THE PROBLEM OF FORMING PRECISION MAGNETIC FIELDS IN SUPERCONDUCTING DIPOLES OF UNK

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The problems arising in the course of construction of superconducting magnetic dipoles are mainly connected with achieving precise magnetic characteristics, reliability, and manufacture of the dipoles in a quite short period of time. From our analysis carried out for the 3-TeV proton synchrotron (UNK),[1] it became clear that these problems can be solved. As a basic scheme for designing the UNK dipoles, we have chosen a two-layer dipole of the shell type.

Requirements for Magnetic Characteristics of the UNK Dipoles

The calculated beam dimensions in the UNK superconducting stage are 40×50 mm^2. A vacuum chamber of somewhat larger dimensions (60×70 mm) has been chosen since we foresee some trouble with irradiation of the superconducting magnets. The design values for betatron oscillations are $Q_x = 40.69$; $Q_z = 40.73$ (Fig. 1). When designing the superconducting ring and magnetic field correction system, we proceeded from the requirement that no traverse of dangerous stop-bands $3Q_x = 122$, $4Q_z = 163$, and $Q_x - Q_z = 0$ should take place during acceleration. This puts limitations on the Q-spread in the beam: $\delta Q_{x,z} \lesssim 0.02$ at the betatron oscillation amplitudes $A_z \leq 20$ mm and $A_x \leq 25$ mm. The admissible values for nonlinearities are listed in Table I, where $(\Delta B_z/B)_n$ is the multipole coefficient of the nth order at a distance of 35 mm from the chamber center.

Table I.

n	2	3	4	5	6	7	8	9	10
$(\Delta B_z/B)_n \times 10^4$	15	0.5	3	2	10	7	40	30	100

The tolerance for the sextupole component ($n = 2$) as indicated carries with it the presumption of a sextupole correction system, which is needed in any case for the tuning of the accelerator chromaticity. A large value for the dipole nonlinearities and correcting ones leads to the necessity of taking into account the contributions $\sim (\Delta B_z/B)_2^2$, which are dependent on the number of the correctors. The tolerance 1.5×10^{-3} is acceptable with 360 correctors connected in two sets, each containing 180 elements and located near the main quadrupoles. The limitations may be less strict if we locate the correcting sextupole windings on each dipole; however, such a complication of the dipole design seems to be unjustified.

Even nonlinearities of 4th or higher orders influence mainly the motion of particles with displaced equilibrium orbits, creating additions to the chromaticity dependent on the betatron oscillation amplitude. They are most dangerous during injection when beam dimensions are maximum and the momentum spread may be almost $\pm 1 \times 10^{-3}$.

At the chosen position of the working point, one should consider the influence of the adjacent resonances of the 2nd-4th orders, as well as the possibility of traversing the resonances of the 7th order with center at the point $Q_x = Q_z = 40.714$ (Fig. 1). The corresponding tolerance for the average value for the skew quadrupole component $(\Delta B_x/B)_1$ is 5×10^{-6}. The tolerances for the r. m. s. spreads of the nonlinear components $\langle(\Delta B_z/B)_2\rangle$,

$<(\Delta B_z/B)_3>$, and $<(\Delta B_{x,z}/B)_6>$ are 3×10^{-4}, 6×10^{-4}, and 1×10^{-3} respectively. Then the amplitude growth during a cycle does not exceed 10%.

Attainment of Required Magnetic Characteristics

There are five main sources for magnetic field disturbances: superconductor residual field, deviation of the cross-section shape of the winding from the perfect one, fabrication errors, deformation of the windings caused by ponderomotive forces, and magnetic shielding saturation.

Disturbances caused by magnetization of the superconductor are mainly determined by the diameter of the superconducting filaments, critical current density of the superconductor and its quality.[2] Figure 2 presents the calculated nonlinearities of the 2nd, 4th, and 6th orders for the UNK dipole with the filament diameter of 10 μm, whose critical current density is

$$j\left(\frac{A}{cm^2}\right) = \frac{1\times10^6}{0.8 + B(T)}.$$

Tolerances indicated in Table I are satisfied in fields higher than 0.4 T. Bearing in mind that we do not complete data on the superconductor properties, we have chosen the injection field of 0.67 T for the UNK superconducting stage, which corresponds to an injection energy of 0.4 TeV.

The calculated magnetic field contains only systematic even nonlinearities. The nonlinearities of the lowest order have greatest influence on the particle motion, thus when designing a dipole we seek to reduce them. The compensation of the nonlinearities of the lower orders is realized by proper choice of the angular dimensions of the layers. As an example, we list in Table II calculated nonlinearities in two- and three-layer dipoles with the

Table II.

n	Type	2	4	6	8	10	12
$\left(\frac{\Delta B_z}{B}\right)_n - 10^4$	2-layer	0	0	15.6	-31.3	15.2	-4.3
	3-layer	0	0	0	-8.8	8.3	-5.7

windings uniformly filled with conductors. The inner radius of the winding is 45 mm.

Proceeding from these data, we have derived the dependence of chromaticity on betatron oscillation amplitudes (Fig. 3). From the figure, it follows that in a two-layer dipole chromaticity satisfies the tolerance $|\xi_{x,z}| \lesssim 10$, corresponding to the Q-spread of 0.02, within the limits of the region occupied by the beam. In a three-layer dipole this tolerance is satisfied practically in the whole aperture of the vacuum chamber. In design of the UNK dipoles, a two-layer dipole was chosen since it is easier to fabricate. If necessary, the quality of a two-layer dipole may be improved by introducing one or two calibrated spacers in the first shell of the coil.

Disturbances caused by deformation of the winding cross section under the influence of the ponderomotive forces may conditionally be classified as deformations of the bands and deformation of the winding itself with respect to the bands. The bands made of laminated stainless-steel rings and half rings with radial dimensions ~ 25 mm are deformed not more than 50 μm at the field of 5 T.

Most dangerous are distortions caused by deformation of the winding itself. The winding, consisting of conductors, insulators and spacers with the cooling channels acquires an elasticity modulus of $\sim 10^5$ kG/cm^2 when a pre - load of 100 to 150 kG/cm^2 is created. The quantity of epoxy compound must be small. Thus pre-stresses in the winding are quite necessary not only to avoid microcracks but to reduce deformations of the winding.

We are now studying some versions of the bands, consisting of rings and half-rings, from the standpoint of their rigidity, creation of pre-stresses in the winding, precise fixing of the winding position in the bands, as well as examining ways to simplify the winding units for large-scale fabrication. Figures 4 and 5 present the construction of bands made from rings and half-rings for lateral shrinkage of the winding. The left and right rings and half rings are assembled with the help of a tongue-and-groove arrangement. Further glueing of the rings and half rings makes fixation more reliable.

A laminated inner support tube with centering lugs to fix the winding in the azimuthal direction will be used to improve the conditions for winding and to increase rigidity.

Figure 6 presents a design of a winding unit with laminated bands that after being warmed up to 200° C, is mounted on the winding cooled in liquid nitrogen.

The position of a shell-type winding may be fixed with the help of rigid bands with a quite satisfactory accuracy only with respect to the inner radius of the bands and at the edges of layers in the azimuthal direction. The azimuthal position of separate conductors is determined both by the deviations in the conductor dimensions and insulation, and the rigidity of separate sections of the winding along the azimuth. We are now investigating technological means that would allow us to fix (or at least to control) the position of a set of conductors in azimuthal position. It is of particular importance to make the position of the boundary between the upper and lower coils very precise. It seems possible for us to provide an accuracy in fixing the layer edges in the azimuthal direction of ±50 μm, and a precision of conductor azimuthal position with rms deviation of 50 μm, and that of layer radial position of ±100 μm, deformations due to ponderomotive forces included.[3] In this all the systematic distortions of the field are within admissible limits with exception of the octupole and skew quadrupole components; these may be corrected with the help of rather simple correction systems.

With the aforementioned accuracies in conductor position, the requirements for the sextupole component and, moreover, for nonlinearities of higher order will also be fulfilled. It is quite necessary that the critical current density spread in separate sets of superconductors should not exceed ±30% so that the spread of nonlinearities due to residual fields in the superconductors would not go beyond the admissible limits. This requirement can be satisfied. Therefore, at the present state of designing the UNK, correction for nonlinear resonances has not been planned. This question will finally be resolved as soon as we obtain experimental data.

Field disturbances due to saturation of the iron shield for the chosen geometry of the dipole are within admissible limits.

One may expect that at the quoted accuracy in fabrication of the magnets a relative spread of the dipole components would be 1×10^{-3}. Using the data from measurement of the magnetic fields, we may arrange the dipoles in such a sequence that dangerous harmonics of the magnetic field distortion would be suppressed. Then the value of the orbit distortions would be determined by the precision of magnetic measurements and by variations of the field in the dipole during one cycle and from cycle to cycle.

For these reasons, the effective spread of the dipole fields will be 5×10^{-4}; that is quite acceptable if a closed orbit correction system is available.

The program of manufacturing the prototypes of superconducting dipoles is now being carried out at NIIEFA and IHEP. The main goal of the program is to work out engineering and technological solutions that would provide the aforementioned accuracies in fabrication of magnets. In the superconducting UNK ring, 360 universal correctors are planned for magnetic field corrections. In each universal corrector there will be a dipole winding with vertical or horizontal fields for orbit corrections, and quadrupole and sextupole windings for chromaticity and Q-corrections. A few lenses located in the long straight sections will be used to correct average constituents of the octupole components and of the skew quadrupole term. The decision on the number, power, and location of these lenses will be made when we get experimental data on the UNK magnet characteristics.

References

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[3] The Energy Saver, A Design Report for the Energy Saver Project, Batavia, Illinois, 1978.

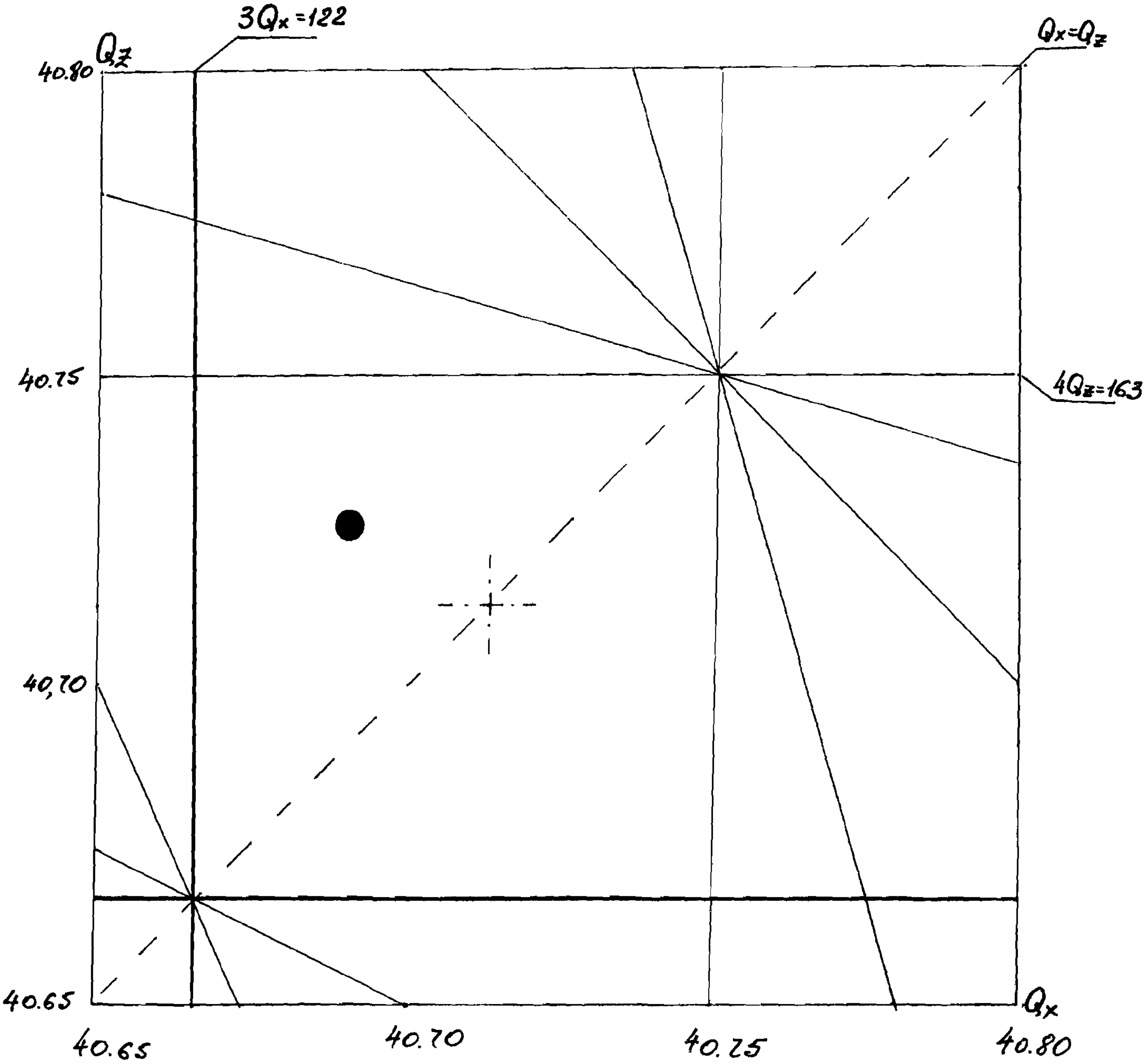

Fig. 1. Position of the working point in the diamond of betatron oscillations.

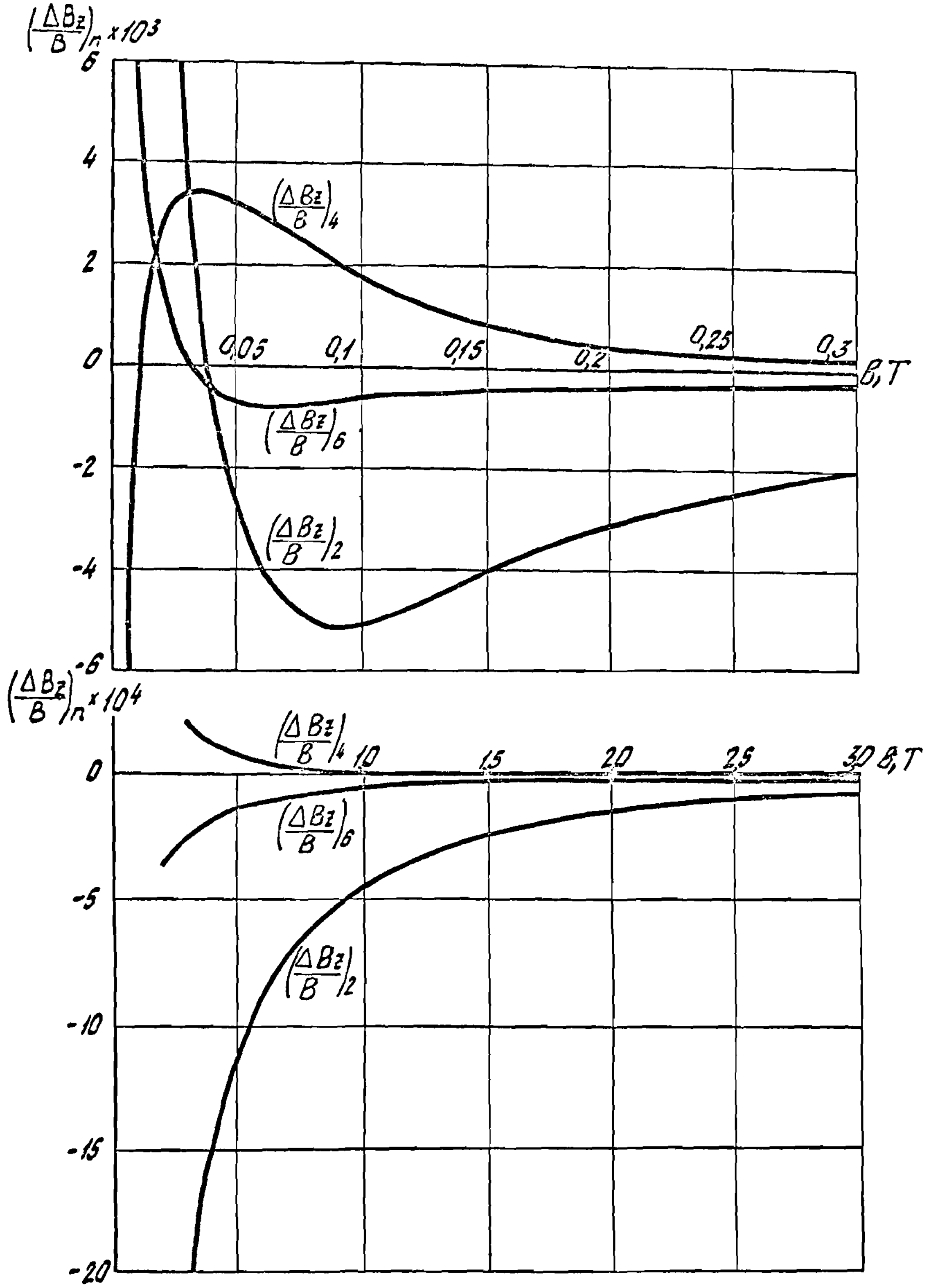

Fig. 2. Nonlinearities of residual fields relative to the field in the vacuum chamber center.

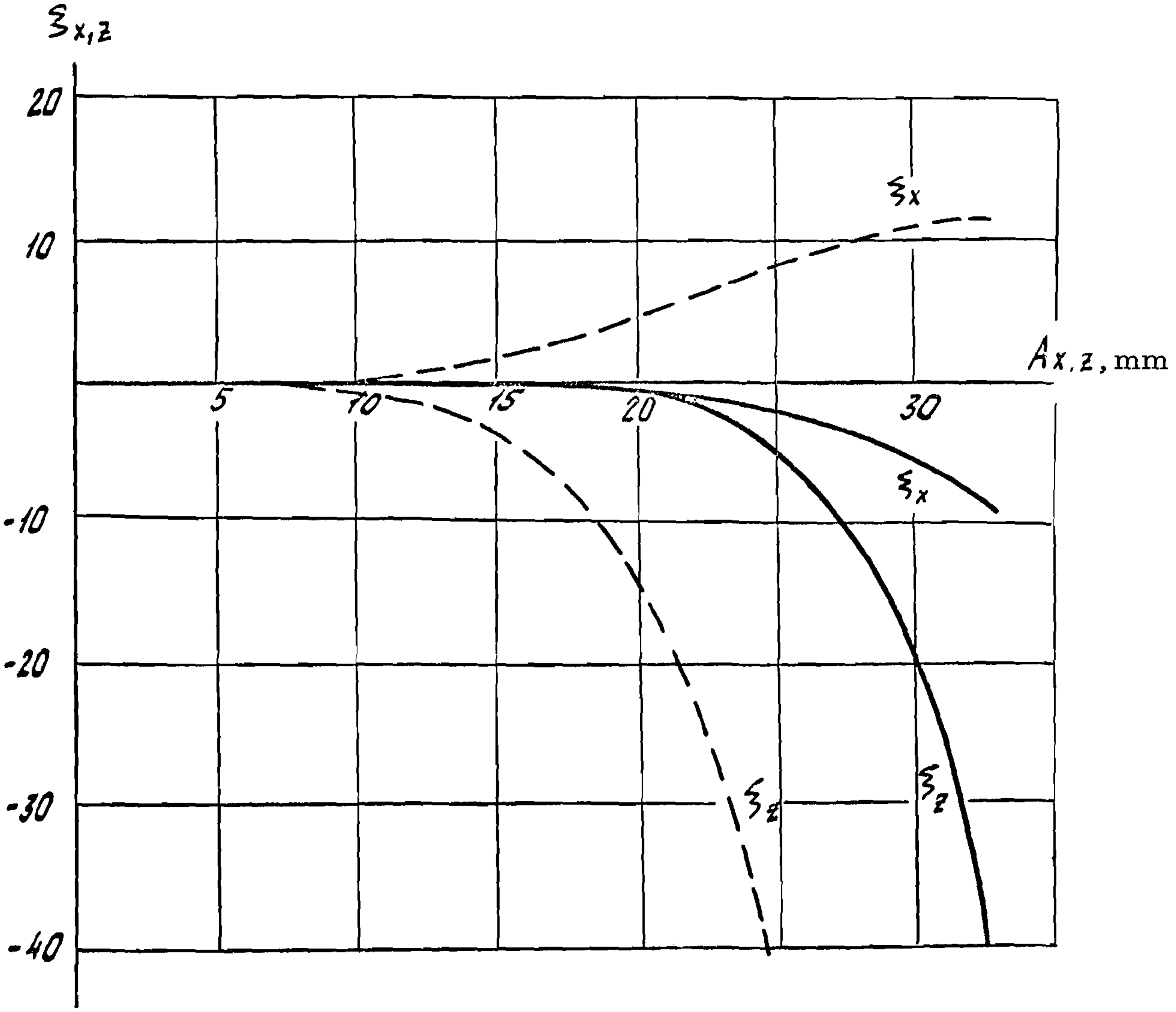

Fig. 3. Chromaticity dependence on the betatron oscillation amplitude.

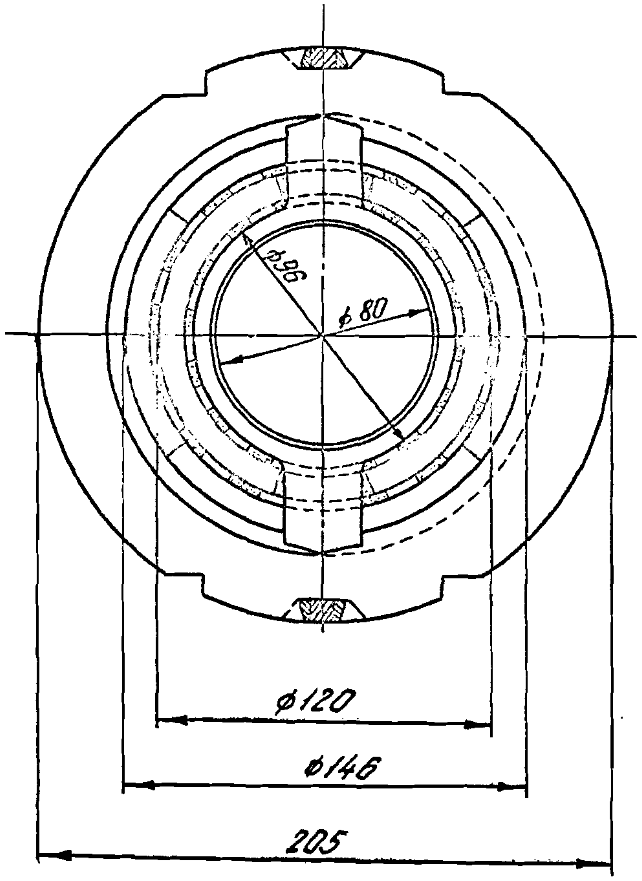

Fig. 4. A design for mechanical shrinkage using bands.

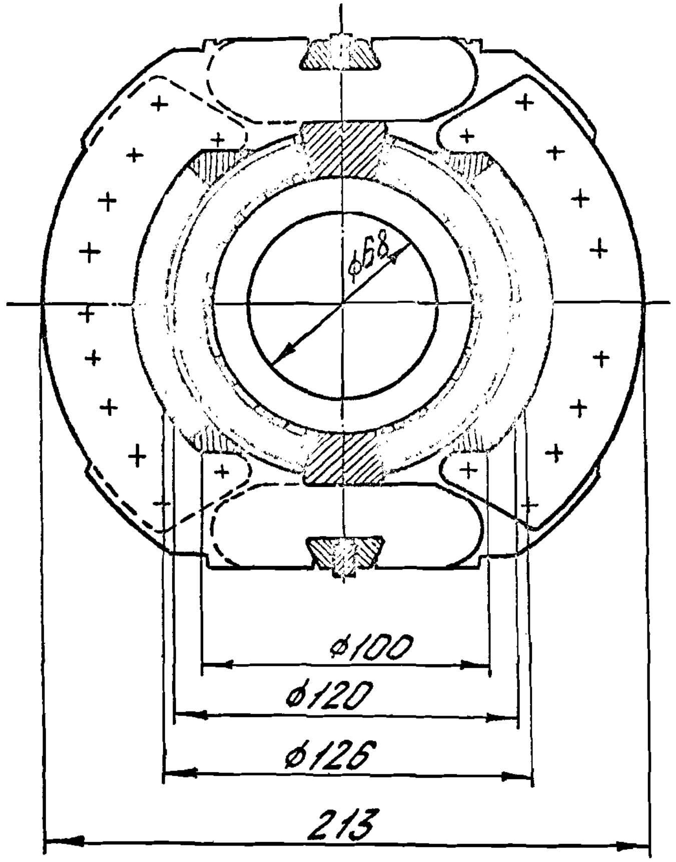

Fig. 5. A design for mechanical shrinkage using half rings.

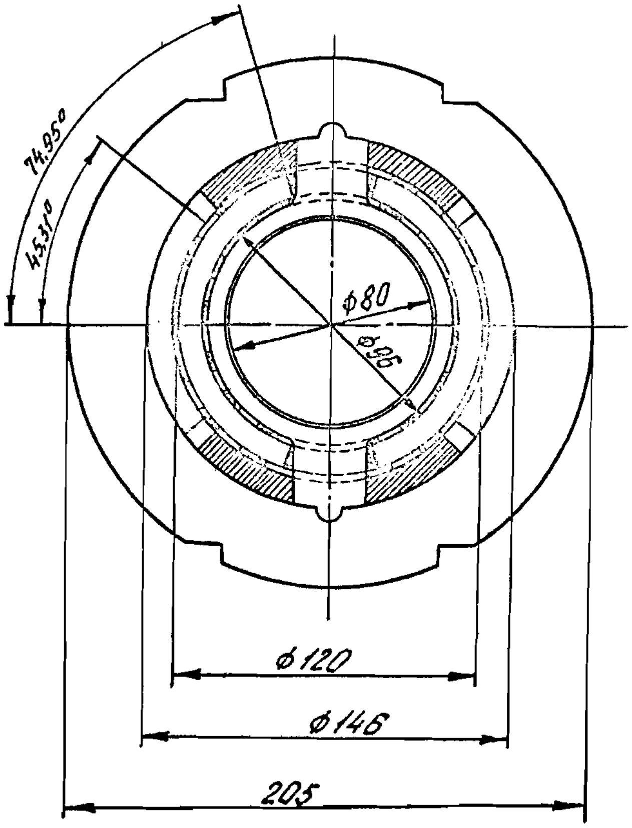

Fig. 6. A design for thermal shrinkage using circular bands.