by using more

of precisely tying the moments of photographing each frame to the magnitude of the magnetic field. In our case the tie to the magnetic field was made according to the time of dumping the electrons onto the target and was carried out with an accuracy of ± 0.5 of the duration of the time interval between frames of the motion-picture recording, which amounted to $\pm 2\%$ of the total acceleration time.

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Note: Figure translations are in progress. See original paper for figures.