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Report 130

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

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P A R T   I I

CORRECTING THE POSITION OF THE MEDIAN SURFACE

The authors discuss the synchrocyclotron's field parameters, which must be checked in order to restrict the axial motion of the accelerated particles. An examination is made of the effect of the non-horizontal positioning of the PTI magnet's pole pieces on the values of the radial field component when measured with a vertically-oriented Hall detector. A procedure is described for correcting the position of the median surface. As a result of the work done, the deviation of the orbital plane of the particles from the mean geometrical plane due to the magnetic field does not exceed 1 cm, whilst distortion of the orbital plane is negligible (<1 mm).

1. I N T R O D U C T I O N

In synchrocyclotrons, betatron oscillations along the radial and axial coordinates take place independently in the non-resonance region. The solution of a linearised equation for axial betatron oscillations in the non-resonance region is of the form [1]

$$\frac{z}{r} = \sum_{k=0}^{\infty} \frac{f_k^r}{k^2 - n} \cos(k\vartheta - \beta_k^r) + C_z \cos(\sqrt{n}\,\vartheta + \varepsilon_z) \tag{1}$$

where $f_k^r = B_k^r / B_{z0}$ is the relative value of the k-th harmonic of the radial field component in the mean geometrical plane of the gap, β_k^r is the phase of the harmonic, and C_z, ε_z are the amplitude and phase of free axial oscillations.

The vertical oscillation amplitudes are determined by the harmonics of the radial field component in the mean geometric plane of the gap and by the fall-off factor n. The effect of the highest field harmonics decreases as a function of $1/k^2$, and the most dangerous value is therefore f_0^r, which determines the mean position of the particle orbit in relation to the mean plane of the gap $\langle z \rangle = r/n \, f_0^r$

The permissible tolerance on the amplitude of the forced axial oscillations and mean deviation of the particle orbit from the mean geometrical plane of the gap was 1 cm, - the same value as that used for correcting azimuthal inhomogeneities in the vertical field component [2].

Measurement of the radial component of the magnetic field can be replaced by measurement of the position of the median surface of the magnetic field in relation to the mean plane of the gap, since there is a unique link between them in the linear approximation:

$$\frac{B_r}{\langle B_z \rangle}\bigg|_{z=0} = \frac{\mathcal{N}(z,\vartheta)\, z_M}{z} \quad , \qquad (2)$$

where B_z and B_{z} are the radial and vertical components of the magnetic field in the mean geometrical plane of the gap, the sign $\langle \; \rangle$ denotes averaging over the azimuth, $\mathcal{N}(z, \vartheta)$ is the fall-off factor at a given point, and z_M is the position of the median surface in relation to the mean plane of the gap.

The distances between the median surface and the mean geometrical plane may pass beyond the limits of the linear dependence of B_z on z, in which case the linearised equation, and its solution (1), is not valid and the relationship (2) is untrue. Consequently, apart from measuring the radial field component in the mean geometrical plane, it is necessary to check the position of the median surface.

The radial field component was measured with an accuracy of $\sim$1 Gauss by a vertically-oriented Hall detector [3]. The position of the median surface was determined by varying the radial field component over the height of the gap with an accuracy of not less than 0.5 cm. The measurement process was considerably simplified and shortened by the use of automated equipment [4].

2. EFFECT OF NON-HORIZONTAL POSITIONING OF THE POLE PIECES

Owing to uneven settlement of the foundations supporting the PTI synchrocyclotron magnet, the pole pieces were subjected to a parallel misalignment in relation to the horizontal plane, the angle of this misalignment being $\Psi = 7 \times 10^{-4}$ rad. In this case, the magnetometer on the base of the vertically-oriented Hall detector does not measure the radial component but the horizontal component of the magnetic field in a radial direction $B_{hor.}$

$$B_{hor.} = B_z - \Psi B_z \sin \vartheta \qquad (3)$$

where ϑ is the angle of azimuth measured from the axis of rotation of the plane of the pole in an anti-clockwise direction. In the present case, $\Psi B_z \sim$ 10G, and the correction term cannot be disregarded.

One way of effecting the correction is to subtract from the measured Hall intensity the value

$$-\alpha \Psi B_z \sin \vartheta ,$$

where α is the sensitivity of the Hall detector. The drawback of this procedure is that it is necessary to determine, during the measurement process, the sensitivity of the Hall detector, which is closely dependent on the ambient temperature, instabilities in its power supply etc.

Another way is to take advantage of the fact that, in a linear approximation, the surface determined as the geometrical location of the points $B_{hor.} = 0$ is situated at a distance of

$$z = -\frac{z}{\mathcal{N}(z,\vartheta)} \Psi \sin \vartheta \tag{4}$$

from the median surface along the Z axis.

When finding the surface $B_{hor.} = 0$, the Hall detector is, in effect, acting as a "zero-instrument", so it is not necessary to determine the detector's sensitivity, and the measurement results are not dependent on a slow drift in the detector's sensitivity and in its operating current. Formula (4) is, however, correct when the distances between the surfaces $B_{hor.} = 0$ and $B_{\eta} = 0$ do not pass beyond the limits of the linear dependence of B_r on z. In the present case, this condition was not fulfilled in some areas of the magnet because of the considerable size of the angle ψ and the small falling-off of the field ($\mathcal{N}$ is small); consequently, the first method was used in order to make the corrections.

3. CORRECTING THE POSITION OF THE MEDIAN SURFACE

The initial estimatory measurements were made by the flexible wire method, using a current [5]. These measurement results could be reproduced to within 0.5 cm. On the basis of the results it was established that the mean position of the median surface at radii in the 25 cm - 290 cm range departed from the mean geometric plane by not more than 2 cm. At radii of over 250 cm the sag in the wire increased and resulted in a larger error. At radii of 310 cm and above the wire was no longer stable. As the median surface in the 25-290 cm range of radii was close to the mean geometrical plane and passed through zero at a radius of 250 cm, it was decided not to use a supplementary winding for re-distributing the currents in the upper and lower windings of the magnet. Consequently, the position of the median surface was corrected by a redistribution of the iron on the upper and lower poles.

After the wire measurements, a Hall detector was used to measure the topography of $B_{hor.}$. The mean $\langle B_{hor.} \rangle$ over the azimuth displayed a sharp drop in the 290-310 cm range of radii. After an attempt to find the position of the surface $B_{hor.} = 0$

in this region, it was found that, within $\pm$ 75 mm of the mean geometrical plane, the required surface did not exist. An attempt to obtain the surface $B_{hor.} = 0$ simply by re-distributing the iron in this range of radii was not successful. It was therefore decided to increase the falling-off in the region of the final radii by removing the 1 mm shims from the external shimming ring on the upper and lower poles around the entire circumference of the magnet. By next removing the 1-mm shims of this ring from the top and re-positioning them at the bottom around the entire circumference of the magnet, a surface of $B_{hor.} = 0$ was successfully obtained within the limits indicated. After some minor local adjustments to the iron in the 260-329 cm range of radii, a satisfactory picture of the median surface was obtained.

In the 9-260 cm range of radii the median surface in the magnet gap was found, but its mean position fell slightly outside the 1 cm tolerance. The position of the median surface was corrected by moving 1 mm and 0.5 mm-thick pieces of iron from one pole to the other. Shimming was done afterwards, beginning from the external shimming rings. In order to determine more easily the thickness of the shims which were to be moved, graphs were plotted of the variations in B_z in the mean geometrical plane when shims of a certain thickness were transferred on various rings. The aim of shimming was not only to obtain a mean value $\langle B_z \rangle = 0$, but also to even out local inhomogeneities. In individual cases, therefore, 0.2 mm-thick shims, measuring half the width of the ring, were transferred.

In order to be able to operate in the region of the central shimming rings (up to a radius of 1.2 m) the coordinate system had to be transferred from the centre of the magnet, because its support plate covered the shims. The field was corrected by using the results of measurements on one diameter. After locating the coordinate system in the centre, the azimuthal picture of the field in this region was adjusted by adding iron to only the upper pole, which resulted in a slight change in the fall-off.

4. RESULTS

The results obtained are given in the table and figure. The figure gives the mean value $\langle B_r \rangle$ along the radius and corresponding displacement of the median surface $\langle z \rangle$ calculated from these data and the known fall-out [2]. Furthermore, the graph is plotted with the points for $\langle z^* \rangle$, which is the mean azimuthal deviation of the median surface obtained by a graphical interpolation of the measurements of the radial field component in the mean geometrical plane and 25 mm above and below it.

It can be seen from the results given that the mean position of the particle orbit departs from the mean geometrical plane by a value no greater than one centimeter.

The relative amplitude of the first harmonic of the radial field component does not exceed 5×10^{-4}, which corresponds to an axial oscillation amplitude of <1 mm.

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Table 1

Mean values of the radial field component and displacement of the median surface in relation to the mean geometrical plane along the radius

R	$\langle B^2 \rangle$	$f_0^2 \times 10^{-5}$	$\langle Z \rangle$	$\langle Z^* \rangle$
cm	G		mm	mm
1	2	3	4	5
9.4	-0.3	-1.8	1	1.0
17.4	-1.7	-9.2	2	
25.4	-1.4	-7.5	1	3
33.4	-0.4	-2.3	1	
41.4	-1.2	-6.2	2	3
49.4	-1.6	-8.6	4	
57.4	-2.0	-1.1	6	10
65.4	-1.4	-7.6	5	
73.4	-0.4	-2.4	2	4
81.4	0.8	4.1	-3	
89.4	1.3	7.2	-5	-7
97.4	1.0	5.2	-4	
105.4	-0.1	-0.6	1	1
113.4	-0.4	-2.4	2	
121.4	0.3	1.8	-1	1
129.4	0.2	1.3	-1	
137.4	1.0	5.7	-4	-6
145.4	0.9	5.1	-4	
153.4	1.2	6.5	-5	-5
161.4	0.8	4.3	-3	
169.4	0.8	4.6	-3	-4
177.4	0.7	3.7	-3	
185.4	1.0	5.3	-4	-4
193.4	0.8	4.6	-4	
201.4	1.2	6.4	-5	-3
209.4	0.7	3.9	-3	
217.4	0.9	4.8	-4	-2

Table 1 (contd.)

R cm	$\langle B^2 \rangle$ G	$f_0^2 \times 10^{-5}$	$\langle Z \rangle$ mm	$\langle Z^* \rangle$ mm
1	2	3	4	5
225.4	1.1	5.9	-5	
233.4	0.9	5.0	-4	-2
241.4	0.9	5.0	-4	
249.4	0.7	3.8	-3	-1
257.4	0.6	3.2	-2	
265.4	1.0	5.4	-4	-1
273.4	0.2	0.9	-1	
281.4	0.7	3.7	-3	1
285.4	0.1	0.8	-1	
287.4	0.1	0.7	-1	
289.4	0	0	1	2
291.3	-0.2	-1.1	1	
293.3	-0.4	-2.1	2	
295.3	-0.4	-2.4	2	
297.3	-0.6	-3.2	2	7
299.3	-0.5	-2.9	2	
301.3	0	0	1	
303.3	0.4	2.5	-2	
305.3	1.0	5.3	-4	-2
307.3	1.2	7.0	-5	
309.3	1.5	8.4	-5	-5
311.3	1.5	8.4	-4	
313.3	1.3	7.3	-3	-5
315.3	0.7	3.7	-1	
317.3	0.5	2.6	-1	
319.3	0.6	3.1	-1	
321.3	1.7	9.3	-1	-1
323.3	3.7	20.7	-1	
325.2	7.0	39.6	-1	
327.2	11.9	68.0	-2	
329.2	17.2	98.9	-2	-2

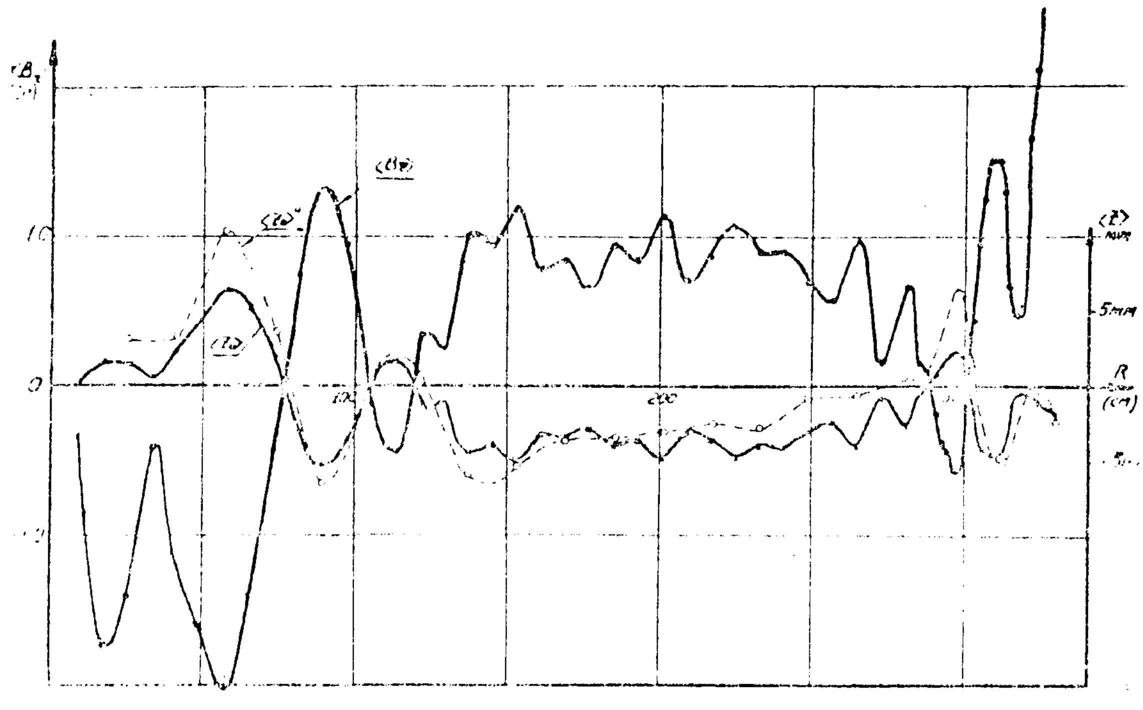

Fig. 1 Results of correcting the median surface on the synchro-cyclotron of the A.F. Ioffe Physico-Technical Institute (Order of Lenin) of the USSR Academy of Sciences.
$\langle B_r \rangle$ is the average azimuthal value of the radial field component in the mean geometrical plane of the gap; $\langle Z_0 \rangle$ is the displacement of the median surface in relation to the mean geometrical plane, calculated from the values of n, B_{z_0}; $\langle z' \rangle$ is the mean azimuthal deviation of the median obtained by a graphic interpolation of the measurements of the radial field component in the mean geometrical plane and 25 mm above and below it.