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MEASUREMENTS AND CORRECTION OF THE MAGNETIC FIELD OF THE 1 GeV SYNCHROCYCLOTRON OF THE A.F. IOFFE PHYSICO-TECHNICAL INSTITUTE (ORDER OF LENIN)

PART 1

SHAPING THE RADIAL FALL-OFF AND CORRECTING AZIMUTHAL NON-UNIFORMITIES

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Requirements are formulated in respect of the magnet field of the synchrocyclotron of the P.T.I. (Order of Lenin) of the USSR Academy of Sciences. A description is given of the technique used for shaping in the fall-off and correcting azimuthal non-uniformities in the magnetic field. The main features of the field produced are: improved focussing in the central region; a slow variation in the fall-off index, free from sharp local jumps; an amplitude of the first field harmonic $\leqslant 2 \times 10^{-4}$.

1. Introduction

One of the most important problems encountered when building a cyclic accelerator is that of achieving the required distribution of the magnetic field [1,2]. The correct choice of the parameters of the field and the accuracy with which these parameters are achieved determine certain fundamental accelerator characteristics, such as the ultimate beam energy and intensity, the energy distribution of the particles in the beam, the extraction coefficient etc.

The magnet of the 1 GeV synchrocyclotron of the PTI has the following basic parameters: pole diameter: 6.850m; pole gap : 500 mm; thickness of the pole tips, which serve as covers for the chamber: 300 mm; shimming gap : 30mm; number of turns on the main winding : 264 ; maximum current in the winding : 5200 A; cooling by water.

In choosing the parameters of the magnetic field of the PTI synchrocyclotron the following considerations were taken as point of reference: the magnetic field distribution must provide the necessary magnetic rigidity on the extraction radius, compensation of the space charge forces, stability of radial and vertical betatron oscillations, and sufficiently small amplitudes of these oscillations.

In the PTI synchrocyclotron, the magnetic rigidity corresponding to an accelerated proton energy of 1 GeV, with a final acceleration radius of 316.5 cm, is provided by a field on this radius having a value of B_k = 17.86 kG when there is a field of 19 kG in the centre of the magnet (the field fall-off is $\sim 6\%$).

The limitation of the intensity of a beam of accelerated particles owing to the space charge effect has been examined in a number of works [2,3]. The results of these works show that it is necessary to concentrate the greater part of the fall-off in the central region of the magnet, and then aim for the maximum possible values of the production of $n\beta$ on the radii of the order of a few centimeters ($n = -\frac{r}{B}\frac{dB}{dr}$, $\beta = \frac{v}{c}$).

In the non-resonance region ($n < 0.2$) of a synchrocyclotron, the betatron oscillations along the radial and axial coordinates take place independently. The problems of the radial and vertical oscillations are therefore considered separately in Parts I and II.

The amplitudes of the forced radial oscillations are determined by the harmonics of the vertical component of the field [1]. The effect of the higher harmonics of the field decreases in accordance with $1/k^2$, where k is the harmonic number; consequently, the most dangerous harmonic is the first one, which gives a radial oscillation amplitude of

$$x_1 = \frac{r}{n} f_1^z, \tag{1}$$

where f_1^z is the relative value of the first harmonic of the vertical component of the field

$$f_1^z = \frac{(B_z)_1}{B_{z0}}.$$

Experience of the operation of present accelerators [4], shows that it is wise to limit the amplitude of the radial oscillations to a value of about 1 cm. This provides the tolerances on the value of the field perturbations. For example, the value f_1^z at various radii must not exceed values of between 2×10^{-4} and 5×10^{-4}.

The magnetic field in the mean geometric plane of the gap was measured with a device based on the phenomenon of nuclear magnetic resonance, with an accuracy of 3×10^{-5}. The distribution of the measurement points over the radius is given in Table 2. The measurements along the azimuth were made at equidistant points; the number of points along the azimuth could be 100, 50, 25, 20 and 10.

The automated equipment used for the measurements in [5-7] enabled the measurement process to be speeded up considerably.

In view of the large number of measurement points most of the data were processed on an electronic computer.

2. Shaping the Fall-off

When shaping the fall-off of the magnetic field, we aimed at obtaining the maximum possible fall-off near the centre of the magnet by reducing it at large radii. The limiting factor in this direction was the design of the chamber: the height of the source, the size of the gap between the shims and the D etc. In addition, it was considered necessary that the fall-off index should vary slowly along the radius without any sharp local jumps.

In accordance with the magnetisation curve, an excitation current of 4600 A was chosen. The fall-off profile was very strongly dependent on the excitation current; consequently, throughout the magnetic measurements, the excitation current was established according to the field at a specific reference point. During checking and adjustment of the field at the reference point it was possible to obtain every two hours, if necessary, stabilisation of the field with an accuracy of several parts in 10^5. By following the standard demagnetisation technique after switching off the magnet with a reverse polarity current of 300 A and after an interval of an hour after switching on, the field distribution was reproduced with an accuracy of 10^{-5}.

The field was shaped by means of annular shims broken down into separate sections. The radial dimensions of the rings, the number of sections (8 sections on most rings) as well as an initial set of shims of various thicknesses were selected at the time the magnet was designed. During the measurement process the initial set underwent substantial modification.

The choice of the sets of shims was based on two sections. To simplify the choice of shim thickness, graphs were first drawn of the effect of the shims on individual rings (see figure 1). With the aid of a field chart, which it was desirable to obtain, we calculated the true field and, with the charts, tried to compensate for the difference by means of the appropriate set of shims. Although such a method is not entirely correct, in our case it was fully justified, and it enabled us to choose the necessary set of shims after only a small number of tests.

Special care was taken when shaping the field in the centre of the magnet. The design allowed for the insertion of iron discs in the shim gap between the core and the covers of the chamber in order to adjust the fall-off in the centre. It was not possible, however, to shape with these discs the local fall-off near the centre because of the screening effect of the covers of the vacuum chamber. The discs were therefore removed and were replaced by additional shim rings and a central cylinder. As the height of the central shim was limited by the design of the source to 55mm it proved more advantageous to use a cylinder for the central shim, and not a cone.

The shim profile in one of the sections is shown in Figure 2. The field fall-off, averaged over the azimuth, and the value of the fall-off index n are shown in Table 1 and Figure 3 as a function of the radius. The value $n\beta$, which characterises the permeability of the magnetic system is shown in figure 4 for the central region of our machine.

3. Correction of Azimuthal Non-uniformities

The set of shims chosen as a result of the measurements in the two sections was installed in all of the remaining sections. After this, the azimuthal non-uniformities of the magnetic field were corrected.

Measurements on the poles which were not fitted with shims showed the existence of field non-uniformities (large in value, but small in their azimuthal dimension) which were due to the use of different grades of iron in the pole tips; these non-uniformities occurred at the junction points of the half-discs which formed the covers for the chamber, at the points where the covers were attached to the magnet core, and at the holes for the rings etc. (see Figure 5). Gaps which appeared in the field (50-120G) were compensated for locally by additional shims. The remaining field non-uniformities of $\sim$ 25 G, having an azimuthal dimension of $\sim \pi/4$ which were due to such factors as an insufficiently accurate compensation of the half-disc joints, inhomogeneities in the metal, the inaccuracy of shim machining, the effect of the magnet's lateral stays, etc., were smoothed off to $\sim$ 5 G.

The magnetic field was very considerably affected by the iron components of the chamber which were near to the gap, - the diffusion pumps and the magnetic screens of the frequency variators. The gap in the field due to these components at radii of between 1.5m and 3.2m ranged from 30 to 60 G and extended azimuthally over almost half the pole, which corresponds to the value of the first harmonic, (1.5 to 3)10^{-3}. The field "gap" was compensated for by additional shims 0.5mm in thickness. After this operation, the value of the first harmonic still exceeded the specified permissible values; shimming was therefore effected for the first harmonic in the azimuthal distribution of the magnetic field by moving the iron from three sections in the region of the harmonic's maximum to the region of its minimum. It should be noted that, at the time of the main magnetic measurements, the frequency variators with magnetic screens had not yet been made; their influence on the field was determined, therefore, by specially made models. The models simulated the effect of the magnetic screens of the variators; the weight (2.5 tons), arrangement and basic dimensions of the iron parts were the same as those of the actual structure. The accuracy of the simulation was checked after the magnetic measurements had been completed, when the variators were built. Table I gives the amplitudes of the first harmonic with the models and with the variators. A comparison shows that the accuracy of the simulation was entirely satisfactory.

Figure 6 gives examples of the azimuthal variations of the field on four radii, obtained after correction of the azimuthal non-uniformities.

4. Results

Table 2 gives the principal data for the magnetic field of the P.T.I. synchrocyclotron [8] : the field value, averaged over the azimuth, at 54 points over the radius, the fall-off index of the average field and the relative value of the amplitude of the first harmonic. The amplitude of the radial oscillations excited by azimuthal non-uniformities of the field was ~ 1cm. The contribution of harmonics higher than the first is negligible. The data in Table 2 were obtained from measurements after the position of the median surface had been corrected [9] .

To conclude, the authors wish to thank D. G. Alkhazov for the attention he has devoted to this work and for discussing the results.

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Table 1

Amplitude of the first harmonic of the vertical component of the field, measured with the models and variators in position

No. of measurement points	R cm	Amplitude of the first harmonic $(B_z)_1$, gauss	
		with models	with variators
32	225,4	0,7	0,7
34	241,4	1,7	1,8
36	257,4	2,3	2,0
38	273,4	2,0	1,9
40	289,4	1,6	2,2
43	309,4	2,6	1,2
45	313,4	0,9	1,3
47	317,3	0,6	1,8
49	321,3	1,2	1,0
52	327,3	5,6	4,3

Table 2

Principal data for the magnetic field of the
1 GeV A.F. Ioffe P.T.I. (O.L.) synchro-cyclotron
of the USSR Academy of Sciences

No. of measurement points	R cm	B_{z0} gauss	n	$f_1^z \times 10^{-4}$
1	2	3	4	5
0	0	18937	0	
1	2,0	18931	0,00051	
2	4,0	18917	0,0018	
3	6,0	18896	0,0038	
4	8,0	18869	0,0058	
5	12,0	18809	0,0091	
6	16,0	18755	0,0103	
7	24,0	18677	0,0137	
8	33,4	18612	0,0123	0,98
9	41,4	18568	0,0116	0,48
10	49,4	18535	0,0104	0,52
11	57,4	18508	0,0098	0,98
12	65,4	18486	0,0096	1,13
13	73,4	18466	0,0096	1,20
14	81,4	18448	0,0107	1,42
15	89,4	18430	0,0121	1,30
16	97,4	18401	0,0140	1,50
17	105,4	18386	0,0159	2,02
18	113,4	18364	0,0165	2,08
19	121,4	18343	0,0166	1,74
20	129,4	18324	0,0169	1,40
21	137,4	18305	0,0178	1,22
22	145,4	18286	0,0190	1,13
23	153,4	18267	0,0203	1,13
24	161,4	18247	0,0218	0,98
25	169,4	18228	0,0227	0,75

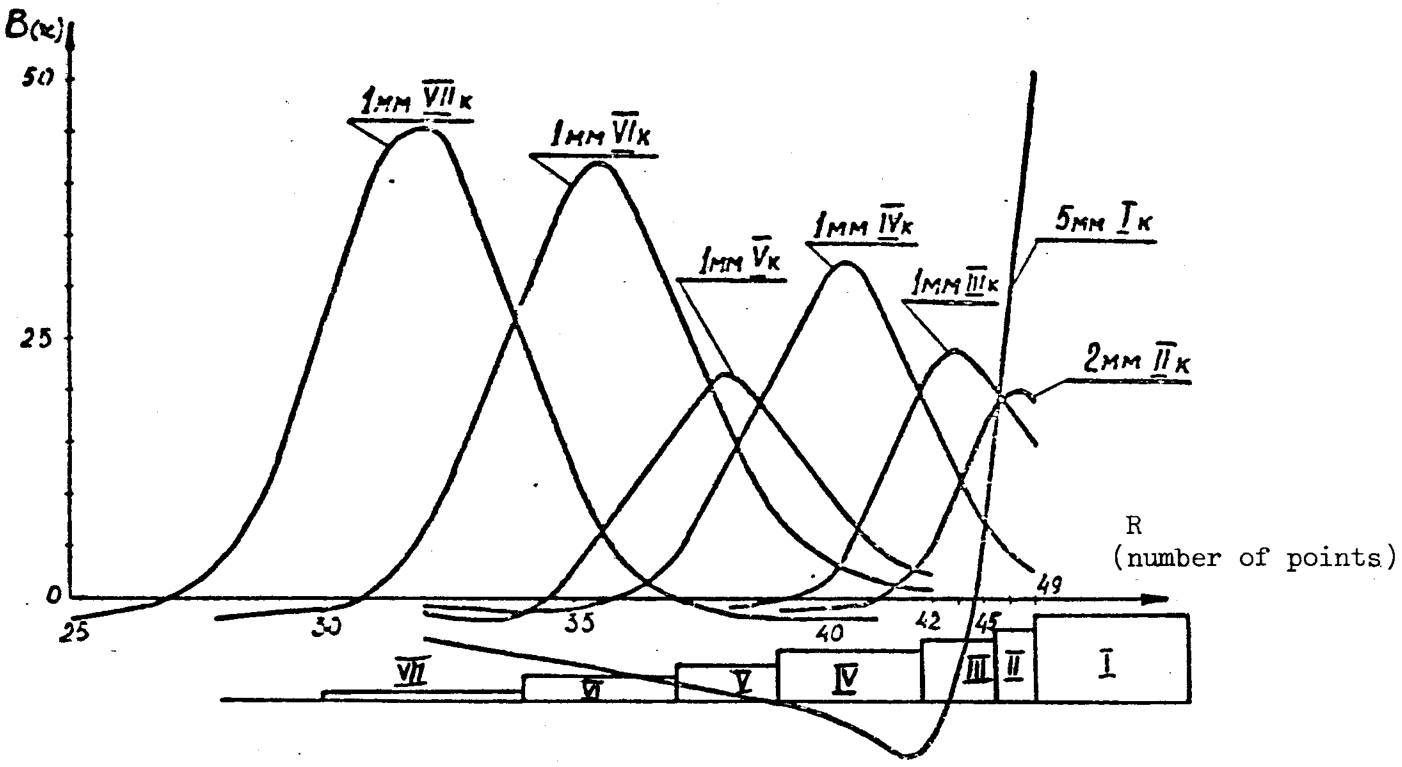

Fig. 1 Field in a mean geometric plane, created by a pair of shims of different rings placed symmetrically on the upper and lower poles.

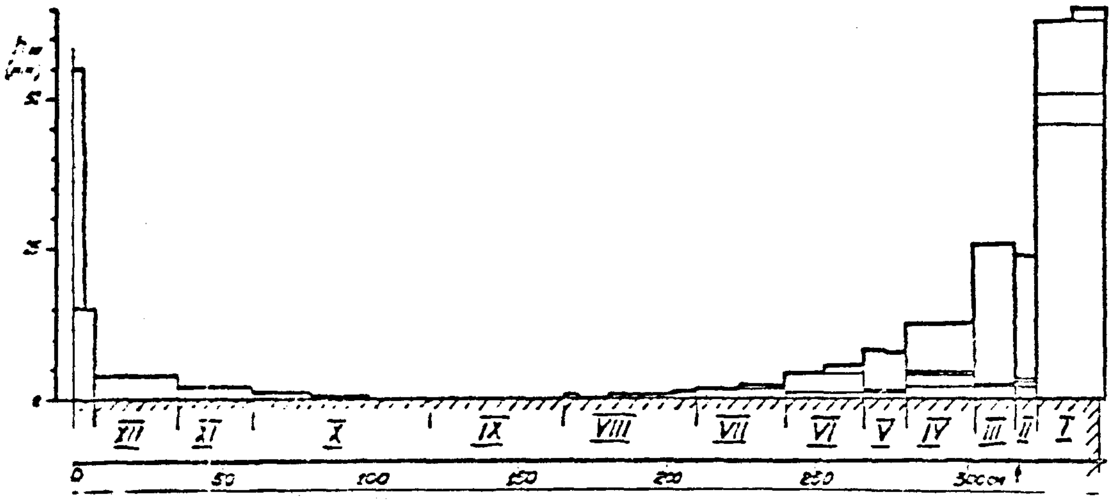

Fig. 2 Shim profile in one of the magnet sections.

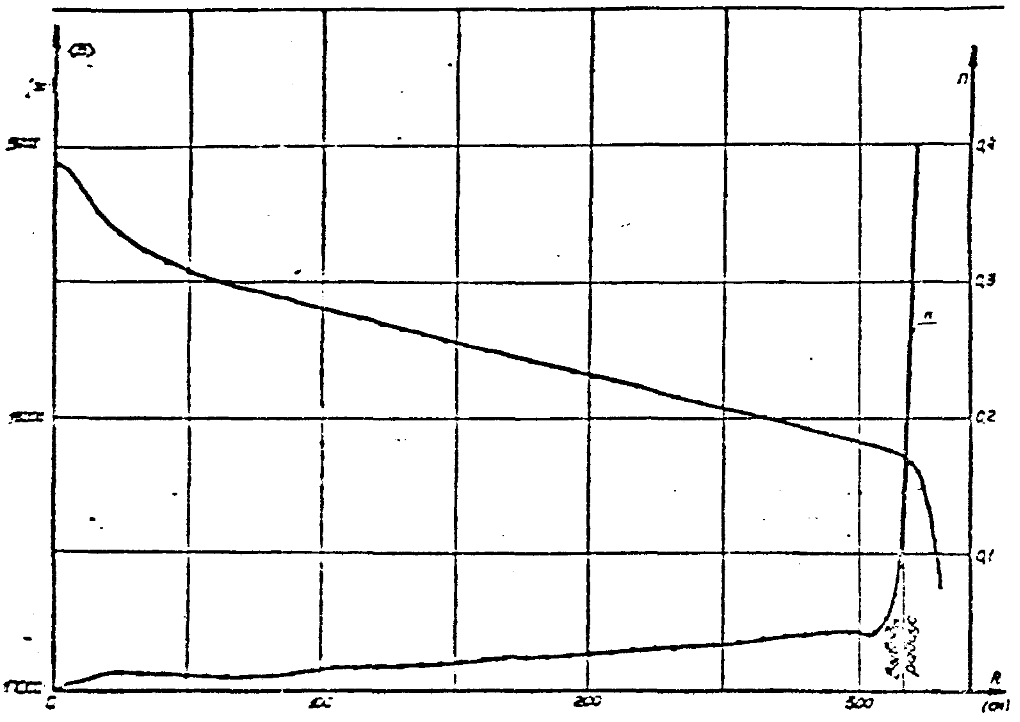

Fig. 3 Field fall-off, averaged over the azimuth, and value of the fall-off index "n" as a function of the radius.

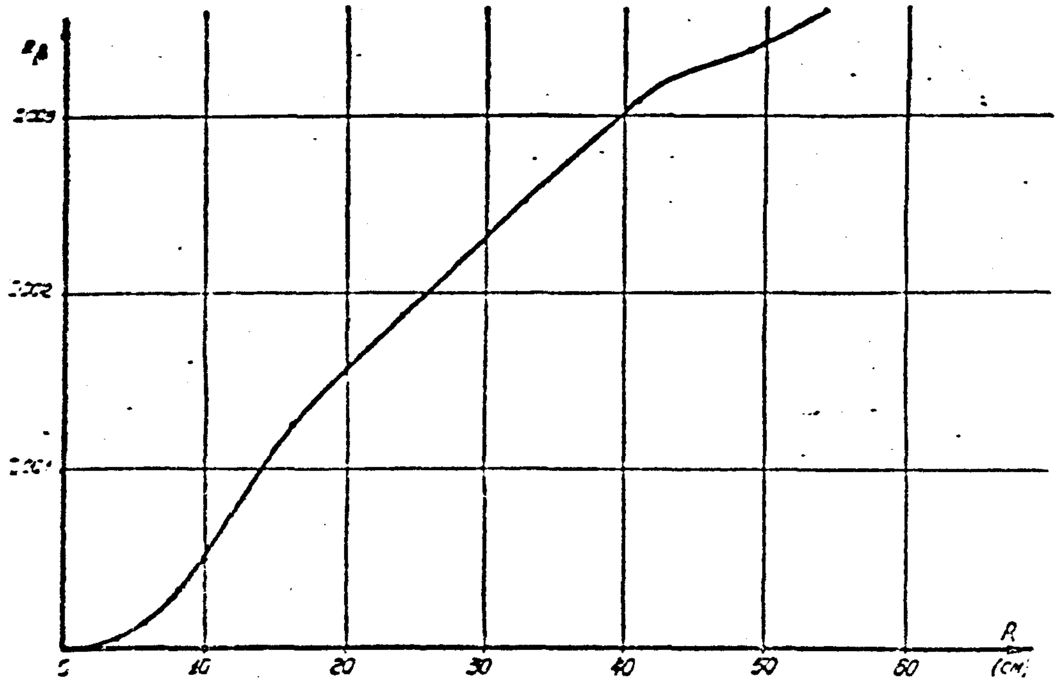

Fig. 4 Value of nβ for the central region of the synchrocyclotron of the A.L. Ioffe PTI (O.L.) of the USSR Academy of Sciences.

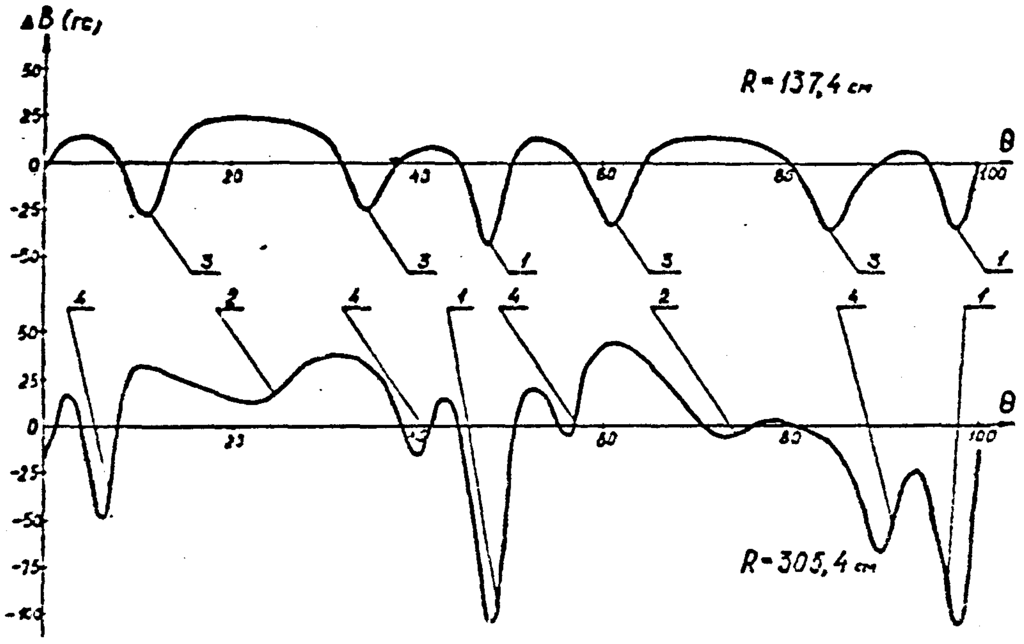

Fig. 5 Azimuthal variations of the magnetic field at radii of 137.4 cm and 305.4 cm, when shims were not fitted on the poles. The influence of the structural components of the pole tips on the azimuthal non-uniformities of the magnetic field can easily be followed from the curves: 1 - butt-weld between the half-discs, 2 - weld-seam; 3 - bolts used for attachment to magnetic core; 4 - holes for the rings.

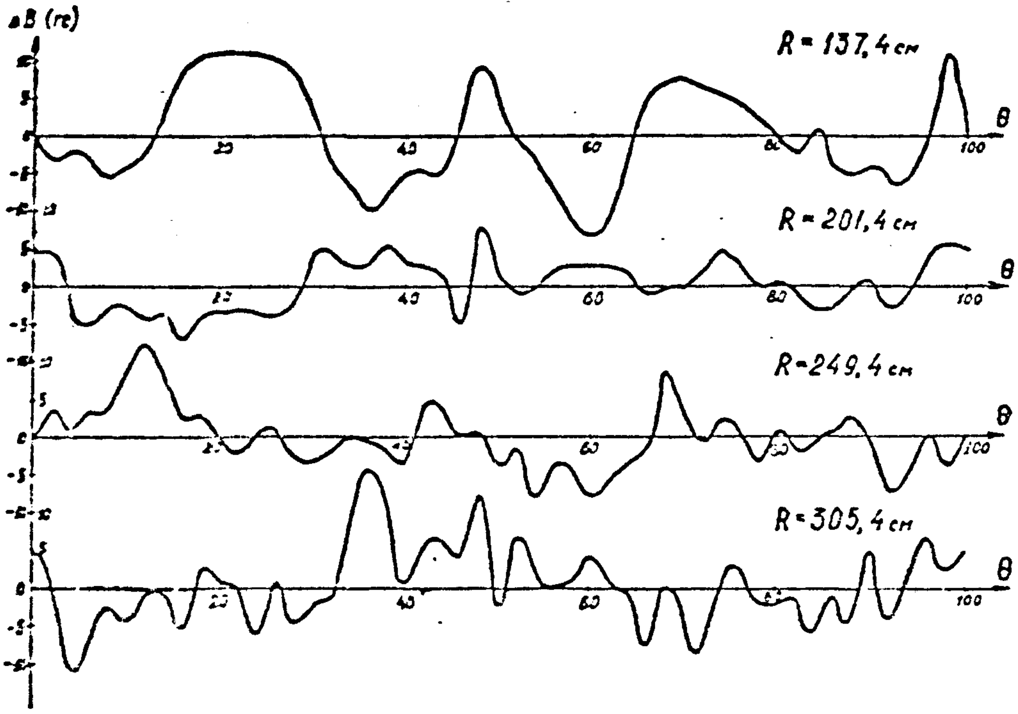

Fig. 6 Azimuthal variations of the magnetic field at the following radii: 137.4 cm; 201.4 cm; 249.4 cm; 305.4 cm. The values were obtained after shimming.