The magnetic system of the monoenergetic cyclotron

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The requirements imposed on the accelerator magnetic field at working radii of Δr = 54 to 410 cm are mainly the following:

1. According to the kind of particles accelerated the average field should be isochronous to an accuracy of $\sim 3 \times 10^{-5}$.
2. The magnetic field variation dependent on flutter should be larger than 0·6.

The required structure of the Thomas type magnetic field can be achieved by means of four identical C-shaped sector electromagnets placed 90° apart. Preliminary calculations have shown that the total iron weight of the electromagnets is ~1200 t and the power supply of the windings does not exceed 1·5 MW.

Experimental modelling of the magnetic system is the most effective method for studying the magnetic field of the monoenergetic cyclotron. For primary studies a sector electromagnet (1:10 scale) was made. The magnet yoke was made of low-carbon steel sheets 8 mm thick. The pole tips, having an angular width of $\alpha = 42{\cdot}5°$ and radial width ΔR = (30 to 440) mm, were made to an accuracy of 0·1 mm. The gap between the plane pole tips was $\delta = 16 \pm 0{\cdot}3$ mm.

The magnet current coils were manufactured from copper tube and consisted of three pairs of sections. This allowed one to change the effective dimensions of the windings so that the design conditions were better fulfilled. The water cooling system permitted the operation for a long period with current intensities j = (30 to 40) A/mm^2.

Magnetic measurements were performed by means of a Hall detector[3] whose accuracy was not worse than ±0·15 ± 0·7 G. The detector was mounted in the gap by using special equipment which permitted its displacement along the azimuth by 360° and along the radius from 0 to 470 mm with accuracies of ±0·1° and ±0·5 mm, respectively. The magnetic system windings were supplied from a stabilised source. A general view of the electromagnet with the Hall detector displacement equipment inside is shown in Fig. 1.

The azimuthal distribution curves of the magnetic field from the sector electromagnet along azimuths at different radii are shown in Fig. 2 (two winding sections are included). It is seen that, except at the initial radii ($r <$ 10 cm), the field is extended to less than the magnetic system period (90°). Thus, all the results obtained from experiments with a one-piece sector

CYC69D19

magnet will be valid for a four-sector system. At small radii the mutual effect of the magnets is small and at this stage of studies may be neglected.

To obtain reliable results in analysing the experimental curves of the magnetic field, detailed measurements in the edge zone of the magnet are needed. In order to decrease the amount of work the azimuthal measurements were made with an alternative interval along the azimuth. The experimental data were treated by computer. The programme was aimed at calculating the average field, the flutter harmonics for $N = 4$ and $m = 1, 2, \ldots, 7$ as well as the frequencies

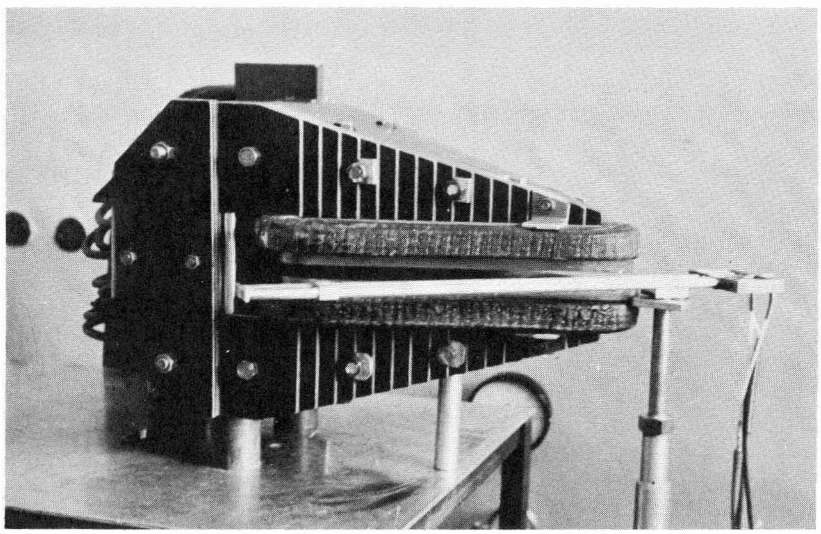

Fig. 1. General view of the sector electromagnet (1: 10 scale) with the Hall detector displacement equipment inside

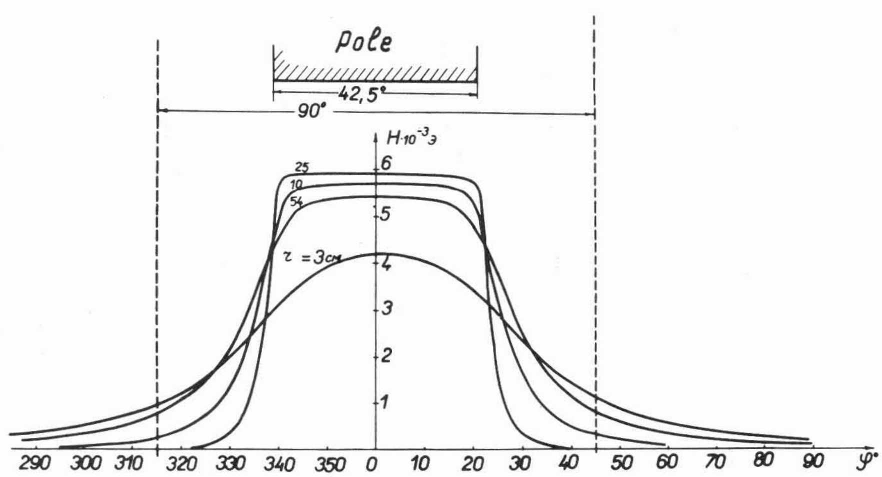

Fig. 2. The azimuthal distribution curves of the magnetic field from the sector electromagnet along the azimuth at different radii

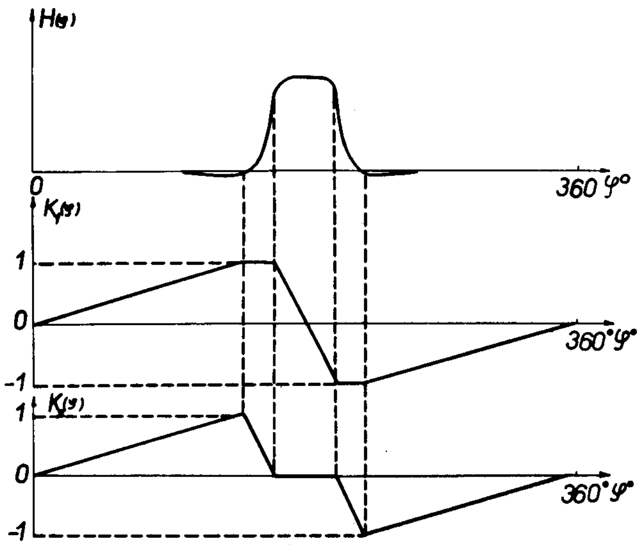

Fig. 3. The functions $K_1\phi$ *and* $K_2\phi$ *for the transformation of the azimuths of the measured points*

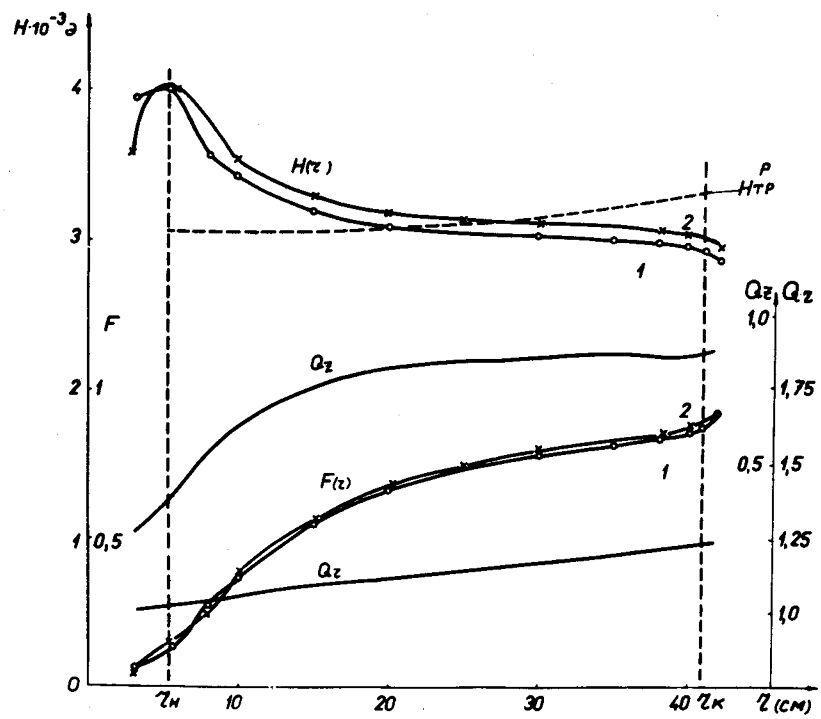

Fig. 4. The results of calculations for experiments with one and two winding sections

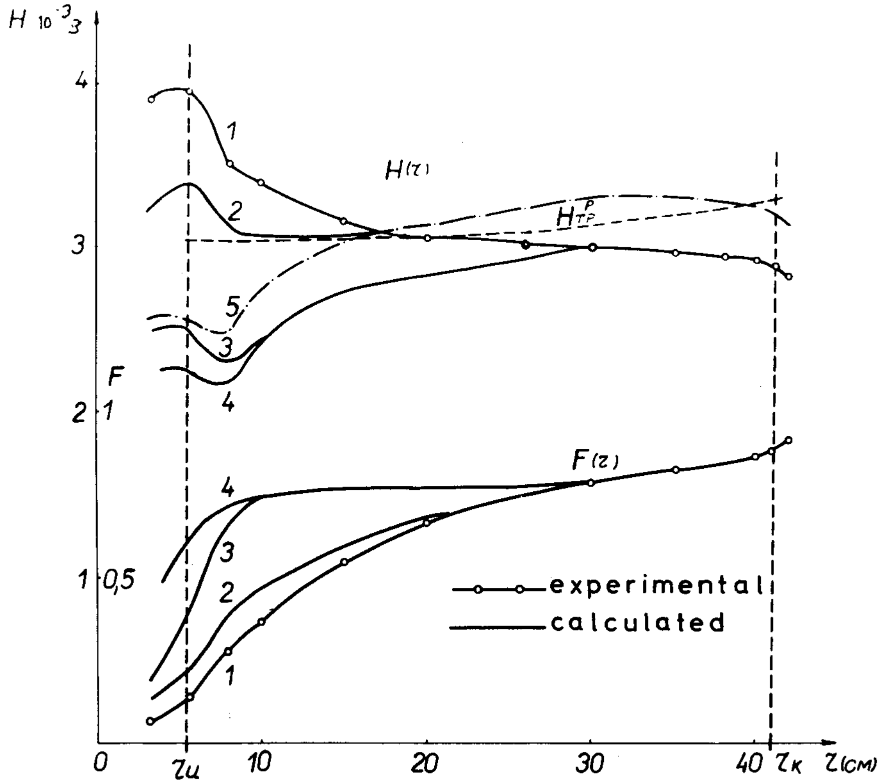

Fig. 5. The results of calculations of the field characteristics for various transformations of the azimuths of the measured points and the gap variations

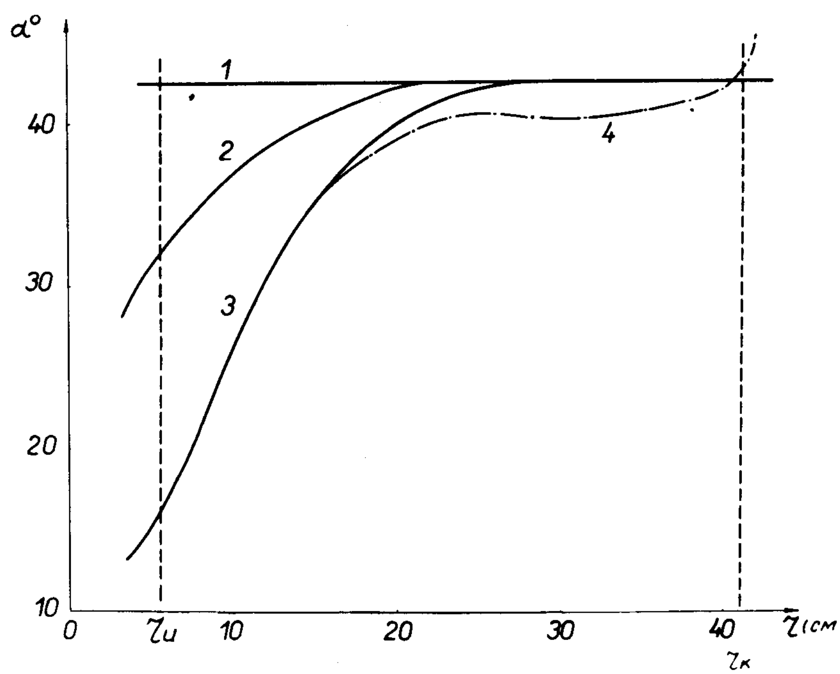

Fig. 6. The curves of the equivalent azimuthal width of the pole tip

of free betatron oscillations according to approximate expressions.[1] In addition the programme allowed for the transformation of the azimuths of the measured points according to the following expression:

$$\phi' = \phi + K_1(\phi) \times L_1(r) + K_2(\phi) \times L_2(r) \tag{1}$$

This makes it possible to vary the angular width of the plane part of $H(r)$ by $2L_1(r)$ and of the edge field by $L_2(r)$. The functions $K_1(\phi)$ and $K_2(\phi)$ are given in Fig. 3.

The results of calculation of the average magnetic field and the flutter for experiments with one and two winding sections are shown in Fig. 4 (curves 1 and 2, respectively). The same figure shows the average field as a function of radius for accelerating protons up to 80 MeV. The dependence of the betatron oscillation frequencies Q_z and Q_r are calculated for experimental flutter (curve 1) and the isochronous average field.

It is seen that the field characteristics are far from the required ones.

To reduce the deviation of the average field from the required one, the angular width of the plane part $H(r)$ of the experimental curves at the initial radii was decreased by means of transformation (1) for $L_2(r) = 0$. The equivalent azimuthal width of the pole tip for this case is shown in curve 2 (Fig. 6). The results of calculation of the field are given in Fig. 5 (curve 2).

It is seen that the flutter is increased with improvement of the character of the average field dependence on radius.

Further change of the angular width of the sector electromagnet, as is shown by curve 3 (Fig. 6), has resulted in significant increase of the flutter (curve 3, Fig. 5). However, at radii less than 7 cm the flutter remains smaller than the required value of 0·6.

The flutter can be increased up to the desired value at small radii by varying the gap of the sector electromagnet. Assuming that the length of the magnetic field reduction is directly proportional to the gap value, we obtain that for δ = 14 mm the flutter increases up to 0·61 at the injection radius (curve 4, Fig. 5).

The required dependence of the average magnetic field can be obtained by slightly varying the angular width of the sector along the radius. So, for curve 5 (Fig. 5) plotted by parallel translation of curve 4, the necessary variation of the angular width $\alpha(r)$ for obtaining the required dependence $H(r)$ at Δr = (15 to 42) is shown by curve 4 (Fig. 6). The shaping of the average field at initial radii can be carried out by means of a system of sector current coils.

Thus, the experimental and calculation studies have shown the possibility of producing the necessary magnetic field for the monoenergetic cyclotron.

ACKNOWLEDGEMENTS

The authors are indebted to D. P. Vasilevskaya, Yu. N. Denisov, V. V. Kalinichenko, A. G. Komissarov, and P. T. Shishliannikov for developing the power supply system as well as for stabilisation and measurement of the magnetic field of the electromagnet.

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