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HIGH-ENERGY CYCLIC ACCELERATORS WITH A SELF-ADJUSTING MAGNETIC FIELD

1. An increase in the maximum energy in modern cyclic accelerators is at present limited by the practically attainable precision in the manufacture and adjustment of the magnetic system. The strictest tolerances are imposed by the requirement that the number of betatron oscillations per revolution be kept constant and that a sufficiently small amplitude of forced betatron oscillations be ensured. In this connection, methods of automatic regulation of the local characteristics of the magnetic field on the basis of information on the behavior of the beam have recently begun to be discussed. The use of such methods would make it possible substantially to reduce the chamber aperture, which would increase the value of the maximum attainable energy and would substantially simplify and reduce the cost of accelerator construction.

The aperture of the accelerator chamber is determined by the free and forced betatron and synchrotron oscillations of the particles. The amplitudes of the free oscillations of the particles are determined by the initial injection conditions and by the nominal parameters of the magnets and of the accelerating system. By a corresponding choice of parameters, the amplitudes of the free oscillations in high-energy accelerators can be made of the order of a few millimeters.

The range of forced synchrotron and betatron oscillations is determined by deviations of the accelerator parameters from the nominal ones. To reduce these oscillations, a system of automatic regulation is also necessary. Automatic regulation of synchrotron oscillations has already been carried out (see, for example, ([1])) by controlling the parameters of the accelerating system. Autocorrection of betatron oscillations, which is the principal subject of the present work, reduces to two basic problems: regulation of the equilibrium orbit and stabilization of the number of oscillations per revolution.

2. Regulation of the equilibrium orbit. For simplicity, instead of the actual motion in an accelerator with strong focusing, we shall consider "smoothed" motion under the action of a certain equivalent constant focusing force. In the case when the period of the magnetic structure is much smaller than the period of the free oscillations, the smoothed motion differs little from the actual one

(^{2}). In the linear approximation, the smoothed motion in the absence of an automatic regulation system is determined by the differential equation

$$x'' + Q^2 x = F_t(\theta), \tag{1}$$

where x is the deviation from the chamber axis (radial or vertical); Q is the number of betatron oscillations per revolution (i.e., when the angular coordinate θ changes by 2π); $F_t(\theta)$ is a perturbation, which is a periodic function of θ with period 2π and varies slowly in time (compared with the period of revolution). In the presence of a system

of automatic regulation, the sum of the initial perturbation $F(\theta)$ and the correction signal $F_k(\theta)$ acts on the object of regulation (the equilibrium orbit). The measuring device (for example, a system of electrostatic electrodes) measures, at the necessary number of points, the deviation $x(\theta)$ of the equilibrium orbit from the chamber axis. The computing device determines, in accordance with (1), the form and magnitude of the perturbation $x'' + Q^2 x$ that caused the given displacement of the equilibrium orbit,* and through an amplifier-converter acts on the system of windings that create the correcting perturbation $F_k(\theta) = -\mathcal{L}(x'' + Q^2 x)$, where $\mathcal{L}$ is an operator characterizing the amplifier-converter. Thus, in the presence of an automatic regulation system the deviation x from the chamber axis is determined by the equation

$$(1 + \mathcal{L})(x'' + Q^2 x) = F(\theta). \tag{2}$$

In particular, if k is the gain coefficient of the amplifier-converter, then the use of an automatic regulation system leads to a reduction of the deviation by a factor of $k + 1$. From (2) it is not difficult to see that if the regulation system is characterized by a delay time T_1, then it effectively attenuates perturbations for frequencies substantially smaller than k/T_1. The value T_1 is determined mainly by the time constant of the regulating magnetic device (~ 1 msec).

3. **Stabilization of the number of betatron oscillations** is possible, for example, by means of special pulsed excitation of coherent betatron oscillations. Under the action of a pulsed electric or magnetic field, a particle bunch begins to perform transverse betatron oscillations $x(\theta)$ with frequency $Q = p \pm 0.25 + \Delta Q$, where p is an integer, and the deviation ΔQ from the nominal value consists of the perturbation δQ and the correction signal $-\delta Q_k$. The signal electrode produces a voltage $u_c(t) = \beta(\theta)x(\theta) = \beta(\theta)x_0 e^{iQ\theta}$, where $\theta = \int \omega\, dt$ ($\omega = 2\pi f$ is the angular frequency of revolution of the particles), and $\beta(\theta)$ is a periodic function of θ determining the sensitivity of the electrode. Expanding $\beta(\theta)$ in a Fourier series, we obtain

$$u_c(t) = x_0 \sum \beta_k e^{i(Q+k)\int \omega\, dt}. \tag{3}$$

With the aid of mixers, to the inputs of which voltages with frequencies $p\omega$ and $\omega/4$ are supplied, and low-pass filters, a voltage $u \sim e^{i\Delta Q \int \omega\, dt}$ is separated out and fed to a frequency detector. The latter produces a voltage proportional to ΔQ, which, through an actuator (correcting quadrupole lenses), is converted into the correction signal δQ_k. If k_1 is the gain coefficient in the regulation loop, then the stabilization system reduces deviations of the quantity Q by a factor of $k_1 + 1$. A method close to that described for measuring Q has been used on the Cosmotron ([3]). The pulsed excitation should be repeated periodically, since because of the spread of the particle momenta the oscillations cease to be coherent after a time of order $(f \cdot \delta Q)^{-1}$. Calculation shows that, at the required pulse repetition frequency, no noticeable buildup of betatron oscillations occurs.

4. The method described above for autocorrection of the accelerator parameters is suitable only for an already formed beam. In this connection, the problem of ensuring the start of acceleration (the first turn), i.e., the initial correction of the magnetic field ensuring the position of the instantaneous orbit at the moment of injection within the pre–

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* It is essential that free betatron oscillations, although they may affect the readings of the indicator device, do not contribute to the output of the computing device, since for them $x'' + Q^2 x = 0$.

within the working region of the vacuum chamber. For this purpose one may also apply the principle of autocorrection.

If, with an uncorrected magnetic field maintained at a constant level corresponding to the injection energy, a bunch of particles is injected, then, after passing through part of the chamber, it will strike its walls. Having measured, on the portion of the orbit traversed by the beam, the beam deviation $x(\theta)$ and calculated from it the perturbation, equal to $x'' + Q^2 x$, one can automatically correct this perturbation so that in the next injection cycle the field on the previously traversed part of the orbit ensures motion of the particles along the axis of the chamber. If the field fluctuations in neighboring magnets are regarded as independent, then the number of "test" injections needed to obtain the first turn will be of the order

$$S = \begin{cases} M_0 & (\text{for } M_1 < M_0), \\ M_0 \left(\dfrac{M_0}{M_1}\right)^{1/3} & (\text{for } M_1 > M_0), \end{cases} \tag{4}$$

where M_1 is the number of magnets in the system; $M_0 = \left(\dfrac{2\pi^2 R}{a}\dfrac{\Delta H}{H}\right)^{1/2}$; R is the radius of the installation; $\dfrac{\Delta H}{H}$ is the initial deviation of the magnetic field;

a is the semiaxis dimension of the cross section of the working volume of the chamber.

It appears possible to implement the principle of magnetic-field correction not by the beam, but by the position of a flexible current-carrying conductor placed in the magnetic field at the edge of the working region of the accelerator. As is known[4], the equilibrium position of such a conductor coincides with the equilibrium orbit of a particle with the corresponding momentum in the same magnetic field. The possibility of using this method is determined by the attainable degree of dynamic similarity of the orbits at the chamber axis and at the location of the conductor.

5. Taking into account the considerations given above, approximate parameters were calculated for a small-aperture proton accelerator to high energy. Without dwelling on the details of the calculation, we shall note only some considerations taken into account in choosing the accelerator version. A three-stage accelerator scheme is expedient: an initial linear accelerator, a preliminary ring accelerator, and a final ring small-aperture accelerator. The transition energy from the first ring to the second is chosen on the basis of the required accuracy of the injection field and the magnitude of the beam emittance. The chamber cross section of the large accelerator is determined by the amplitude of the betatron and synchrotron oscillations. The number of betatron oscillations per turn is limited by the width of the forbidden band in the parametric resonance of betatron oscillations and by the allowable momentum spread for synchrotron oscillations. The harmonic number of the accelerating-field frequency is also determined by the allowable momentum deviations.

Characteristic features of the small accelerator are a high repetition rate of acceleration cycles, due to the need for multiple injection to work out the first-turn regime and to fill the chamber of the large ring with particles, and also a high harmonic number of the accelerating-field frequency, due to the stringent requirements on the momentum spread of the particles injected into the large ring.

A substantial difficulty may be the implementation of precision pulsed deflecting systems ensuring the transfer of particles from the small accelerator to the large ring with a sufficiently small spread of initial conditions.

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