УСКОРИТЕЛИ
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ELEMENTARY PARTICLE ACCELERATORS

IN ENGLISH TRANSLATION

ELEMENTARY PARTICLE ACCELERATORS

(USKORITELI ELEMENTARNYKH CHASTITS)

(Supplement No. 4 of the
Soviet Journal of Atomic Energy
ATOMNAYA ENERGIYA)

Atomic Press, Moscow – 1957

IN ENGLISH TRANSLATION

CONSULTANTS BUREAU, INC.
227 West 17th Street
New York 11, N. Y.

Printed in the United States

Price per copy $15.00
Price to subscribers of J. Atomic Energy $10.00

EDITOR'S NOTE

The All-Union Conference on the Physics of High-Energy Particles was held in Moscow from May 14 to May 22, 1956. Papers on elementary-particle accelerators were reported and discussed at the sessions of one of the sections. Abstracts of the majority of the papers were published before the start of the conference ("Abstracts of the Reports to the All-Union Conference on the Physics of High-Energy Particles," Acad. Sci. USSR Press, 1956).

At the present time, many of the reports have already been published in a number of journals, including the journal "Atomic Energy."

The present Supplement to the journal "Atomic Energy" offers the reader a group of reports which, at the present time, either have not been published at all or published in incomplete form.

Certain of the papers included in the collection were contributed to the CERN symposium on charged particle accelerators (Geneva, June,1956). These include the following: "Magnetic Characteristics of the 10-Bev Proton Synchrotron" by A.A. Zhuravlev, E.G. Komar, I.A. Mozalevskii, N.A. Monoszon and A.M. Stolov, "Certain Features of High-Energy Cyclic Electron Accelerators" by A.A. Kolomenskii and A.N. Lebedev, and "The Sector Cyclotron" by E.M. Moroz and M.S. Rabinovich.

The paper "Concerning the Theory of Particle-Beam Focusing in a Linear Accelerator by System of Transverse Lenses" by A.A. Sharshanov deals with the contents of part of the paper "Strong Focusing in Linear Electron Accelerators" (K.N. Stepanov and A.A. Sharshanov) presented at the All-Union Conference on the Physics of High-Energy Particles.

The reports published in this collection should be useful for specialists working with cyclic or linear elementary-particle accelerators.

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PHYSICAL FACTORS IN THE DESIGN OF THE 10-BEV PROTON-SYNCHROTRON

V.I. Veksler, A.A. Kolomenskii, V.A. Petukhov and M.S. Rabinovich

Cyclic accelerators of the synchrotron type are used to obtain protons with the highest energies presently available. All accelerators in operation or proposed for accelerating protons to energies greater than 1 Bev are synchrotron machines.* In the majority of cases the application of strong focusing is a concomitant of synchrotron acceleration.

The theory of synchrotron operation, developed by us in 1948-1950 in conjunction with the work carried out in studies of a 180-Mev machine of this type at the P.N. Lebedev Institute of Physics, Academy of Sciences, USSR, and the construction of the 10-Bev synchrotron have furnished a reliable basis for delineating the design principles of machines of this type.

In the present report, which is devoted to the physical factors involved in the design of the 10-Bev proton synchrotron at the Academy of Sciences, USSR,** the following topics are considered:

1) a general theory for the motion of particles at different stages of the acceleration cycle: injection by the injector-accelerator, particle injection (capture), the acceleration phase, particle extraction;

2) the effect of different perturbations; resonances in betatron and synchrotron oscillations;

3) tolerances for the various parameters;

4) basic requirements for the auxiliary apparatus.

A number of related problems are considered in reports devoted to a 180-Mev proton synchrotron model which has been built and operated at the Physics Institute of the Academy of Sciences.

We now give certain of the basic characteristics of the accelerator at the Academy of Sciences USSR which are used in the present report:

Maximum particle energy	10 Bev
Energy at injection	~9 Mev
Length of acceleration cycle	3.3 sec
Mean particle-energy increment per revolution	~2.2 kev
Orbit radius	28 m
Number of straight sections	4
Length of each straight section	~8 m
Aperture of vacuum chamber	200 x 36 cm^2
Width of working region (magnetic field index n = 0.55-0.75) with the correction windings energized:	
a) at injection	~135 cm
b) at the end of acceleration	~90 cm

*In the Russian literature, a proton-synchrotron (synchrophasotron) is customarily taken to mean a circular, self-phasing accelerator with fixed radius, variable magnetic field, and variable acceleration-voltage frequency.

**As is known, this accelerator, which has been turned over to the Joint Institute for Nuclear Research, was first put into operation in April of 1957.

Betatron Oscillations

We consider the particle motion in a coordinate system based on the family of coordinate lines formed from the instantaneous closed orbits and the curves orthogonal to these orbits. It can be shown that the oscillation equation assumes the following form

$$x'' + \varkappa^2(\sigma)\, g(\sigma)\, x = 0, \qquad x = \rho,\ z, \tag{1}$$

where ρ and $\underline{z}$ are respectively the radial and vertical coordinates and the primes denote the differentiation with respect to σ, the length taken along the orbit:

$$\kappa^2(\sigma) = \begin{matrix} 1 - n(\sigma) \text{ for radial oscillations} \\ n(\sigma) \text{ for vertical oscillations} \end{matrix}$$

$\underline{x}$ is the deviation from the orbit; $g(\sigma) = \dfrac{1}{R^2(\sigma)}$; $R(\sigma)$ is the radius of curvature. The function $g(\sigma)$ is periodic with period σ_0. In the cases which are of practical interest (far from resonance) the solution of Equation (1) can be written in the form

$$x = De^{i\mu\frac{\sigma}{\sigma_0}}\psi(\sigma) + \text{c. c.}^{*}), \tag{2}$$

where $\psi(\sigma)$ is a periodic function (the complex Floquet function).

The modulus of the function $\psi(\sigma)$ and the complex-conjugate function $\psi^*(\sigma)$, which we normalize so that the Wronskian is equal to $-2i$, has a number of interesting properties. The maximum deviation of the particles at any azimuth σ can be given as follows:

$$A^2 = \frac{\Phi(\sigma)}{\Phi(\sigma_i)}\left[x_{\text{int}}^2 + \Phi^2(\sigma_i)(\gamma_{\text{int}} - \gamma_{\text{opt}})^2\right], \tag{3}$$

$$\gamma_{\text{opt}} = \frac{x_{\text{int}}}{2}\left(\frac{d\ln\Phi}{d\sigma}\right)_{\sigma_i},$$

where γ_{opt} is the optimum value of the angular deviation γ. The focusing is characterized by the quantity $\Phi^2(\sigma_i)$ which may be assumed to be the effective radius of the machine. If we reduce $\Phi^2(\sigma_i)$ it is possible to increase the angular deviation without increasing the oscillation amplitude. The minimum amplitude is achieved with $\gamma = \gamma_{\text{opt}}$ where γ_{opt} depends on x_{int}. This fact is of importance in long injection when $x = \rho$ changes from zero to ρ_{inj}, the distance from the injector plates to the mean orbit.

For the synchrotron which is being considered

$$\Phi(\sigma_i) = \frac{R^2}{1-n} - 1.1,$$

whence it is obvious that the focusing does not deteriorate by more than 5% because of the straight sections. Thus, if the only effect of the straight sections were on the focusing properties, these sections could be several times longer. During the time of injection γ_{opt} varies from 0 to 3'. This quantity is significant if one takes account of the fact that an error in the injection angle of approximately 10' is sufficient to prevent particles from being captured in the acceleration phase.

Effect of Distortions of the Magnetic Field on Particle Motion

Distortions of the magnetic field can be taken into account if we introduce the function $q = q(\sigma)$ on the right-hand side of Equation (1). To describe any "nonresonance" perturbation it is sufficient to find the distorted closed orbit. Of all the solutions of Equation (1), we are interested only in those which are periodic, i.e.,

---

*c.c. denotes the complex conjugate.

$$x_M(\sigma) = \frac{\psi(\sigma) e^{iN\mu}}{2i(1-e^{iN\mu})} \int_{\sigma}^{\sigma+\Pi} q(s)\psi^*(s)\,ds + \text{c.c.} \tag{4}$$

where $\psi(\sigma)$ is the Floquet function; N is the number of straight sections; Π is the perimeter of the orbit and μ is a characteristic exponential index.

This formula is not suitable for practical calculation; hence it is convenient to expand Equation (4) either in a Fourier series or in a series of eigenfunctions of Equation (1).

The eigenfunctions of this equation have been determined and tabulated for the 10-Bev machine. These functions were used in a calculation carried out to check the effect of distortions of the magnetic field on particle motion.

Here we shall limit ourselves to a consideration of certain examples. Suppose the solution in (4) is expanded in a Fourier series. As is well known, in circular accelerators (without straight sections) a decisive role is played by the first harmonic. We introduce the resonance factor in the expression for the orbit distortion

$$M_\rho = \frac{1}{\kappa_{res}^2 - \kappa^2} = \frac{1}{1-(1-n)} = \frac{1}{n} \text{ for radial oscillations}$$

$$M_z = \frac{1}{\kappa_{res}^2 - \kappa^2} = \frac{1}{1-n} \text{ for vertical oscillations.}$$

The frequency of rotation is taken as unity. Hence the first factor corresponds to resonance with the radial oscillations for $n_{res} \approx 0$; the second corresponds to resonance with the vertical oscillations for $n_{res} \approx 1$. In a circular accelerator these resonances are found at the boundaries of the stability region; however, the presence of straight sections shifts the resonances toward the inside of this region. For example in the 10-Bev synchrotron $n_{res} = 0.16$ for the radial oscillations and $n_{res} = 0.84$ for the vertical oscillations.

From the expression for the resonance factor $M_{\rho,z}$ it is clear that because of changes in the values of $(n_{res})_{\rho,z}$ due to the presence of the straight sections, the effect of field perturbations is increased significantly. All other things being equal, distortion of the instantaneous orbit turns out to be 30-40% greater and distortion of the medium plane is as much as 2-3 times greater than in a corresponding accelerator without straight sections.

Calculations and experiments with the models have shown that a magnet is required in which the distortions of the orbit do not exceed ± 20 cm in the radial direction and ± 6 cm in the vertical direction. These requirements have been satisfied using straight sections approximately 8 meters in length; these sections are also acceptable from other points of view (radiofrequency system, particle extraction, etc.). A further increase in the length of the straight sections would impose more stringent requirements on the accuracy of the magnetic field.

Resonances with Fast (Betatron) Oscillations

Resonances with fast oscillations are extremely dangerous. It is this effect which determines to a great extent the choice of the magnetic-field index n.

We use the symbol $Q_{\rho,z} = \frac{N\mu_{\rho,z}}{2\pi}$ to denote the number of betatron oscillations executed by the particle per turn.

In a periodic magnetic system, such as the weak-focusing accelerator with straight sections being considered here, the following resonances appear in the linear approximation: a simple (external) resonance in combination with the parametric resonance ($Q_{\rho,z} \approx k$, where k is a whole number); a parametric resonance ($Q_{\rho,z} \approx k \pm 1/2$); and combination resonances ($Q_\rho \pm Q_z \approx k$) – sums and differences of the values of Q.

The expression for the characteristic number $\mu_{\rho,z}$ is of the form:

$$\cos\mu_{\rho,z} = \cos\frac{2\pi\varkappa}{N} - \frac{\varkappa L}{2R}\sin\frac{2\pi\varkappa}{N}, \tag{5}$$

where L is the length of the straight section.

For a simple resonance with the parametric resonance ($Q \approx 1$)

$$(n_{res})_z \approx 1 - \frac{NL}{2\pi R}, \qquad (n_{res})_\rho \approx \frac{NL}{2\pi R}, \tag{6}$$

which yields $(n_{res})_z = 0.84$. The first and second eigenfunctions (harmonics) of ΔH_z are resonant for ρ-motion, the first harmonic H_ρ for z-motion and the second harmonic of Δn for ρ-motion and z-motion (ΔH_z, H_ρ and Δn describe the perturbations).

In the parametric resonance ($Q \approx ½$)

$$(n_{res})_\rho \approx 0{,}75 + \frac{NL}{8\pi R}, \qquad (n_{res})_z \approx 0{,}25 - \frac{NL}{8\pi R}, \tag{7}$$

which yields $(n_{res})_\rho = 0.79$, $(n_{res})_z = 0.16$. The first harmonics of ΔH_z and Δn are resonances for ρ-motion and the first harmonic of Δn for z-motion.

In large synchrotrons (with $N = 4$) such as that being considered here, the numerical values in (6) and (7) turn out to be very close:

$$(n_{res})_{\rho,z} \approx 0.8, \quad (n_{res})_{\rho,z} \approx 0.2.$$

The difference resonance, which appears in the transfer of oscillation energy from the radial motion to the vertical motion and vice versa, corresponds to a value

$$n_{res} \approx 0.5, \tag{8}$$

when the frequencies of the ρ- and z-motions are equal. If there are straight sections, in addition to (8) there are still two other values n_{res}, which lie inside the stability region although very close to the boundaries:

$$n_{res} \approx \left(\frac{NL}{4\pi R}\right)^2, \qquad n_{res} \approx 1 - \left(\frac{NL}{4\pi R}\right)^2.$$

The sum resonance is encountered in a circular accelerator only at the boundaries of the stability region ($n_{res} = 0$, $n_{res} = 1$). If there are straight sections which satisfy the usual condition $NL/4\pi R \ll 1$, the production of this resonance in a weak-focusing magnet is impossible.

In addition to the linear resonances, under certain conditions it turns out that certain nonlinear resonances are dangerous, for example the resonance at $n \approx 0.2$, which corresponds to $Q_\rho = 2Q_z$ and plays an important role in frequency-modulated cyclotrons.

An investigation has shown that the danger zone (in terms of resonances) in the present machine is the region in which the following condition applies:

$$0.55 < n < 0.75.$$

The widths of the resonances, which depend essentially on the magnitude of the perturbations have been calculated; an estimate has also been made of the oscillations (or resonance damping) in passing through a resonance during injection, the time during which the beam spirals into the target, and extraction.

All these data have been used in setting up the requirements on the configuration of the magnetic field in the accelerator gap.

We may note that different resonances play different roles in the acceleration process. It has been shown that under certain conditions the effect of certain resonances, particularly at $n \approx 0.79$, $n \approx 0.84$, $n \approx 0.5$, may be beneficial, for example in increasing the injection efficiency or in extraction of particles from the chamber.

We have considered the problem of resonance "blow-up" due to the synchrotron oscillations in the acceleration process. The results of the theory have been compared with experiment in an operating model of a synchrotron which accelerates protons to energies of 180 Mev. It should be noted that the analytic calculations involve a number of mathematical difficulties because of the nonlinearity of the basic phase equation. The calculations were carried out on a basis of asymptotic methods developed by N.N. Bogoliubov and Iu.M. Mitropol'skii for use in nonlinear mechanics.

In the linear approximation the following expressions are obtained for the amplitude of the phase oscillations after passage through resonance:

$$\left.\begin{aligned} \alpha_{max}^{lin} &= \sqrt{\frac{\pi}{2\,|\dot{\omega}_\Phi|}}\cdot\frac{\omega_0}{(1-n)\,\tau}\cdot\frac{h_j}{H}, \quad \left(\tau = 1+\frac{L}{2\pi R}\right); \\ \alpha_{max}^{lin} &= \sqrt{\frac{\pi}{2\,|\dot{\omega}_\Phi|}}\; c_j; \\ \alpha_{max}^{lin} &= \sqrt{\frac{\pi}{2\,|\dot{\omega}_\Phi|}}\; \omega_\Phi \cot\varphi_0 b_j, \end{aligned}\right\} \qquad (10)$$

where h_j, c_j, b_j are the amplitudes of the resonance harmonics for H, ω_0, V_0; ω_0 is the frequency of the accelerating voltage, the amplitude of which is V_0; ω_Φ is the frequency of the small synchrotron phase oscillations; φ_0 is the equilibrium phase.

In the nonlinear case which is applicable to oscillations of H we use the approximation formula:

$$\alpha_{max}^{non-lin} \approx \frac{4.8}{1+{}^5/_3\cot^2\varphi_0}\left[\sqrt{\frac{\pi}{2}}\cdot\frac{\omega_0}{\omega_\Phi}\cdot\frac{h_j}{H}\cdot\frac{1}{(1-n)\tau}\right]^{1/2}. \qquad (11)$$

On the basis of Equations (10) and (11) we have set the allowances on the resonance harmonics h_j, c_j and b_j for which the amplitude of the phase oscillations remain less than one radian (the excursion of the factor in brackets to the right of φ_0 is approximately 1.5 radians).

The supply for the electromagnet winding of the accelerator is a six-phase full-wave rectifier; the first harmonic of the field ripple is at a frequency of 600 cps. For this reason the magnetic-field ripple was investigated with an oscilloscope.

Below are shown the results of an analysis of these curves (obtained without energizing the special circuit for suppressing ripple) in a Fourier series*:

$$h_{600} = 3.5\cdot 10^{-2} \text{ gauss;}$$

$$h_{1200} = 10^{-2} \text{ gauss;}$$

$$h_{1800} = 3.5\cdot 10^{-2} \text{ gauss.}$$

*In accordance with the last data the following values are obtained for the ripple amplitudes (in percent of the main field H):

Field strength, gauss	Frequency, cps		
	600	1200	1800
150	2,3	0	0.3
4000	5	2	1
11 600	7.8	3	1.5

Calculations have shown that these harmonics, though small in amplitude can lead to an important excursion of the phase oscillations. In the radio-frequency apparatus there is provision for adjusting the amplitude V_0 during the acceleration process so that the frequency of ω_Φ does not pass through 600 and 1800 cps.

Hence the most dangerous harmonic is at 1200 cps; passage through this frequency cannot be avoided. The results of a calculation of the amplitude of the phase oscillations produced by this harmonic are given in the following table where we show data corresponding to different values of V_0.

V_0, kv	$\cos \varphi_0$	α_{max}^{lin}, rad	$\alpha_{max}^{non-lin}$, rad
9.6	0.25	0.9	0.70
5.8	0.40	1.3	0.85
4.8	0.48	1.5	1.00
4.0	0.57	2.2	1.05

Using a special scheme for suppressing ripple it was possible to reduce the amplitude of the resonance harmonics by a factor of 6 or 7.

Another extremely dangerous factor for the operation of the accelerator is the effect of noise in the magnetic field, and frequency and amplitude of the accelerating voltage. The square root of the mean-square amplitude of the phase oscillations (at the end of acceleration) due to noise, is given by the expression

$$\langle a^2\rangle^{1/2} \approx \frac{K}{\omega_\Phi}(\pi\Phi T)^{1/2}, \tag{12}$$

where T is the acceleration time, K is a factor which depends on the type of noise (for the magnetic field $K = -\frac{\omega_0}{H}\cdot\frac{1}{(1-n)r}$; Φ is the spectral density of the noise, defined by the expression

$$\int_0^\infty \Phi(\omega)\,d\omega = \frac{1}{T}\int_0^T \Gamma^2(t)\,dt, \tag{13}$$

where $\Gamma(t)$ is the noise (for example, $H = H_0 + \Gamma(t)$, H_0 is the calculated field). Starting from the requirement that $a_{max} \lesssim 1$ rad, we can set the allowable spectral densities on the noise for H, ω_0 and V_0:

$$\Phi_H \approx 2.5\cdot 10^{-9}\ g^2/(\text{rad/sec}),$$

$$\Phi_{\omega_0} \approx 1\ \text{rad/sec},$$

$$\Phi_{V_0} \approx 9\cdot 10^{-9}\ \text{sec}.$$

It should be emphasized that the methods used in the calculations do not allow us to solve completely the complex mathematical problem involved in the loss of phase stability due to resonance harmonics and noise and that these theoretical results must be supplemented by experimental work.

Injection and Capture in the Acceleration Phase

Different methods of injection have been investigated: betatron, synchrotron, etc.; on the basis of the results of the investigation a system of injection which takes place in two stages has been chosen.

The first stage – in which the instantaneous orbit spirals in with the accelerating field shut off – lasts approximately 200-300 μsec. The second stage – in which the accelerating voltage is switched on and capture and acceleration occur – is approximately as long as one period of the synchrotron oscillations (approximately 1 μsec).

Using a specially developed analytical approach we have calculated the injection efficiency for different initial conditions and beam characteristics as well as various values of V_0 and other parameters. To increase the injection efficiency provision is made for control of (compensation) the first and second harmonics of the azimuthal asymmetry and the first harmonic of the perturbation of the median plane of the magnetic field as well as the values of n in the operating region over a range of approximately ± 0.1.

Entrance of Particles into the Vacuum Chamber

A linear proton accelerator with an energy W = 9 Mev (with preliminary injection at 600 kev) is used as the injector for the machine; this linear accelerator satisfies the following requirements which derive from the capture conditions: energy spread at the output – 10% of the particles have $\Delta W/W \lesssim 0.003$; the cross section of the beam is approximately 1 cm, the angular spread is approximately 0.1°.

To achieve optimum conditions for trapping in the region between the linear accelerator and the vacuum chamber of the synchrotron changes can be made in the opening angle of the beam, its cross sections (with respect to ρ and z) and the point at which it is inflected with respect to the axis of the chamber.

In addition, provision is made for changing the inflection angle of the beam axis in the horizontal and vertical directions.

Of the various possible ways of coupling the injector to the accelerator, which has a two-legged magnet yoke, it was decided to use that variant in which the beam exiting from the linear accelerator, first moves perpendicularly with respect to the straight section. The beam is deflected through 90° by passage through a deflection magnet (~75°) and a deflection condenser (~15°). In addition, the beam passes through a system of double correction magnets (for parallel displacement of the beam), alignment condensers, which bend the beam axis and a system of magnetic focusing lenses. The deflection magnet also serves as an additional lens. A special system is provided which makes it possible to change the pole tips and faces of the magnet, thus making it possible to change independently over wide limits the focal distances in the horizontal and vertical planes.

Extraction of the Particle Beam

The construction of the machine makes it possible to carry out experimental work with the extracted proton beam as well as neutron and meson beams which are generated on targets located inside the chamber. The targets which are intended for this purpose are displaced along the radius as the magnetic field is changed. This provision guarantees collisions of the beam with the target within the operating region which is reduced because of the effect of saturation of the magnetic field.

The geometry of the straight sections makes it possible to extract (on the outer side) negative mesons with energies almost equal to the maximum energy possible, i.e., approximately 9 Bev. In principle, positive mesons with energies up to 4.5 Bev can be extracted (on the inner side) in the region inside the accelerator ring. The beams of extracted mesons are analyzed and partially focused by the magnetic field of the synchrotron. It is proposed to achieve further focusing by the use of a system of quadrupole lenses. It should be possible to extract comparatively low-energy secondary particles through a window in the magnet yoke in which are located lenses which provide additional focusing.

We have investigated the possibility of extracting the proton beam using the discontinuity of the instantaneous orbit due to loss of particle energy in the target and the application of a deflecting magnet. A detailed calculation was made to study the parameters of the beam extracted from the synchrotron chamber as a function of particle scattering in the target, energy fluctuations, and the dimensions of the particle "spot" on the target. It was found that the use of a deflection magnet with an inhomogeneous field improves significantly the characteristics of the beam for extraction in the straight section: both the beam cross section and the divergence angle in the horizontal plane are reduced and the particle density is increased by approximately a factor of 10.

By steering the beam onto a target using a slow reduction of the accelerating voltage it is possible to "stretch out" the pulse to 100 μsec; this feature is found useful in a number of experiments with the beam.

MAGNETIC CHARACTERISTICS OF THE 10-BEV PROTON SYNCHROTRON OF THE JOINT INSTITUTE FOR NUCLEAR RESEARCH

A. A. Zhuralev, E. G. Komar, I. A. Mozalevskii, N. A. Monoszon and A. M. Stolov.

General Remarks

The magnetic field of the proton synchrotron at the Joint Institute for Nuclear Research is characterized by the following parameters:

Peak magnetic field intensity at the equilibrium orbit ($R = 2800$ cm) $-H_{max} = 13{,}000$ gauss.

Field intensity at injection. $H_0 = 150$ gauss.

Gap height between the poles at the equilibrium orbit $\delta = 40$ cm.

Width of the pole piece $b = 200$ cm.

The quality of the magnetic field can be characterized by the relative dimensions of the chamber region (with respect to width) over which the field index $n = -\frac{dH}{dr} \cdot \frac{R}{H}$ is approximately of constant value, by the size of the azimuthal non-uniformities in the magnetic field, and by the departures of the surface of magnetic symmetry (where $H_r = 0$) from the median plane of the chamber ($r = R - R_0$ is the departure of the radial coordinate from R_0).

Any increase in the energy of the accelerator which is associated with an increase in the ratio of the radius to the intensity of the magnetic field at the equilibrium orbit requires more stringent maintenance of a given radial relation for the magnetic field intensity since insignificant departures in the intensity of the field from the desired relation lead to a sizable change in the index n.

Distortions of the "gradient" $\frac{dH}{dr}$ of the intensity of the magnetic field can be produced by inaccurate machining of the gap profile, by residual magnetization, and by dynamic effects which are associated with the time variation of the intensity of the magnetic field. Changes in n due to inaccurate fabrication increase as the ratio $\frac{\delta}{R}$ decreases. In the electro-magnet of the proton synchrotron at the Joint Institute for Nuclear Research the relative gap size is small, being 1.43%. The effects of the residual magnetization and dynamic processes in the magnetic system are proportional to $\frac{R}{H_0 \delta}$. The field intensity at injection H_0 usually decreases as the maximum energy of the accelerator is increased. With relatively weak injection fields and small values of the ratio $\frac{\delta}{R}$ the distorting effects of the residual magnetization and dynamic processes are increased.

Because of the small radial dimension of the chamber, which is 7% of the total radius, the tolerances on the azimuthal non-uniformities of the magnetic field are much more stringent.

The relatively small dimensions of the air gap of the accelerator tend to restrict possible deviations of the surface of magnetic symmetry of the accelerator from a plane; in turn, this makes more severe the requirements on the displacements of the pole pieces and on the eddy currents in various construction elements (for example, the vertical walls of the chamber).

Because of the need for meeting extremely severe magnetic tolerances, it was necessary to work out effective methods for correction of the magnetic field before the accelerator was built. A small model was built for preliminary investigation of the magnetic characteristics; the final study of the magnetic characteristics and the development of methods for correcting the magnetic field were performed on several segments; each segment is 1/48 of the circular magnet.

Static Characteristics

The required magnetic field index was provided by using conical pole pieces (Fig. 1) (with an angular opening $\alpha = 9.3 \cdot 10^{-3}$ rad) with beveled edges. In Fig. 2 are shown curves for the magnetic field index n over the width of the magnet gap, obtained in a segment with field intensities varying from 2 to 13 kilogauss. The measurements were carried out in the median plane of the magnet under static conditions (with the exciting coil of the segment supplied by direct current). With a field intensity of H_c = 2000 gauss at the center of the chamber the width of the effective working region, defined by values of the field index which do not come too close to resonances ($0.55 < n < 0.75$), is approximately 150 cm. An experimentally determined magnetic field distribution curve is in rather good agreement with the results of a calculation based on the assumption that the magnetic permeability $\mu = \infty$. With a field intensity of 10,000 gauss the width of the working region is 90 cm; with a field intensity of 13,000 gauss it is 35 cm. The use of windings located inside the chamber makes it possible to increase the dimensions of the effective working region up to 80 cm, at 13,000 gauss a value which is more than sufficient at the end of acceleration.

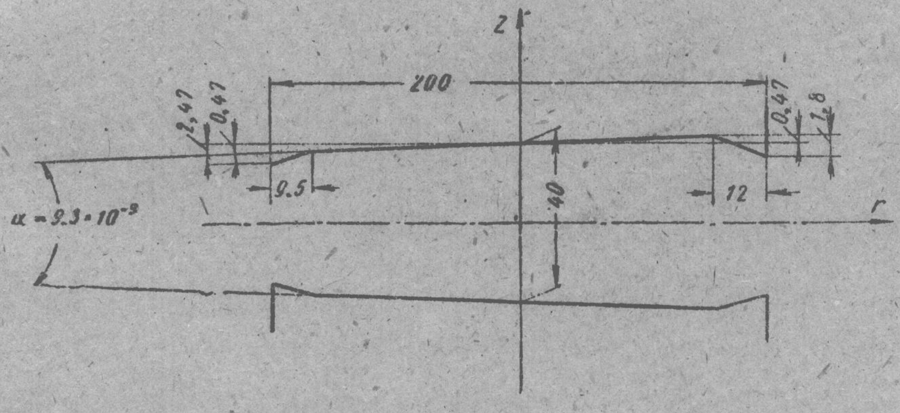

Fig. 1. Profile of the pole pieces (dimensions in cm).

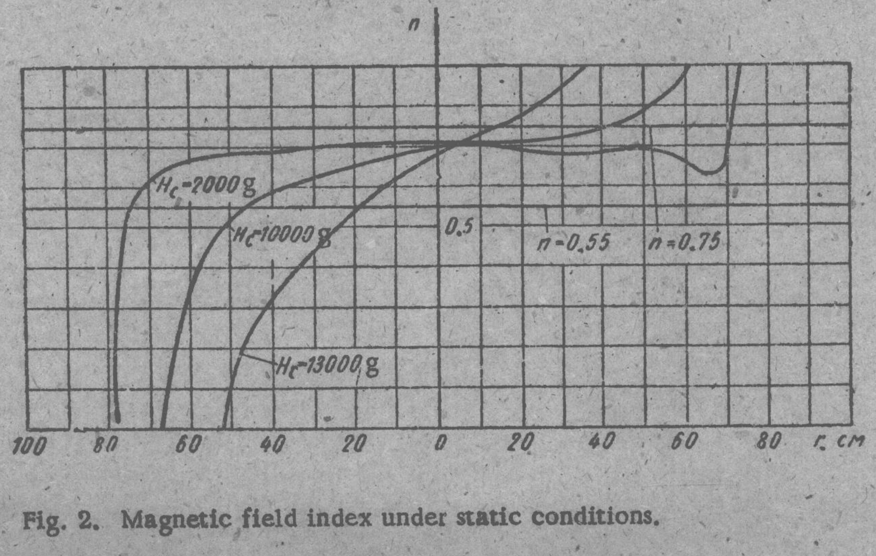

Fig. 2. Magnetic field index under static conditions.

In Fig. 3 are shown values of the field index at a field intensity of 150 gauss, obtained for various values of the residual field H_0, prior to excitation of the magnet coil. When the current is reduced slowly the residual field is 43 gauss. Under these conditions the dimensions of the working region at the beginning of injection are found to be too small because of distortions due to the residual field.

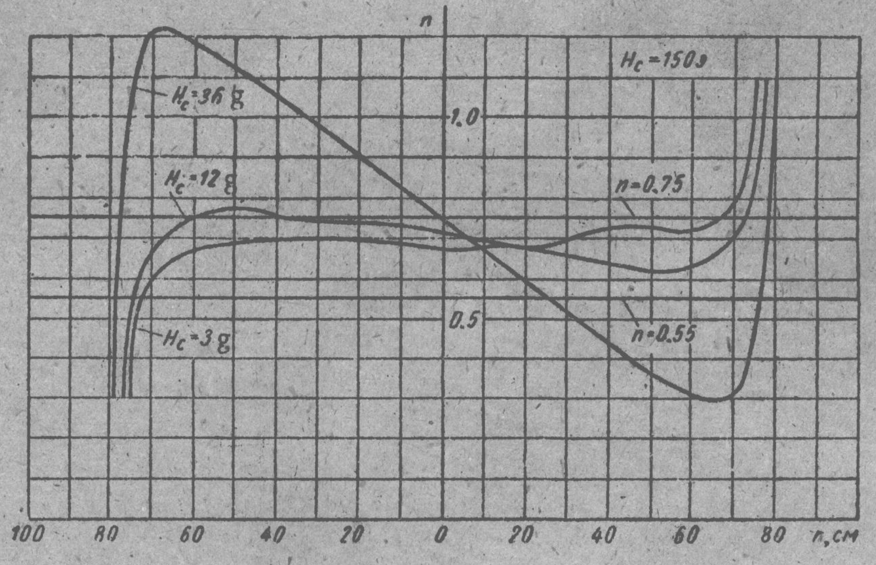

Fig. 3. Effect of demagnetization on field index.

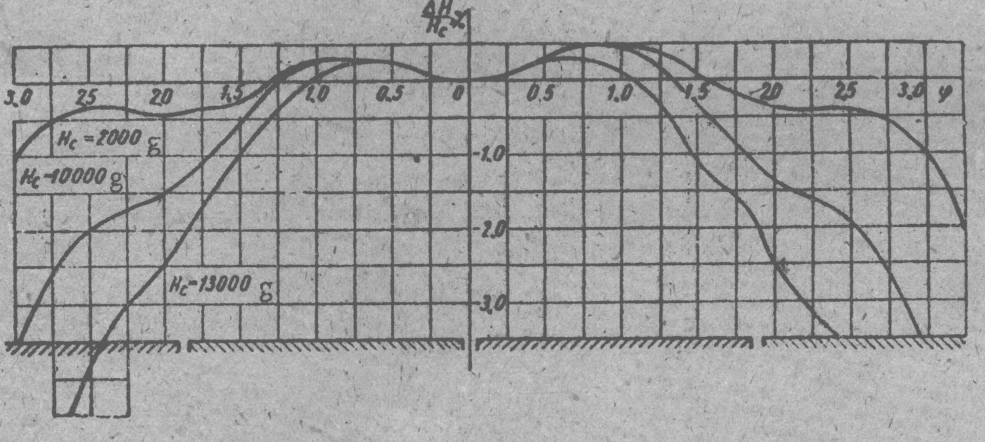

Fig. 4. Azimuthal variation of magnetic field under static conditions.

By demagnetizing the magnet with ac it is possible to reduce considerably the value of the residual field and its distorting effect. With a residual field intensity of 3 gauss the width of the working region is 150 cm with a field of H_c = 150 gauss at the center of the chamber. A special device has been developed which operates automatically in the period between acceleration cycles to reduce the remanent field. This apparatus makes it possible to change the demagnetization conditions and provides the required accuracy in reproduction of the mode of operation.

In Fig. 4 is shown the azimuthal variation of the magnetic field intensity under static conditions as obtained in a segment of the accelerator magnet with various values of the magnetic field. The distribution curve contains negligibly small harmonics; these have virtually no effect on the acceleration process. The cores of the magnet are provided with special windings which make it possible to compensate for azimuthal non-uniformities at the first and second harmonics. There are two windings for each of these harmonics and each is shifted in phase with respect to each other by 90°; thus it is possible to vary both the amplitudes and phases of the correcting fields.

Because of the rigid requirements on the azimuthal uniformity of the magnetic field, it is necessary to take into account inhomogeneities introduced by leakage currents in the water which cools the winding. For this reason a scheme for connecting the quadrants of the magnet was developed such that the leakage currents could not produce a first harmonic inhomogeneity in the field ΔH.

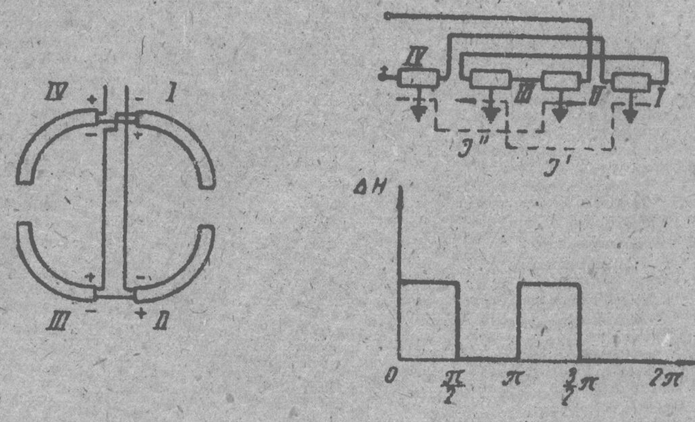

Fig. 5. Diagram showing the connections of the quadrant windings and the effect of leakage currents on the azimuthal field distribution.

In Fig. 5 is shown a schematic diagram of the method of connecting the quadrant windings and a rough picture of the azimuthal field non-uniformity ΔH produced by leakage currents in the water which cools the windings.

Dynamic Characteristics

The dynamic studies of the magnet segments were carried out by supplying the windings from a special source which furnished triangular current pulses. The field rate-of-rise $\dot{H}$ was approximately 3,000 and 1500 gauss/sec. As is apparent from Fig. 6 the azimuthal variation of magnetic field intensity under dynamic conditions does not differ essentially from the field distribution in the static case. The only differences are in the somewhat larger amplitudes in the higher harmonics of the azimuthal field non-uniformities.

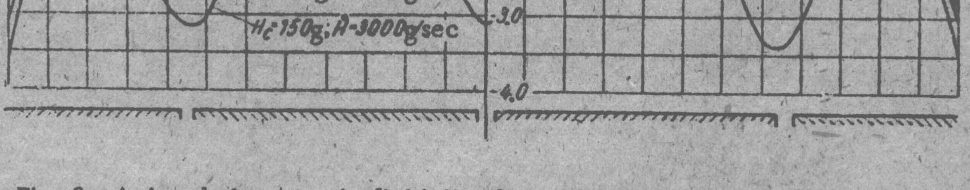

Fig. 6. Azimuthal magnetic field distribution under dynamic conditions.

In Fig. 7 are shown curves of the magnetic field index as a function of coordinate (across the width of the accelerator chamber) for a field rate-of-rise $\dot{H}$ = 3000 gauss/sec. In this case the residual field is not taken into account.

In contrast to the static case, in which the functions n = f(r) are approximately horizontal lines within the limits of the working region, in the dynamic case these functions are approximated by lines which are

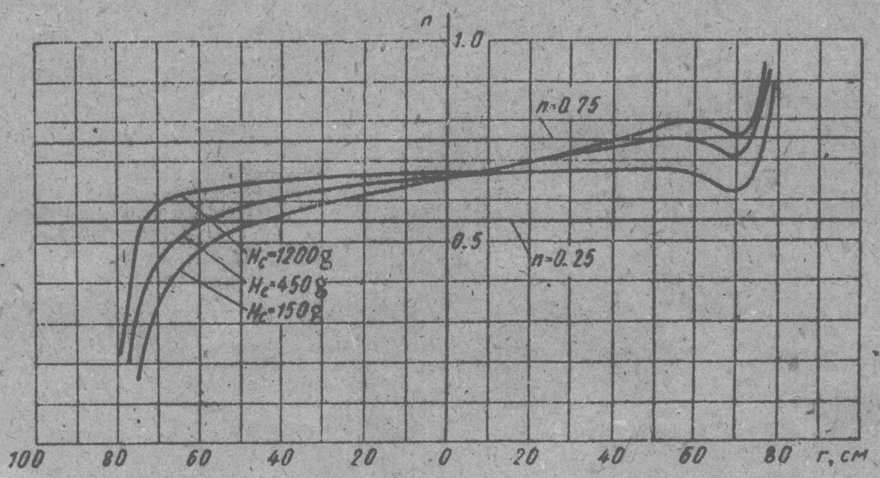

Fig. 7. Distortion of the magnetic field index under dynamic conditions.

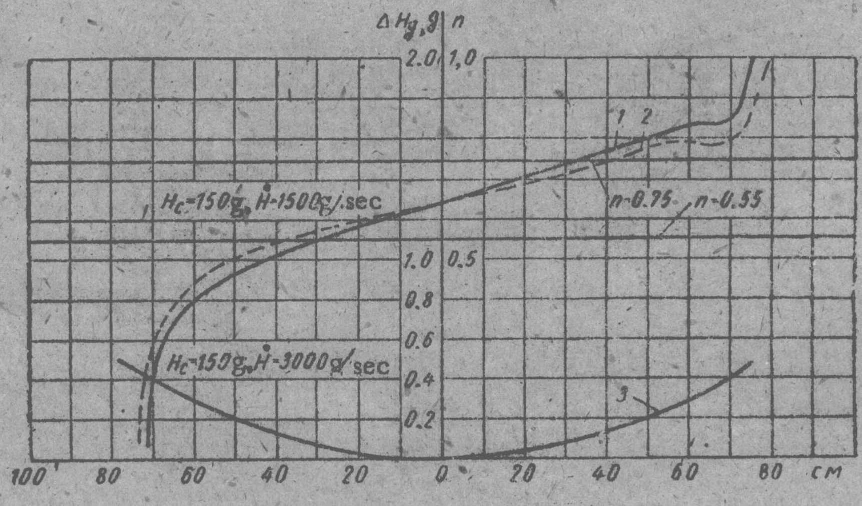

Fig. 8. Distortion of the magnetic field index under dynamic conditions (Curves 1 and 2). Curve 3 is the additional field ΔH_g created as a consequence of the dynamic effect (the difference of the fields under static and dynamic conditions).

inclined with respect to the horizontal axis (Fig. 8). The slope angles are reduced as the absolute values of the field intensity are increased and at 150 gauss are essentially independent of the rate-of-rise of the field.

In Fig. 8 is also plotted intensity distribution for the additional field ΔH_g produced by the dynamic effects. In contrast with the effect of the residual field, the dynamic effects lead to an increase in the field intensity at the edges of the chamber as compared with the central part.

It is easy to show that if the dynamic distortion of the field index is defined by a straight line of slope β with respect to the abscissa this distortion can be compensated for by a current of density i at the surface of the pole pieces, where the density increases in approximately linear fashion from the center to the periphery:

$$i = 0.8\frac{H_e}{R}\cdot\frac{\delta}{2}\beta r\left[1+\frac{3}{2}\beta\frac{r}{\delta}\right]\text{amp/cm}.$$

The effect of a surface current with variable density can easily be obtained by non-uniformly distributed conductors, through which the same current flows, which are placed over the surface of the pole pieces; this current has a time variation that corresponds to the changes of ΔH_g. A voltage to supply the compensation windings is provided by the electromotive force induced in these windings as the accelerator field increases. A schematic diagram of the compensation-winding circuit is shown in Fig. 9. The required current time variation is obtained by an appropriate selection of the real and inductive parts of the load.

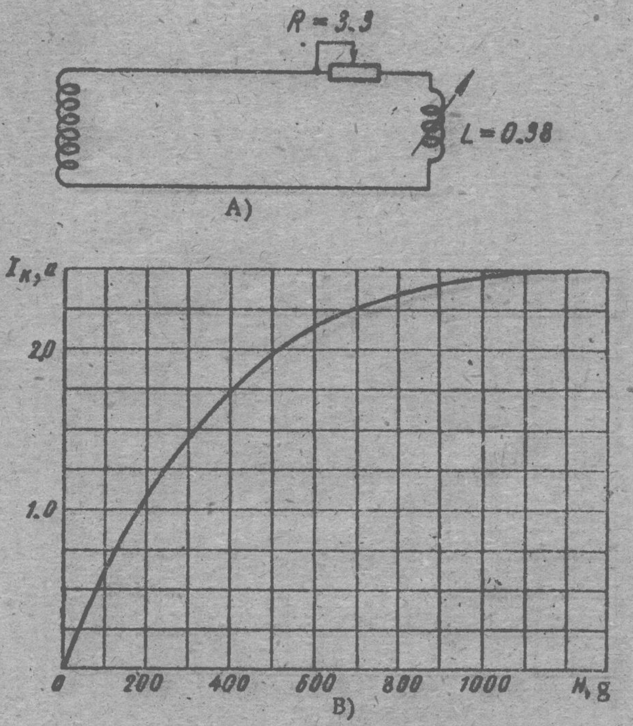

Fig. 9. A) Compensation scheme for dynamic distortions (R in ohms, L in henrys); B) the current rate-of-rise in the compensating winding.

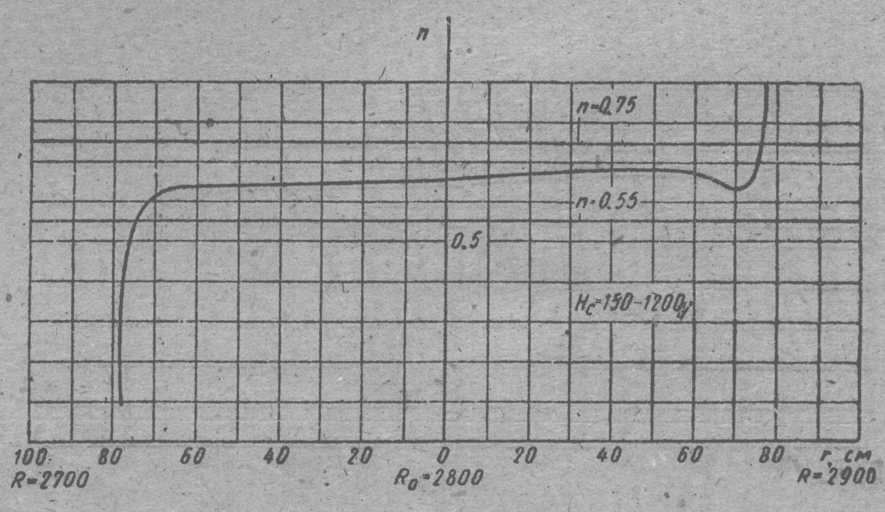

Fig. 10. Variation of the field index in the gap after compensation of dynamic distortions.

In Fig. 10 is shown an experimental curve for $n = f(r)$ obtained with the compensation winding connected as shown in the diagram. The methods developed to correct distortions in the field index make it possible, by changing the mode of operation of the compensating units, to use the mutually compensating effect of the residual magnetization and dynamic effects.

The departures of the surface of magnetic symmetry from the median plane of the chamber are due to dynamic effects and inaccurate adjustment of the pole pieces.