621.384.611

STRONG-CURRENT HIGH-ENERGY PARTICLE ACCELERATORS—MESON FACTORIES

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Usp. Fiz. Nauk 85, 651-678 (April, 1965)

1. INTRODUCTION

THE first powerful particle accelerators for electron and proton energies on the order of hundreds of MeV[1], constructed and put into operation some 15 years ago in the Soviet Union and in the USA, have made available to the scientists entirely new capabilities for research in atomic physics. This has given rise to a new branch of science, the physics of high-energy particles, which deals with the structure and properties of fundamental particles, and with the clarification of the laws governing their generation and interaction.

The subsequent construction of accelerators for even higher energies (up to tens of GeV)[2] increased by many times the power of the means employed to study the microworld and by the same token contributed very strongly to the expansion of the horizons of the new science.

As a result of all of this, the science of the structure of matter has made a tremendous leap forward during the last decade, and has become enriched with many outstanding discoveries. These included the observation of a large number of new particles (π^0, K, and ρ mesons, the muonic neutrino, the Σ, Ξ, Ω etc. hyperons) and antiparticles (antiproton, antineutron, antihyperon) and the establishment of many fundamental laws concerning the interactions of these and previously known particles (law of parity conservation in weak interactions, laws of isotopic spin conservation, conservation of baryon charge and strangeness in strong interactions), the discovery of the most important laws involved in the processes of creation and decay of particles, the determination of the quantum characteristics of the particles (spin, parity, mass, lifetime, charge) etc.

At the same time, the accumulated experimental data and the modern theoretical concepts of nuclear processes show convincingly that if much more progress is to be made in the study of the microworld it is very important to solve successfully the following two problems in the field of physics and technology of accelerators:

1. Increase by a factor of 100 or 1000 the intensities of the particle beams at energies already obtainable from accelerators.

2. Design accelerators for possibly higher energies, up to thousands of GeV and more.

These problems occupied one of the central places at the 1963 International Conference on High-energy Accelerators in Dubna.

In this article we attempt to describe the general principles of solving the first of these problems for accelerators with energies up to 1 GeV, to cast light on the principles of theory and of modeling, and give a brief description of various developed designs for new accelerators with currents up to 1000 μA.

Because these accelerators yield currents of nucleons and pions or muons which are larger by hundreds and thousands of times than those hitherto available, they have been given the picturesque name "meson factories."

II. PROSPECTS UNCOVERED BY STRONG CURRENT ACCELERATORS

Analysis shows that the greatest potential for variegated research in the near-BeV region of energies will be afforded by proton cyclotrons for energies of 650—800 MeV. This article is not intended to detail fully all the possibilities offered to science by strong-current accelerators. We shall attempt to note only the principal ones among them.

In the field of strong interactions of elementary particles, such accelerators will make it possible, for example with the aid of high precision experiments with nucleons and pions, to check on the existence of symmetries of these interactions, a question of principal significance for the theory; they will also make it possible to obtain new information on nuclear forces, on the interaction between pions, about which almost nothing is known at present, etc.

Opportunities will arise also in the study of the structure and properties of atomic nuclei.

In the study of weak interactions, in spite of the great progress which has been made in recent years, such fundamental problems as the correctness of the theory of universal weak interaction, the existence of CP invariance, and other cardinal questions still remain unclear.

In the field of electromagnetic interactions, one of the most timely problems of modern physics of elementary particles is the establishment of the limits of applicability of quantum electrodynamics.

Further progress in the last two trends of study of the microworld depends directly on an increase in the intensity of the accelerators by hundreds or thousands of times, which would make possible a broad program of experiments of high precision with leptons, primarily the capture of muons by nucleons, the determination of the mass of the muonic neutrino, a detailed study of the beta decay of the pion, a clarification of the question of why the muon is necessary and why, having a mass of 200 times larger than the electron, it interacts with other particles like an electron, etc.

Strong-current accelerators will offer also great possibilities for research in other sciences such as biology, nuclear chemistry, radiation medicine, and solid-state physics.

The discovery of the earth's radiation belts, which contain protons with energies from several MeV to 700 MeV, and solar flares, which produce intensive streams of high-energy corpuscular radiation, has raised the question of radiation protection for astronauts who embark on prolonged flights or on flights over distant orbits. As a result, recent publications have been discussing the use of strong-current proton accelerators for the simulation of conditions of travel of space ships through the earth's radiation belts and the belts of other planets, and the solution of many problems connected with providing safety for human flight in outer space[3].

Finally, accelerators for energies of hundreds of MeV with currents on the order of a milliampere, can be the base for future construction of even more powerful atomic machines, operating in conjunction with neutron multipliers and of interest from the point of view of generation of atomic fuel (Pu^{239}) from waste of ordinary reactor uranium depleted by the burnup of uranium-235[3].

III. PHYSICAL PRINCIPLES OF PARTICLE ACCELERATION IN RELATIVISTIC CYCLOTRONS

In a cyclotron with an axially symmetrical magnetic field, the acceleration of charged particles following multiple passage by these particles through the same gap with an accelerating electric field of constant frequency becomes limited quite rapidly. This limit is imposed by the increase in the period of revolution of the accelerated particles

$$T = \frac{2\pi E}{ecH} \tag{1}$$

(E and e are the total energy and charge of the particle, c the velocity of light, and H the intensity of the magnetic field on the closed orbit), and is brought about, on the one hand, by the growth of the total energy of the particle and, on the other hand, by some decrease in the intensity of the magnetic field along the radius. This decrease is necessary for particle focusing and imposes a limitation on the energy attainable in the cyclotron.

The connection between the maximum energy (W_{max}) and the amplitude of the accelerating voltage (V_0) in the cyclotron is determined by the expression

$$W_{max} = 4\sqrt{\frac{eV_0E_0}{\pi K}} \tag{2}$$

(E_0 is the particle rest mass,

$$K = 1 - \frac{n}{1+n}\frac{1}{\beta^2},$$

where

$$n = \frac{R}{H(R)}\frac{dH}{dr}\bigg|_{r=R},$$

r and R are the radial coordinate and the radius of the closed orbit, $\beta = v/c$, and v is the particle velocity). It follows therefore that the acceleration of the protons to a (kinetic) energy above 25 MeV in a cyclotron is practically impossible.

The discovery of the phase stability principle[4] has made it possible to lift this limitation and created great possibilities for the development of new types of cyclic accelerators for different energies. In particular, the fm synchrotron (an accelerator in which, like in the cyclotron, an axially-symmetrical stationary magnetic field that falls off along the radius is employed) turned out to be highly suitable for the acceleration of protons, deuterons, and alpha particles to energies of several hundred MeV.

However, owing to the variation in the frequency of the accelerating electric field, the capture of the ions into the acceleration mode is possible only in a relatively short time interval during each period of frequency modulation. Such a pulsed mode of acceleration in the proton synchrotron limits the average current of the accelerated particles. At the values of the accelerating voltage attainable in the now existing 400–700 MeV proton synchrotrons, namely 10–15 kV, this current usually does not exceed 1–2.5 μA[5]. An increase in the intensity of the beam by increasing the amplitude of the accelerating voltage entails considerable technical difficulties.

The desire to use the advantages of the cyclotron with respect to beam intensity, due to the continuous capturing of the ions in the acceleration mode, has stimulated a search for ways of overcoming the energy limitations of the cyclotron. By using an axially-asymmetrical magnetic field it is possible to maintain the ion revolution frequency constant (isochronism) during the course of acceleration, and to ensure conditions for axial and radial stability of motion of the accelerated ions[6]. It turned out that a cyclotron capable of covering the energy range of a contemporary proton synchrotron must employ a magnetic field whose intensity H_z varies radially and azimuthally (in the symmetry plane) like

$$H_z = H(r)[1 + \varepsilon(r) f(r, \varphi)], \tag{3}$$

where H(r) is the average value of the intensity on a circle of radius r, $\epsilon(r)$ is the depth of variation of the magnetic field, and φ is the azimuthal coordinate.

The isochronism of motion of the ions on the closed orbit is attained by choosing the variation of the average field H(r), disregarding the corrections necessitated by the deviation of the closed orbits from circular, in the form

$$H(r)=\frac{H_0}{\sqrt{1-\left(\frac{r}{r_\infty}\right)^2}}, \tag{4}$$

where H_0 is the field intensity in the center of the accelerator, $r_\infty = c/\omega$, and ω is the angular frequency of ion revolution.

The axial stability is ensured by producing alternating gradients of the magnetic field on the closed orbit.

As to the character of periodicity of the function $f(r, \varphi)$ in r and φ, it will be shown later that a greater degree of spirality leads to a decrease in the required depth of variation of $\epsilon(r)$, and that the form of the spirality is not decisive for the dynamic properties of the accelerator and can be chosen on the basis of the efficacy of the method of producing the variation.

1. Linear Theory of Stability

The dynamic characteristics of particle motion in relativistic cyclotrons can be obtained from the linear theory of motion for the entire range of energies, excluding the zone of excitation of oscillations, in which the natural frequencies reach resonant values.

However, unlike the known types of accelerators (cyclotron, synchrocyclotron, proton synchrotron), in relativistic cyclotrons the interval of the natural-oscillation amplitudes for which the linear approximation is valid is greatly reduced by the essentially nonlinear law governing the variation of the magnetic field intensity in the median plane.

The simplest magnetic-field structure of a relativistic cyclotron in the symmetry plane can be represented in the following form (in cylindrical coordinates):

$$H_z = H(r)\{1+\varepsilon(r)\sin[\alpha(r)-N\varphi]\}. \tag{5}$$

Here $\alpha(r)$ is a function characterizing the spirality of the magnetic field in the median plane, and N is the periodicity of the field structure. The presence of higher harmonics in the field structure (2N, 3N, ...) does not lead as a rule to qualitative changes in the dynamic processes in the accelerator. Therefore, to clarify the results, we shall carry out the theoretical analysis without loss of generality for a field described by (5). The corresponding corrections for magnetic fields with higher harmonics [formula (3)] are presented without discussion.

If we disregard the mutual coupling produced by the nonlinear terms, then each of the quantities in (5), namely H(r), $\epsilon(r)$, $\alpha(r)$, and N, characterizes a definite dynamic effect in the relativistic cyclotron. The radial variation of the average accelerator field H(r) determines the isochronism of motion of the particles with different energies, while the quantities $\epsilon(r)$, $\alpha(r)$, and N determine the axial frequency of the free oscillations, $d\alpha/dr = 1/\lambda\!\!\!^{-}$ determines the limit of applicability of the linear theory, and N determines the limiting energy of the particles in the accelerator.

For an azimuthally-periodic magnetic-field structure (5), in which a particle moves with momentum

$$p=\frac{e}{c}H(R)R, \tag{6}$$

there is a solution of the equation, describing planar motion with a period equal to the period of the field structure. This solution corresponds to a closed orbit and, in first approximation can be written for $\epsilon > 1$, in the form[7]:

$$r = R+\frac{\varepsilon R}{N^2-1-n}\sin[\alpha(r)-N\varphi]-\frac{\varepsilon^2\left(n+\frac{3}{2}+l\right)R}{2(1+n)[N^2-(1+n)]}, \tag{7}$$

where

$$l=\frac{R}{\varepsilon}\frac{d\varepsilon}{dr}\bigg|_{r=R}.$$

It follows from (7) that the character of the trajectory of the closed orbit coincides with the law governing the variation of the magnetic field at a specified radius. The natural frequency of the free oscillations of the particles relative to this closed orbit can be determined in the first approximation from the expressions*

$$Q_r=\sqrt{1+n}\sqrt{1+\frac{3}{2}\left[\frac{\varepsilon R}{N^2}\alpha'(R)\right]^2} \tag{8'}$$

for radial oscillations and

$$Q_z=\sqrt{\left[\frac{\varepsilon R}{N}\alpha'(R)\right]^2-n+\frac{\varepsilon^2}{2}} \tag{8''}$$

for vertical oscillations ($\alpha'(R) = d\alpha/dr|_{r=R}$).

For relativistic cyclotrons, n ranges from zero at initial energy to $E^2/E_0^2 - 1$ when the total energy of the particle reaches a value E. This change in n is connected with the requirement that the particle rotation be isochronous at different accelerator radii, for relativistic cyclotrons at high energies—meson factories—it gives rise to a wide range of radial-oscillation frequencies

$$2 > Q_r \geqslant 1. \tag{9}$$

The frequency of the axial oscillations Q_z, as follows from (8), can be regulated by choosing suitable func-

*In the presence of higher harmonics in the field structure expressions (8′) and (8″) become more complicated:

$$Q_r^2=(1+n)\left[1+\frac{3}{2}\left(\frac{\varepsilon_1 R\alpha'}{N^2}\right)^2\sum_{m=1}^{\infty}\left(\frac{\varepsilon_m}{m\varepsilon_1}\right)^2\right],$$

$$Q_z^2=-n+\left[\left(\frac{\varepsilon_1\alpha' R}{N}\right)^2+\frac{\varepsilon_1^2}{2}\right]^2\sum_{m=1}^{\infty}\left(\frac{\varepsilon_m}{\varepsilon_1}\right)^2,$$

where ϵ_1 is the amplitude of the N-th harmonic and ϵ_m is the amplitude of the mN-th harmonic.

tions $\epsilon(R)$ and $\alpha'(R)$. To avoid resonant excitation of the axial oscillations in the zones of linear resonances during the course of the acceleration, usually one imposes an additional condition, which is written in the form

$$0.5 > Q_z = \text{const.} \tag{10}$$

Condition (10) can be satisfied for the main interval of the radii of the acceleration zone, with the exception of the center of the machine, where $Q_z = 0$.

The frequency Q_z, in relativistic cyclotrons with steeply spiral field structure ($R\alpha' \gg 1$), depends essentially on the amplitude of the free axial oscillations b. This effect is connected with the nonlinear dependence of the variation of the magnetic field (ϵ) along the z axis, which leads to an increase in the average value of the variation for ions with axial-oscillation amplitude different from zero. The deviation of the frequency from (8) is determined by the expression[8]

$$\Delta Q_z = \frac{\varepsilon^2 \alpha'^2 b^2}{4Q_z}\left[\left(\frac{R\alpha'}{N}\right)^2 + \frac{3}{2} + \left(\frac{N}{R\alpha'}\right)^2\right], \tag{11}$$

where b is the amplitude of the axial oscillations.

As follows from (11), for annular synchrocyclotrons with spiral structure of the magnetic field, this effect can impose a limitation on the maximum amplitudes; for relativistic cyclotrons, besides increasing "rigidity" of the axial oscillations, an increase takes place in the region of resonant interaction of the oscillation.

2. Linear Resonant Effects

In real accelerators, besides the main harmonics of the magnetic field structure (N, 2N, 3N, etc.) there are always harmonics of a multiple of one revolution of the particle (1, 2, 3, etc.). The appearance of these harmonics is connected with imperfections in the manufacture of the pole pieces, inhomogeneity of the ferromagnetic material, and inaccurate erection of the individual elements relative to one another. In spite of the fact that the magnitude of these harmonics does not exceed as a rule several tenths of 1% of the fundamental harmonic (N), resonant amplification of the oscillations sets in in zones where the natural frequencies assume integer or half-integer values. Since the process of resonant excitation in these zones is described by linear differential equations, these resonances are called linear, to distinguish them from the zones of nonlinear resonance as considered in Sec. IV.

A relativistic cyclotron always contains a zone of simple (whole-number) resonance and a zone of parametric resonance in the center of the accelerator, where the frequency of the radial oscillations is

$$Q_r = 1. \tag{12}$$

Excitation of oscillations in these zones is connected with the first and third harmonics in the field structure at small accelerator radii. Thus, the amplitude of the radial oscillations, due to simple resonance, is estimated from the formula

$$a = \frac{\pi \sqrt[4]{\pi}}{\Gamma(1/4)} \varepsilon_1 (E_0 \Delta E)^{\frac{1}{4}} r_\infty, \tag{13}$$

where $\Gamma(1/4)$ is the Euler gamma-function.

For the most typical relativistic cyclotrons, in which the energy acquired in one revolution lies in the range ΔE = 100–500 keV and the magnetic field at the center of the accelerator is H_0 = 7–9 kOe (corresponding to $r_\infty = E_0/eH_0$ = 450–350 cm), the allowed relative magnitude of the first harmonic ϵ_1 should be of the order of 10^{-4}.

Parametric excitation of oscillations in the central zone of the accelerator leads to an exponential growth of the amplitude over the width of the resonance band. If we assume a 1–1/2-fold increase in the amplitude when the particle passes through this zone, then the limitation on the relative magnitude of the second field harmonic (ϵ_2) is written in the form

$$\varepsilon_2 \leqslant 2\sqrt{\frac{\Delta E}{\pi E_0}}. \tag{14}$$

An analogous effect is observed when the kinetic energy of the particles accelerated in relativistic cyclotrons approaches $0.5E_0$, and the frequency of the free oscillations reaches a value

$$Q_r = 1.5. \tag{15}$$

If no special measures are taken to suppress the third harmonic of the structure of the magnetic field in the zone Q_r = 1.5 to a value*

$$\varepsilon_3 \leqslant \sqrt{\frac{2\Delta E}{\pi E_0}}, \tag{16}$$

then a considerable increase in the amplitude of the radial oscillations will take place on going through this zone.

3. Phase Motion

Particle acceleration is produced in relativistic cyclotrons by the resonant high frequency electric field of the accelerating system, which can be constructed either in the form of a quarter-wave line, or in the form of special resonators.

The isochronism of the motion at different radii of the accelerator is attained by choosing suitable variations of the average magnetic field intensity H(r). In

*The difference between the coefficients of (14) and (16) is connected with the different influences of the second and third harmonics of the field on the form of the closed orbit, and also with the doubling of the width of the resonance zone in the second case as compared with the central zone of the accelerator.

spite of the fact that in relativistic cyclotrons the closed orbits (7) differ from circles, the isochronism condition can be written in the form known for the ordinary cyclotron

$$H(\mathscr{L}) = \frac{H_0}{\sqrt{1-\beta^2}}, \tag{17}$$

where $H(\mathscr{L})$ is the average value of the magnetic field intensity on the closed orbit $\mathscr{L}$.

For a particle whose energy is $E = E_0(1 - \beta^2)^{-1/2}$, the function (17) for all relativistic cyclotrons is quite close to the expression (4), which is written without account of the influence of the field variation on the isochronism. However, the rather rigid tolerances with respect to deviation from resonance makes it necessary to take this effect into account and to correct the mean value of the magnetic field in the zone of the final radii of the accelerator.

The waviness of the closed orbit gives rise to two phenomena that influence the period of particle revolution. On the one hand, the lengthening of the orbit due to the waviness increases the period of revolution; on the other hand, the dynamics of particle motion in the magnetic field (5) is such that the average radius of the closed orbit is smaller than the value of R given in (6), thus appreciably reducing the period. The latter effect turns out to be stronger and causes some decrease in the magnetic field intensity at each radius, as compared with (4):

$$H(R) = \frac{H_0}{\sqrt{1-\frac{R^2}{r_\infty^2}}}\left[1 - \frac{\varepsilon^2(2+n+2l)}{4N^2(1+n)}\right]. \tag{18}$$

In (18) the quantities ϵ, n, and l are functions of R.

In real accelerators there is always a deviation from (18), connected with the inaccurate shimming and stabilization of the magnetic field. If we denote the relative deviation of the magnetic field intensity from (18) by $\Delta H(R)/H$, then the expression for the phase shift of the particle, upon acceleration to a final energy

$$E_k = \frac{E_0}{\sqrt{1-\beta_k^2}}$$

can be written in the following form[9]

$$\Delta\varphi = \xi\frac{E_0}{\Delta E}\frac{\Delta H(R)}{H_0}\beta_k^2, \tag{19}$$

where ξ is a coefficient that depends on the character of the function $\Delta H(R)$; $\xi_{max} = \pi$ when ΔH = const. From an analysis of (19) it follows that isochronous particle motion is just as decisive in relativistic cyclotrons (meson factories) as in classical cyclotrons. There are two ways to solve this problem: either increase the accuracy of shimming and stabilization of the average field to a quantity on the order of 10^{-4}, with a moderate energy increment per revolution (200—300 keV), or increase the energy increment (500—1000 keV) with a less stringent magnetic-field tolerance. Compromise solutions in the indicated range of parameters are used in the presently developed relativistic cyclotron designs (Sec. V).

An additional effect which exerts an influence on the phase motion in relativistic cyclotrons is the difference in the amplitudes of the free oscillations of the beam particles[10]. The period of revolution of a particle of fixed momentum decreases with increasing oscillation amplitude. As a result, the beam broadens in azimuth during acceleration. The scale of the broadening of the beam can be estimated by using the expression*

$$\Delta\psi = \frac{\pi}{3}\frac{E_0}{\Delta E}\left(\frac{E^3}{E_0^3} - 1\right)\frac{a^2}{r_\infty^2}. \tag{20}$$

This effect, as follows from (20), can be decisive in the choice of the permissible interval of free ion oscillation amplitudes in the case of accelerators with a small energy increment per revolution (ΔE).

The azimuthal broadening of the beam during the acceleration makes it difficult to use the possible mechanisms of phase focusing of ions[11], or to use a system for ion transit phase correction with the aid of pickup electrodes[12,13].

4. Nonlinear Resonant Effects

A complete analysis of particle motion in a relativistic cyclotron is impossible without consideration of the nonlinear effects which arise in a very narrow interval of natural frequencies, causing a resonant increase in the amplitude of the corresponding oscillations. These effects, generally speaking, are due to the nonlinearity of the average magnetic field and to the radial dependence of the amplitude and phase of variation of the magnetic field. In a relativistic cyclotron with a steep-spiral field structure, the decisive factor is the nonlinearity caused by the dependence of the phase of variation on the radius, since the corresponding terms in the equations of motion are proportional to λ^{-k}, whereas for accelerators of other types they are proportional to R^{-k}. The frequency of the radial oscillations changes during the course of acceleration over a wide range (9), and assumes a series of values at which nonlinear resonant interaction takes place between the free oscillations and the fundamental harmonic of the magnetic field. The equation for the most effective internal nonlinear resonances has the form

$$qQ_r \pm pQ_z = N, \tag{21}$$

where q, p = 0, 1, 2, ...; q + p is the order of the nonlinear resonance. The most dangerous are nonlinear resonances of the radial oscillations, corresponding to p = 0, since they have the lowest order. In Table I are given the accelerated-proton energies (in MeV),

*Formula (20) is written without account of the attenuation of the oscillation amplitude during the course of the acceleration.

Table I

N/Q_r	$N/3$	$N/4$	$N/5$
4	273	0	—
6	800	435	181
8	1340	845	538

obtainable when a given nonlinear resonance is attained, calculated on the basis of the linear theory. In the investigation of the equations of radial particle oscillations in the zones of nonlinear resonances, it is necessary to consider nonlinear terms of two types. Terms of the type $C_1(\rho/R)^k$ can change the oscillation frequency Q_r only slightly, whereas when $k = q - 1$ terms of the form $C_2(\rho/\lambda\!\!\!^{-})^k \sin(N\varphi)$ produce a resonant increase in the amplitude of the oscillations (ρ is the radial deviation of the particle trajectory from the closed orbit). A characteristic feature of the relativistic cyclotron, distinguishing it from synchrotrons with hard focusing, is the small influence of the nonlinearity of the average field (n is small in a cyclotron) on the frequency of the radial oscillations. At the same time, the appreciable spirality of the magnetic field structure gives rise to effective internal resonances of high order (q), which usually do not occur in accelerators of other types. A sufficiently detailed investigation of the nonlinear resonances, both in the static mode (Q_r = const) and on going through the resonant zone, can be carried out with the use of asymptotic methods [14]. This yields in first approximation invariant relations between the amplitude and phase of the radial oscillations in the zone of a definite nonlinear resonance [8]. Analysis of these relations leads to several conclusions.

First, for sufficiently small amplitudes, at fourth-order resonance, the value of the stabilizing nonlinearity of the average field, at which small amplitudes are stable, does not depend on the oscillation amplitude. However, even at relatively large spirality of the magnetic field this value is not ensured by a small index of the average field; therefore, small amplitudes are always unstable in the zone of fourth-order nonlinear resonance of a relativistic cyclotron, whereas the increase in amplitude per revolution is $\Delta a \sim (a/a_0)^3$. The character of motion at larger amplitudes can be determined from an examination of the corresponding invariants [8].

Second, in resonances of fifth order and above, the singular point on the phase plane, corresponding to the given resonance, is a center. However, in the case of a steeply-spiral magnetic field structure ($\lambda\!\!\!^{-}$ = 7—10 cm), the dimension of the separatrix in the case of fifth-order resonance corresponds to radial-oscillation amplitudes smaller than 1 cm, and this resonance is not dangerous only for a definite rate of dynamic passage through the resonance zone. The increase in the oscillation amplitude after passing through the fifth-order resonance zone is determined in first approximation by the relation

$$a = a_0 \left\{1 - 1{,}1\cdot 10^{-2}\,\frac{\varepsilon R a_0^3}{Q_r \lambda\!\!\!^{-4}}\left(\frac{E_0}{\Delta E}\right)^{\frac{1}{2}}\right\}^{-\frac{1}{3}}. \qquad (22)$$

The dimension of the separatrix for the sixth-order resonance is usually several centimeters, and this resonance cannot cause appreciable particle loss even in the quasistatic mode.

The width of the internal-resonance zone can be determined from the expression

$$\Delta Q_r = \frac{\varepsilon R}{a Q_r}\left[J_{q-1}\left(\frac{a}{\lambda\!\!\!^{-}}\right) - J_{q+1}\left(\frac{a}{\lambda\!\!\!^{-}}\right)\right], \qquad (23)$$

where $J_{q-1}(a/\lambda\!\!\!^{-})$ are Bessel functions of order $q - 1$. In the central region of the relativistic cyclotron ($Q_r \approx 1$) there takes place a nonlinear resonance of N-th order. The radius of the resonance zone is determined for $a < \lambda\!\!\!^{-}$ by the formula

$$r_{res} = \frac{r_\infty^2}{2^{N-1}(N-1)!\,\lambda\!\!\!^{-}}\left(\frac{a}{\lambda\!\!\!^{-}}\right)^{N-2}. \qquad (24)$$

In addition to the nonlinear resonances in the radial oscillations, at some radii in a relativistic cyclotron there can occur resonant coupling of oscillations, in accordance with (21) by the fundamental harmonic of the magnetic field. In this case, if there is no distortion of the medium plane, p assumes only even values. Figure 1 shows a diagram of the free-oscillation frequencies for N = 8, showing the nonlinear resonances up to seventh order inclusive. The dashed lines designate the approximate motion of the working point in the acceleration process. It can be shown that for coupling resonances there is an invariant relation

$$\frac{a^2 Q_r}{q} \mp \frac{b^2 Q_z}{p} = C(a_0, b_0). \qquad (25)$$

A detailed investigation using asymptotic methods shows that, for example, when $a \le \lambda\!\!\!^{-}/2$ (N = 8), the most dangerous coupling resonance ($5Q_r + 2Q_z = 8$) exerts practically no influence on the axial motion. Other coupling resonances, excited by the fundamental harmonic, have a higher order and therefore can be disregarded when $a \le \lambda\!\!\!^{-}/2$.

5. Limiting Intensity in a Relativistic Cyclotron and a Synchrocyclotron

The beam intensities attained in a relativistic cyclotron and in a synchrocyclotron can be compared on the basis of the limitation which is imposed by the beam space charge on the axial stability of motion of the accelerated ions.

In a relativistic cyclotron, the decrease in the frequency of the axial oscillations of the particles (ΔQ_z), due to the action of the space charge, can be determined from the expression (within the framework of the linear theory) [15]

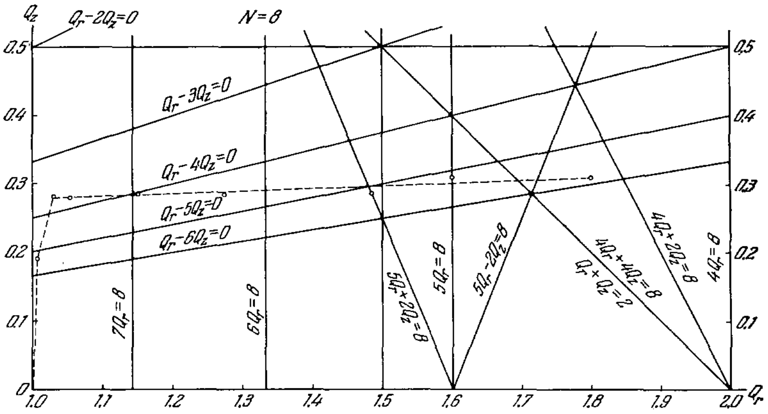

FIG. 1. Diagram of resonances.

$$\frac{\Delta Q_z}{Q_z} = 1 - \sqrt{1 - \frac{2\pi i e}{\Delta \bar{E}\cdot \Delta\varphi_n b f Q_z^2}}, \qquad (26)$$

where i is the current of the accelerated ions, f the ion revolution frequency, $\Delta\bar{E}$ the average ion energy increment per revolution, 2b the vertical dimension of the beam, and $\Delta\varphi_n$ the azimuthal dimension of the beam.

The change in frequency, connected with the space-charge effect of the axial oscillations, in a synchrocyclotron at small radii (but large radius of the first phase oscillation), can be obtained with accuracy sufficient for estimate from the expression[12]

$$\frac{\Delta Q_z}{Q_z} = 1 - \sqrt{1 - \frac{2\pi i e (\pi K_s)^{1/2}}{(\Delta E)^{1/2} b F E_0^{1/2} Q_z^2 \psi}}, \qquad (27)$$

where

$$\psi = \oint \sqrt{\cos\Phi + \cos\Phi_s - (\pi - \Phi - \Phi_s)\sin\Phi_s}\, d\Phi$$

(for the separatrix of the solution of the phase equation), F is the modulation frequency, and Φ is the phase of the accelerating field; the subscript s relates the corresponding parameters to the equilibrium ion.

If we assume in (26) and (27) parameter values that are permissible or customarily used in relativistic cyclotrons and synchrocyclotrons, then for an identical change in the frequencies of the axial oscillations the ratio of the current of the accelerated ions in the cyclotron and in the synchrocyclotron amounts to 200—1000. A formal estimate of the limiting intensity ($\Delta Q_z = Q_z$) in a relativistic cyclotron (26) with $Q_z = 0.3$ gives a current value 10—15 mA. Further appreciable increase in the intensity in a relativistic cyclotron can be attained by increasing the hardness of the focusing system (for $Q_z > 1$).

6. Beam Extraction Methods

In a relativistic cyclotron it is impossible to use internal targets. This is due essentially to two factors: first, the intolerably high level of radioactivity, which would be induced in the material of the accelerator units by the high-intensity proton beam scattered by the targets; second, by the practical impossibility of removing from the target the heat released in it by passage of a powerful proton beam. This leads to the categorical requirement of developing and incorporating in relativistic cyclotrons systems for extracting the beam from the accelerator chamber, with an extraction coefficient close to unity.

Development of methods for extracting the beam follows two trends. The first method is based on the effect of resonance dumping of the ions in the magnetic channel with the aid of a mechanism that builds up radial oscillations in the frequency zone $Q_r = 1.5$ or $Q_r = 2$.[16] In the region of fourth-order nonlinear resonance $Q_r = 8/4$, the pitch of the ions in one revolution is proportional to $(a/a_0)^3$, and reaches several centimeters. Experiments carried out with an electronic model in Oak Ridge[17] have shown that when such a method of extraction from the accelerator chamber is used, it is possible to obtain a beam extraction coefficient close to 0.95.

The resonant method of extracting particles from an accelerator makes it necessary to choose a definite maximum accelerator-particle energy. The kinetic energy corresponding to the resonance zones is 845 or 435 MeV respectively (see Table I). If the accelerator is intended for the acceleration of ions to an energy which does not coincide with these values, the use of the resonant method is somewhat difficult. In this connection, it is of interest to use nonresonant methods of beam extraction from an accelerator, which are based on mechanisms of excitation of oscillations in the nonresonant region of the oscillation frequencies. A possible method of bunching the particles in the nonresonant region is to use mechanisms connected with the closed orbit of the accelerator. The radial velocities of the ions at the point of inflection of the trajectory of a closed orbit greatly exceed the velocities which are due to the free oscillations.

By appreciably distorting the form of the closed orbit, through the use of a set of lower harmonics in the structure of the magnetic field, it is possible to separate one azimuthal direction in the closed orbit.

Table II

	Particles	B, G ($r = 0$)	Final radius, cm	Maximum energy, MeV	Frequency of revolution, Mc	Number of spirals	Form of spirals, cm	ΔE_{min}, keV
JINR	d	13700.0	53.0	13.0	10.45	6	$r = 16.2\,\varphi$	5.0
JINR	e^-	41.926	34.8	0.510	117.4	8	$r = 40.6\sqrt{\varphi}$	0.425

When using perturbations in this zone, one can expect a high extraction coefficient[18]. Experimental data on the extraction of beams in nonresonant regions of oscillations are lacking at present.

IV. MODELS OF RELATIVISTIC CYCLOTRONS

The first experimental investigations of stability, and also of the phase motion in cyclotrons with magnetic field of type (3), were carried out in accelerator models at the Joint Institute of Nuclear Research[7] and at the Oak Ridge National Laboratory[17].

The main parameters of the models are listed in Table II.

These models were used to solve the fundamental problems connected with the physics of such accelerators. It was established with the first model experimentally that in the cyclotron mode (absence of phase stability) it is possible to accelerate ions for 2500 revolutions, investigate the resonant excitation of oscillations in the center of the accelerator ($Q_r = N/q \approx 1$ at $q = N$), and also demonstrate the possibility of formation, with the aid of shims, of a complicated structure of magnetic fields bent along the line of the corresponding spirals ($\alpha(r) - N\varphi = \text{const}$). The pole piece of the electromagnet of the model is shown in Fig. 2.

The electronic model of the isochronous cyclotron at the Oak Ridge National Laboratory was used to solve experimentally two problems in the physics of such accelerators. The first was connected with the dynamic processes occurring in the acceleration of particles with energy $E \approx 2E_0$. It has been shown by simulation that in the case of an eight-spiral magnetic-field structure the ions pass without noticeable increase in amplitude through all the resonance zones corresponding to the fundamental harmonics of the field (N, 2N, ...). The second question solved with this model concerned the extraction of the accelerated particles from the accelerator chamber. It was established experimentally that the resonance method of extraction in a zone where the frequency of the radial oscillations is $Q_r \approx 2$ makes it possible to obtain a yield coefficient close to 0.95[19].

The structural elements of the electronic model are shown in Fig. 3. A photograph of the beam on a fluorescent target is shown in Fig. 4.

V. DESIGN PROJECTS OF RELATIVISTIC CYCLOTRONS—MESON FACTORIES

By now three projects of relativistic cyclotrons have been discussed fully and in detail in the literature and in conferences: the relativistic cyclotron (RC) of the JINR laboratory of nuclear problems (Dubna)[18] the isochronous Mc^2 cyclotron of the Oak Ridge National Laboratory (USA)[19], and the H$^-$ cyclotron of the California University of Los Angeles[20].

In the construction of relativistic cyclotrons it becomes necessary to solve many problems which either did not arise previously in accelerator practice, or did not arise so acutely. The solutions adopted are the results of compromises between many contradictory requirements connected with the dynamics of particle motion, the high accuracy with which the accelerator

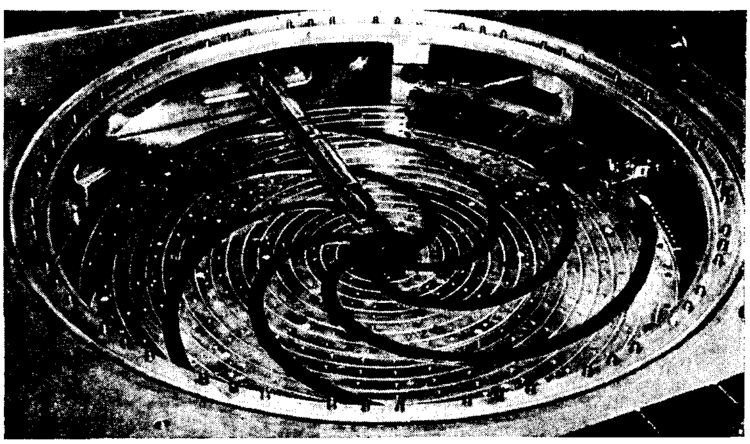

FIG. 2. Pole piece of the JINR accelerator model.

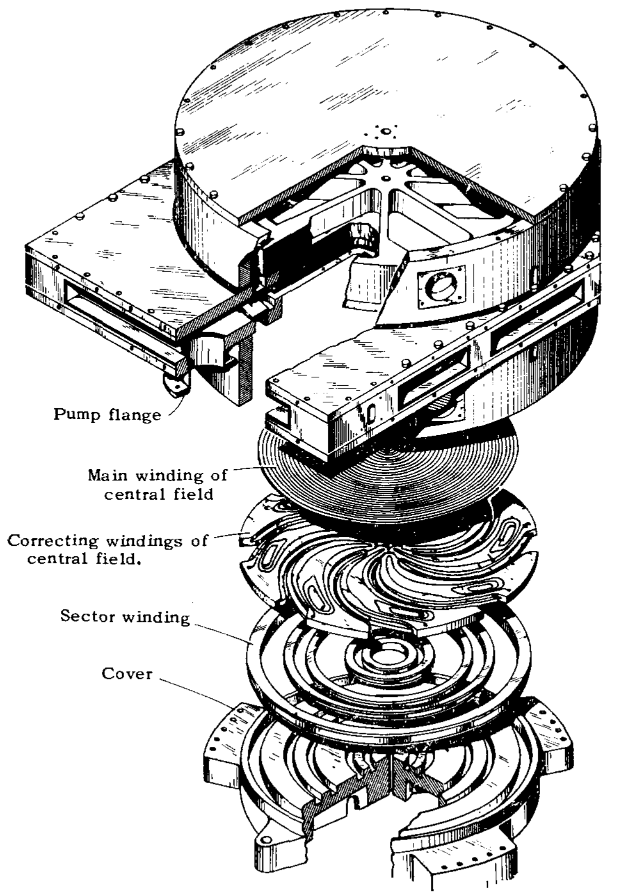

FIG. 3. Electronic model of isochronous cyclotron of the Oak Ridge National Laboratory.

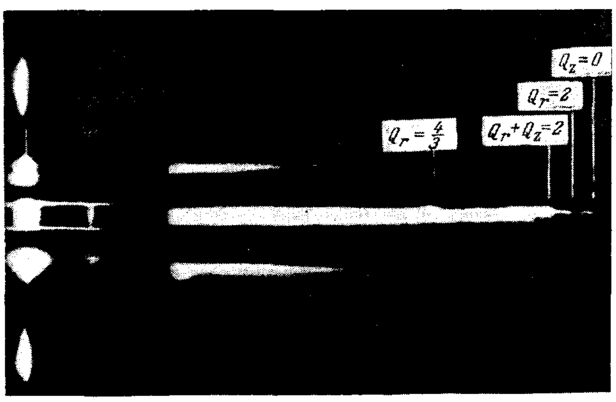

FIG. 4. Photograph of beam on a fluorescent target in the electronic model.

parameters must be met, and the appreciable activation of the accelerator units, of the particle paths, etc.

The greatest imprint on the solution of the problems has been made by the expected high intensity of the penetrating radiation (primarily neutrons) from the working accelerator and the high induced radioactivity of the parts of its chamber and of other devices.

The three considered meson factory projects differ in their approach to the solution of individual problems and in their relative subordination, thus leading to entirely different structural formulation of the accelerator design. Each of the projects has definite advantages over others at some stage of construction and operation of the accelerator, and also with respect to certain characteristics, but on the whole the experimental capabilities of all three machines are to a considerable degree similar.

The main parameters of the cyclotrons are listed in Table III, and their general forms are shown in Figs. 5—10.

1. Relativistic 700-MeV Proton Cyclotron

A distinguishing feature of the design of the relativistic cyclotron of the JINR Nuclear Problems Laboratory is that it is designed to use the electromagnet of the JINR 680-MeV synchrocyclotron.

In this case it is advantageous to produce the required variation by means of iron shims only. The latter circumstance limits the possible maximum of the variation and involves the need of using a minimum pitch of the radial structure of the field. This requirement, at a minimum structure pitch, is satisfied most closely by a magnetic field whose lines of maxima and minima lie on Archimedes spirals

$$r = N\lambda\varphi.$$

The choice of the radial pitch of the magnetic field structure ($2\pi\lambda$) is dictated, besides the condition for passing through the resonance zones, also by the minimum gap between the spiral shims on the final radii of the accelerator. Investigations have shown that the optimal variation of the magnetic field is obtained when λ is equal to half the gap[21].

The *minimum gap between the spiral shims* is determined in turn by the requirements that it is necessary to place in it the accelerating system, which is

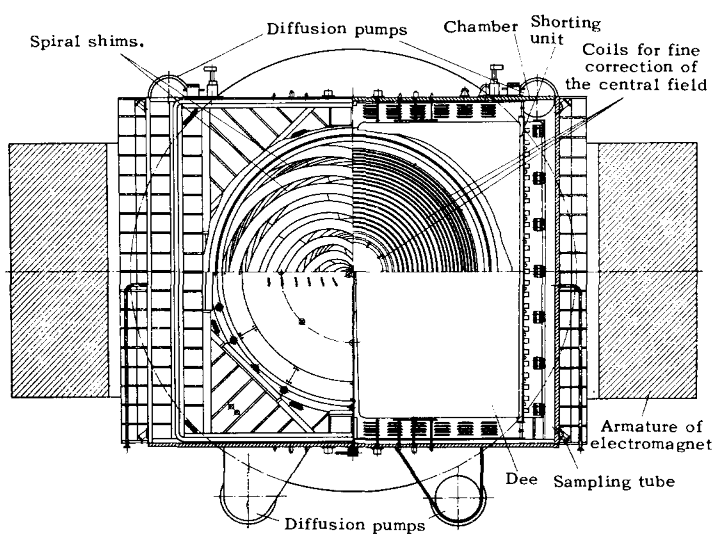

FIG. 5. Relativistic cyclotron (RC) of JINR (plan).

Table III. Principal parameters of meson factories: Relativistic cyclotron (RC) (Dubna), Mc^2 cyclotron (Oak Ridge), H^- cyclotron (Los Angeles),

	RC	Mc^2 cyclotron	H^- cyclotron
Maximum energy of internal beam, MeV	700	900	625
Energy of extracted beam, MeV	700	810	200—625
Maximum current of internal beam, μA	500	200	500 at 500 MeV 95 » 600 » 40 » 625 »
Radius of final orbit, cm.	325	610	1040
Injection energy	0	1 MeV	150 keV
Average value of magnetic field intensity of final radius, Oe	13 770	8820	4000
Number of spirals (sectors)	8	8	6
Angle between spiral and circle with final radius	11°	35°	12°
Gap between the spirals (pole pieces of sectors), cm.	14.6—22.0	20.3	76.2
Variation of magnetic field on the final radius, H_N/H	0,3	1.0	0.2
Frequencies of free oscillations axial	0.24—0.29	0.2—0,3	0.2—0.3
radial	1.0—1.8	1.0—2,0	
Frequency of accelerating electric field, Mc	12.05	13,72	11.04
Multiplicity	1	2	3
Number of accelerating gaps	2	4	2
Number of dees (resonators)	2	2	2
Maximum energy gained per revolution, keV	400	1000	520
Aperture of dee, or vertical gap between resonators, cm.	5	10.2	21.6
Gap between accelerating electrode and the cover of the chamber	3.4	—	5.08
Diameter of pole piece, cm.	700	1250	2230
Weight of electromagnet, tons	7700	5000	7100
Electromagnet supply power, kW	2100	7000—8000	3500
Maximum high frequency power, kW	2850	872	2750
Vacuum volume of chamber, m^3	65	2600	250
Working pressure in chamber, mm Hg	$5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	10^{-7}

made in the form of two dees comprising quarter-wave segments of an inhomogeneous line.

The central magnetic field along the radius is obtained by shaping the poles of the magnet and by a system of concentric current coils; the periodic part of the structure of the field is shaped, as already noted, by a system of spiral shims, shifted by an angle $2\pi/N$.

The vacuum chamber of the accelerator is rectangular in shape. The upper and lower bases of the housing have holes of 7 meters diameter, in which are inserted nonmagnetic discs on which spiral shims

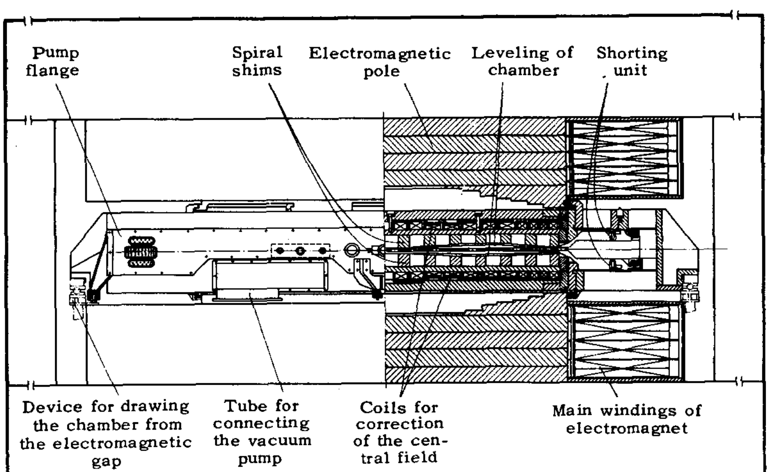

FIG. 6. Relativistic cyclotron (RC) of JINR (vertical section).

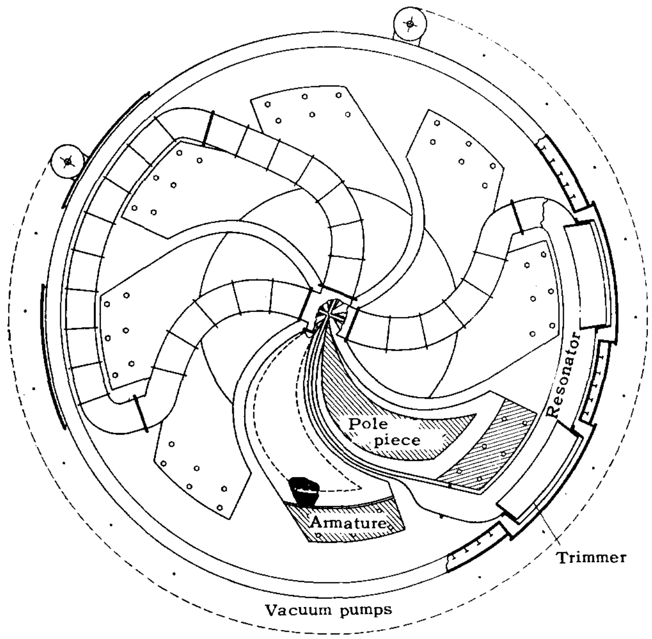

FIG. 7. Isochronous Mc^2 cyclotron of the Oak Ridge National Laboratory (plan).

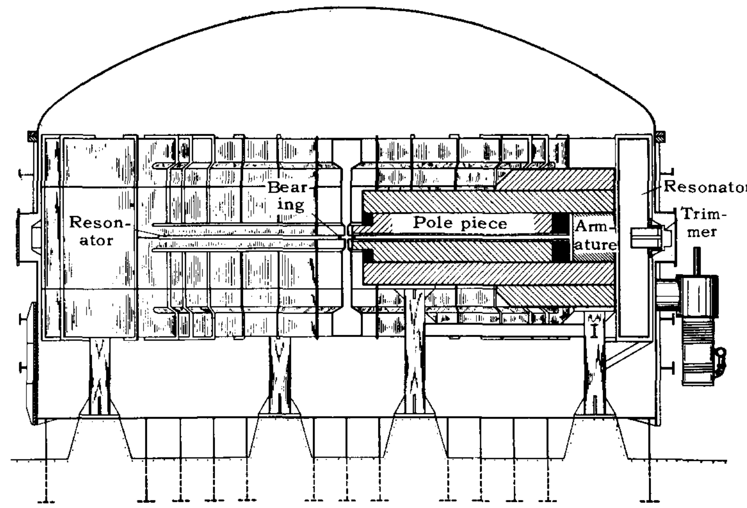

FIG. 8. Isochronous Mc^2 cyclotron of the Oak Ridge National Laboratory (vertical section).

and the coils for shaping and correcting the magnetic field are installed. Such a construction makes it possible to remove the chamber from the magnet gap and to perform the necessary operations with the required accuracy by means of manipulators from protective cabins. The dees can be drawn out of the chamber separately when the side flange is removed.

2. Isochronous Mc² Cyclotron

The magnetic system of the isochronous Mc^2 cyclotron consists of eight C-shaped sectors with spiral pole pieces; each sector has separate excitation windings.

In the structure of the magnetic field, the lines of maximum intensity lie on spirals $r = A\sqrt{\varphi}$.

Such a magnetic scheme makes it possible to effect acceleration with vertically oriented resonators occupying the space between neighboring magnetic sectors. The design provides for two such resonant cavities, each subtending over two neighboring magnetic sectors. The vertical gap of the electromagnet is not required to accommodate the dees, and its size is determined only by the aperture of the beam and by the heights of the windings placed over the inner surface of the pole piece, that is, it can be sufficiently small, and consequently the variation of the magnetic

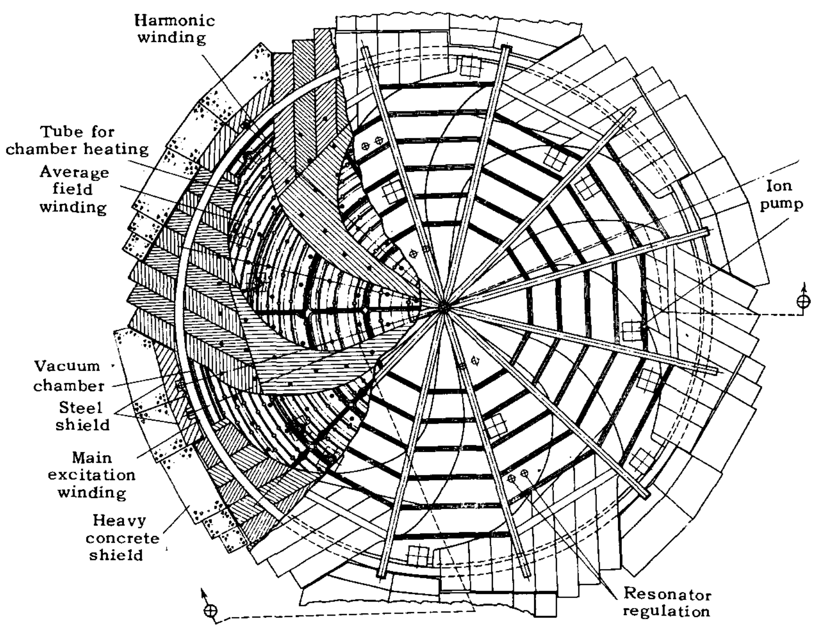

FIG. 9. H⁻ cyclotron of California University (plan).

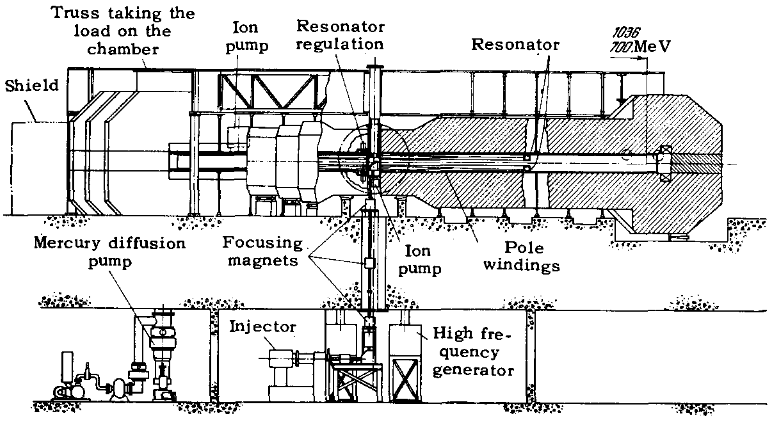

FIG. 10. H⁻cyclotron of California University (vertical section).

field can be sufficiently large. A weaker spirality can therefore be used.

In such a construction all the elements of the magnetic and accelerating systems should be completely contained in the vacuum chamber, the volume of which is 2600 m^3. The construction and evacuation of such a chamber are problems with which modern practice can cope, but the extensive use of manipulators makes working inside the accelerator difficult.

The injector used is a high-voltage 1-MeV accelerator placed outside the cyclotron room.

3. H^- Cyclotron for 625 MeV

Acceleration of negatively charged hydrogen ions in the H^- cyclotron makes it possible to solve the problem of high efficiency (almost 100%) extraction by stripping one or two electrons when the ions pass through a thin foil located at a suitable radius. In such an extraction scheme it is possible to obtain beams of extracted protons over a sufficiently wide energy range.

On the other hand, for the acceleration of negative ions it is necessary to provide conditions under which the ion losses during the acceleration process, due to the stripping of the electrons by the residual gas and due to the electric dissociation in the magnetic field, would not exceed some permissible value relative to the level of induced radioactivity inside the chamber. For these reasons, the pressure in the vacuum chamber of the H^- cyclotron must not exceed 10^{-7} mm Hg, and the maximum value of the magnetic field intensity at the final radius is limited to 4600 Oe; in this case the production of an intensity of 40 μA in an extracted beam with energy 625 MeV will be accompanied by losses in the acceleration process, equivalent to a current of 25 μA of 625-MeV protons. When a beam of low energy is extracted, the losses due to the electric dissociation in the magnetic field decrease, and the intensity of the external beam can be increased at the same level of equivalent losses in the chamber.

The magnetic system of the H^- cyclotron is made up of six C-shaped sectors. The magnetic system is excited by concentric coils common to all sectors, namely two main coils and 17 pairs located on the surface of the pole pieces.

The shapes of the sector pole pieces are such that there is no spirality up to half of the final radius; beyond this there is an increasing spirality, with the angle between the circle and the spiral amounting to 12° on the final radius.

The low magnetic field intensity makes it possible to obtain the required variation with a sufficiently large gap (76 cm).

The stainless steel-vacuum chamber, which is located in the gap of the electromagnet, has walls 2.2 cm thick. The necessary rigidity is provided by braces secured to structures above and below the electromagnet. Access to the chamber is possible when the upper poles of the sectors are removed. The required vacuum is produced in the chamber by 14 ion pumps.

The accelerating system is constructed in the form of four quarter-wave dees. Each dee is separated in turn into eight individual quarter-wave resonators installed symmetrically on the upper and lower covers of the chamber.

VI. SHIELDING AGAINST RADIATION

Radiation shielding of strong-current accelerators is a most complicated and vital problem. This becomes clear if we recognize that in meson factories with 0.5 mA beam currents the integral currents of neutrons with energies of tens and hundreds of MeV reach 10^{16} sec^{-1}, and the activity of a target following the irradiated by the beam of 3×10^{15} protons/sec is hundreds of gram-equivalents of radium. The conditions under which the personnel operates during preventive maintenance and repair of the equipment in such accelerators becomes to a considerable degree analogous to work with nuclear reactors. In this connection, the designs of the chambers and all the units located in the activation zone of the accelerator proper, and also of the devices used for focusing and collimation of the most intense particle beams, should provide for dismantling, inspection, and repair with the aid of a set of moving cabin manipulators and cranes with cabins which are reliably shielded against gamma radiation. It is obvious that this holds also for the targets that serve as sources of secondary particles.

Special experiments with different materials used in these designs have shown that there is little difference between materials with respect to degree of activation under prolonged irradiation by high-energy protons[22,23]. It has thus been established that there are no special possibilities in this respect, all the more since the materials from which the main elements of the accelerator are made (magnet, dees, plating of the resonant system, and many others) are rigorously prescribed by entirely different conditions.

Material irradiation experiments and nuclear research have shown that the most suitable material for targets to serve as sources of secondary-particle beams (n, π, μ, etc.) is graphite.

To obtain the most efficient and economical shielding against neutrons in experimental pavillions and surrounding structures, as a rule, the strong-current accelerator proper is placed in a concrete vault with sufficiently thick and partially dismountable walls (see Fig. 11, which shows by way of illustration a plan of the shielding for the JINR relativistic cyclotron). The experimental pavillions, in which the radiation intensity during beam experiments is also high, have their own concrete shields, but of smaller thickness.

The primary proton beam and the most intense of secondary-particle beams are attenuated after passing through the target in specially designed sufficiently thick concrete traps. These traps have good heat transfer, since the power released in them can reach hundreds of kilowatts.

The design of radiation shielding for the accelerator takes account of the fact that the attenuation half-value layer of 700-MeV ($\lambda_{1/2}$) neutrons in ordinary concrete (density 2.4 g/cm^3) amounts to 42 cm[24]. In many cases a combined shield of concrete and cast iron or lead is used. For concrete and lead $\lambda_{1/2}$ is 16.5 and 15 cm, respectively[25].

VII. PRODUCTION AND UTILIZATION OF PARTICLE BEAMS FROM MESON FACTORIES

In all the synchrocyclotrons operating at present, the secondary particle beams are obtained predominantly from targets installed inside the accelerator chambers.

In contrast, in order to prevent excessive activation of the accelerating units, provision is made in the designs of relativistic cyclotrons used to obtain beams of mesons, neutrons and polarized nucleons for the use of external targets placed in the path of the extracted proton beam.

The tendency towards a fullest and most rational utilization (from the point of view of solution of scientific problems) of the high intensity of such accelerators is manifest in practice in the fact that provisions are made to install in the path of the extracted photon beam several movable targets simultaneously. The focusing and deflection of this beam, and also of the secondary-particle beams, is by means of channels consisting of hard-focusing lenses and deflecting electromagnets. As a rule, all these devices are equipped with remote control and regulation equipment.

The various secondary beams obtained in this manner are guided to the corresponding experimental pavillions through collimators built into the shielding walls (on the order of 8 or more meters of ordinary concrete). As a rule, the number of such pavillions does not exceed three. In the design of the JINR relativistic cyclotron[18], as can be seen from Fig. 11, one pavillion is located directly in the accelerator building, and two others are in a different housing. In the Oak Ridge Laboratory design[3] the pavillions are located one behind the other parallel to the proton beam and are designated the proton, pion, and muon pavillions (Fig. 12). A third solution is found in the design of California University[20] (Fig. 13).

The absolute intensities of beams of various particles, expected from the meson factories, are illustrated in Table IV, in which use is made, for example, of the data of the JINR 700-MeV relativistic cyclotron[18], calculated for an extracted proton beam of ~ 450 μA. The same table shows for comparison the intensities of the beams from the presently operating JINR 600-MeV synchrocyclotron, which produces an accelerated-proton beam of 2.3 μA. We see that on the average the intensity of the secondary beams increases by a factor of a thousand or several thousand. A particularly strong increase in the intensity is observed for the 300-MeV π^+-meson beam, because of the unique method used to obtain it by means of the reaction $p + p \rightarrow \pi^+ + d$, which has a maximum cross

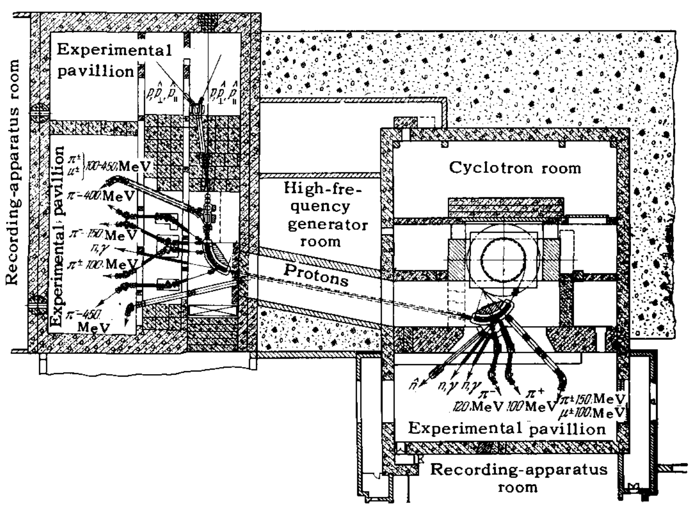

FIG. 11. Particle beams from the JINR relativistic cyclotron.

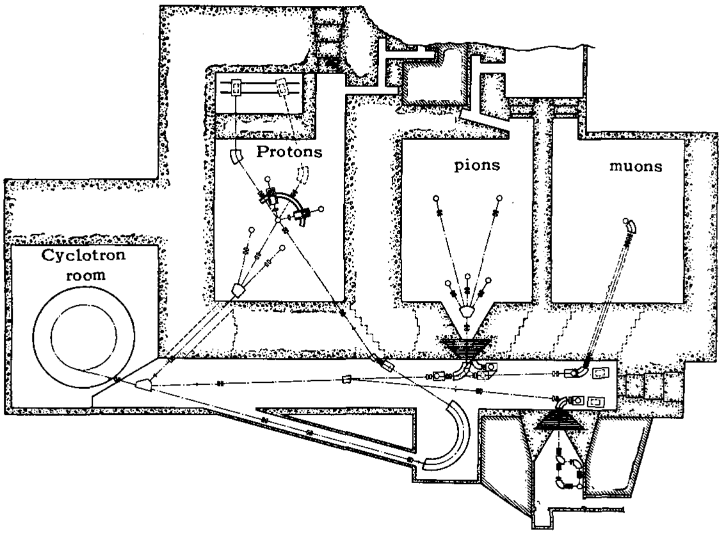

FIG. 12. Particle beams from the isochronous Mc² cyclotron of the Oak Ridge Laboratory.

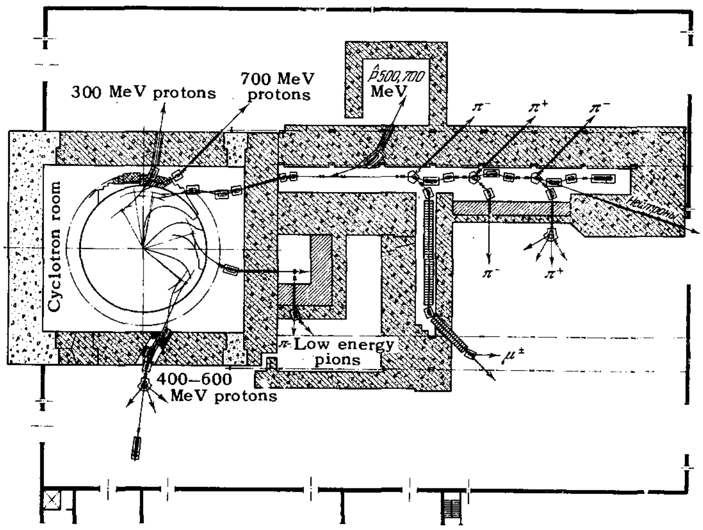

FIG. 13. Particle beams from H⁻ cyclotron of the California University (Los Angeles).

section at a proton energy near 600 MeV and which gives a sharply forward-peaked pion beam.

In the design of the JINR relativistic cyclotron there is provision also for obtaining a beam of muonic neutrinos from $\pi \rightarrow \mu + \nu_\mu$ decay, and for performing experiments with it in a laboratory well shielded against neutrons. To improve the conditions for shielding against neutrons, this laboratory is located below the level of the main proton beam and at an angle of 90° to it. During the course of the neutrino experiments it is possible to place in the main proton beam a special massive target which generates pions (neutrinos).

Provision is also made in this design for irradiating with the primary proton beam targets intended for research in the field of nuclear spectroscopy and nuclear chemistry, as well as for rapid transfer of the targets to a special high-speed laboratory. Radiobiological and other investigations can also be made. The designs of the strong-current accelerators of the USA laboratories also provide for research in these fields.

Table IV. Relative intensities of the secondary-particle beams from the JINR 700 MeV relativistic cyclotron (RC) and 680 MeV synchrocyclotron.*

Particles	Energy, MeV	Intensity (sec^{-1}) at given area	
		RC	SC
Transversely polarized protons	640	$4\cdot10^{10}$ (20 cm^2)	$4,5\cdot10^7$ (10 cm^2)
Longitudinal polarized protons	640	$4\cdot10^{10}$ (20 cm^2)	$3\cdot10^7$ (10 cm^2)
Neutrons	Over the extent of the spectrum	$1\cdot10^8$ (20 cm^2)	$3\cdot10^6$ (20 cm^2)
Transversely and longitudinally polarized neutrons	Over the extent of the spectrum	$1\cdot10^5$ (20 cm^2)	—
Positive pions	155±5	$2\cdot10^9$ (200 cm^2)	$4.5\cdot10^4$ (20 cm^2)
	300±8	$1\cdot10^{10}$ (200 cm^2)	$2.5\cdot10^5$ (80 cm^2)
	400±10	10^9 (200 cm^2)	—
Negative pions	155±5	$3\cdot10^8$ (200 cm^2)	$4\cdot10^4$ (60 cm^2)
	300±8	$6\cdot10^8$ (200 cm^2)	$4\cdot10^4$ (75 cm^2)
	400±10	$5\cdot10^7$ (200 cm^2)	—
$\mu^\pm$ mesons	100—400	1% of $\pi\pm$- mesons	
Negative pions	125	—	$3\cdot10^5$ (80 cm^2) **
Negative muons	65	—	$3\cdot10^4$ (80 cm^2) **
Neutrinos	30	$5\cdot10^7$ cm^{-2} sec^{-1}	—

*Intensity of beams is given for a distance 15 meters from the target.

**Intensity of the π^- and μ^- meson beams obtained using a channel of 28 hard-focusing lenses

VIII. USE OF LINEAR PROTON ACCELERATOR AS A MESON FACTORY

Besides the relativistic cyclotron, a linear proton accelerator for 700—800 MeV energy with intensity on the order of 1 mA can also serve as a meson factory. At the 1963 CERN conference on meson factories, two 750-MeV designs for a linear proton accelerator were proposed, as well as one for 300 MeV.

The most advanced is the design proposed by Yale University[26]. Using this design as an example, we can become acquainted with the main characteristics of meson factories of this type. The design calls for the construction of a linear proton accelerator for 750-MeV energy and an accelerator-proton current of 1 mA. The most important characteristic of the linear accelerator is the duty factor, that is, the ratio of the length of the macropulse of accelerated particles to the period between pulses. An increase in the duty factor greatly increases the cost of the high-frequency power sources, while a decrease makes it necessary to accelerate larger current pulses. The investigations have shown that the optimal duty cycle using existing power sources is 5%, that is, the current of the particles in the pulse should be 20 mA.

The accelerator consists of two sections: the first section, 137 meters long, is an accelerating system using drift tubes and operating at 200 Mc, in which the protons are accelerated to 200 MeV ($\beta \approx 0.57$); the second section, 413 meters long, is a diaphragm-loaded waveguide operating at 800 Mc. The waveguide is divided into sections 5 meters long, operating with a π-type standing wave.

The injector is a 750-keV Cockroft-Walton generator. A buncher of the klystron type is located between the injector and the first drift tube.

The length of the macropulse is 2 msec. The authors of the design note that a pulse of such duration cannot be provided by existing klystrons feeding a waveguide section, and modernization of the klystrons is essential. The total high frequency power is ~ 4 MW.

The macropulse constitutes 4×10^5 micropulses of 0.07 nsec duration, spaced 5 nsec apart. If we assume that the cross section of the beam is 1 cm^2, then the density of the particles in the micropulse is 3×10^8 cm^{-3} at an average current of 1 mA and a duty cycle of 5%. The accelerated bunches are stabilized radially by quadrupole lenses installed inside the drift tubes and between sections of the waveguide system; a total of 240 lenses is used.

The authors of the project believe that a linear proton accelerator used as a meson factory can ensure the following:

a) A beam intensity on the order of 1 mA at 750 MeV proton energy;

b) The possibility of regulating the energy, starting with 200 MeV, in steps of 7—10 MeV up to the final energy value;

c) 100% extraction of the accelerated beam from the accelerator at good beam quality (phase volume $4.6\pi \times 10^{-4}$ cm-rad);

d) the possibility in principle of accelerating polarized protons;

e) the performance of physical experiments which require very short pulses of accelerated particles (0.07 nsec).

At the same time, many problems necessitate additional research. Such questions as how changes in the load (the power of which at maximum current is 750 kW), brought about by the beam, affect the operating conditions of the high-Q resonators, how to regulate with high precision the amplitude and the phase of the high-frequency field in the 75 resonators of the accelerating system, how to set the quadrupole lenses with high accuracy, and many others call for more thorough study.

At the present time many laboratories are carrying out research aimed at reducing the high-frequency power absorbed by the walls of the resonators and by the drift tubes, thereby increasing the duty cycle to 100%. Resonators with walls made of a superconducting material cooled to liquid-helium temperature are being investigated. It has been shown experimentally that the loss power is decreased thereby by a factor of 10^4. It is pointed out, however, that serious difficulties may arise when operating with a system of resonators whose Q amounts to 10^8—10^9.

It must be noted that the macropulse duty cycle used (5%), together with the need for having very short pulses (0.07 nsec) in the microstructure, leads to relatively large densities of the accelerated particles in the microstructure for a transition from one accelerating frequency to another to be feasible. At an average current of 1 mA, the density in the proton bunch of the Yale linear accelerator is approximately 10 times larger than in the relativistic cyclotron whose design was considered earlier[18]. Therefore a system that ensures stability of the accelerated bunches should have sufficient focusing strength, to compensate for both the defocusing of the accelerating high-frequency field, as well as for the influence of the space charge of the bunches, which are particularly large at low velocities of the injected particles ($\beta_i \approx 0.4$). From this point of view, the relativistic cyclotron is apparently most promising as a meson factory should the need arise for increasing the intensity to tens and hundreds of milliamperes.

CONCLUSIONS

Modern elementary-particle physics is dealing with the problem of greatly increasing the intensity of the beams of the particles obtained from high-energy accelerators, as one of the principal conditions that ensure its further progress in discovering the laws of the microworld. In the present review we attempted to present a brief description of the physical principles of the most important problems in the theory and of the concrete designs developed by various laboratories, for strong-current accelerators (meson factories) for energies up to 1 GeV. The construction of such accelerators with current on the order of 1 mA is perfectly feasible at the present stage of development. As a result of their construction, the physicists will be able even in the next decade to use in their experiments meson beams up to 10^{10} sec^{-1}. The powers of the beams of accelerated protons will reach in these meson factories large values, hundreds of kilowatts, or 1 megawatt. However, there is a method that can in principle (Chapter III, Sec. 5) lead to accelerators with high-energy particle beams which is even hundreds of times larger in power.

In our opinion, such an atomic machine will be used more readily to solve practical problems than for pure science. The conceivable prospects of development of the latter in the energy range up to 1 GeV can be ensured apparently quite fully by production of the described meson factories.

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Translated by J. G. Adashko