# MAGNETIC CHARACTERISTICS OF THE 10 BEV PROTON SYNCHROTRON

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**(presented by E. G. Komar)**

## *I. General remarks*

The magnetic field of the Electrophysical Laboratory accelerator has the following parameters:

Peak magnetic field intensity on the equilibrium orbit (R = 2800 cm.) – $H_m$ = 13,000 oersted.

Field intensity at injection $H_0$ = 150 oersted.

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

Pole width b = 200 cm.

The magnetic field quality can be characterized by the relative dimensions of the chamber region (in direct ratio to its width) where the field index

$$n = \frac{dH}{dr}\frac{R}{H}$$

is approximately of constant value, by the magnitude of the azimuthal nonuniformity of the magnetic field and the deviations of the surface of magnetic symmetry (characterized by H = 0) from the median plane of the chamber.

An increase of the accelerator energy with increase in the ratio of the radius to the value of magnetic field intensity on the equilibrium orbit makes it necessary to maintain more accurately the present value of magnetic field intensity gradient dH/dr since negligible fluctuations of dH/dr value lead to significant variations of the index.

Distorsions of magnetic field gradient may be caused by inaccurate adjustment of the contour of the magnet gap, influence of residual magnetization and dynamic effects caused by the varying magnetic field and n changes, caused by inaccurate machining of the contour and increasing with the reduction of the $\delta/R$ ratio. In the accelerator described the relative value of the magnet gap $\delta/R$ is considerably smaller than in other existing large synchrotrons and equals – 1.43%.

The influence of residual magnetization and dynamic processes in the magnetic system is proportional to $R/H_0\delta$. The field intensity at injection usually decreases with an increase of the accelerator maximum energy; this effect created, as far as the described unit is concerned, additional difficulties.

Because of the comparatively small value of the radial dimension of the chamber, which is 7% of the radius, the specifications for the azimuthal nonuniformity of the field are more severe than those set for other accelerators of smaller energy.

The comparatively small dimension of the accelerator air gap restricts possible deviations of the surface of magnetic symmetry of the accelerator from a plane and this in turn makes tolerances of pole shoes shift and eddy currents in different constituents of the structure (as in the vertical walls of the chamber for instance) more rigid.

As it was necessary to obtain magnetic characteristics which would meet rather rigid specifications, it was necessary before building the accelerator to work out effective methods of correcting the magnetic field. A small model was built for carrying out preliminary investigations of magnetic characteristics. The final study of magnetic characteristics and the development of methods for correction of the magnetic field were carried out on one of the electromagnet blocks which constitutes $^1/_{48}$th part of the whole magnet.

## *2. Static characteristics*

The necessary radial decrease of magnetic field was provided by the conical surfaces of pole pieces (see fig. 1) with an angular distance $\alpha = 9{,}3.10^{-3}$ and beveled edges.

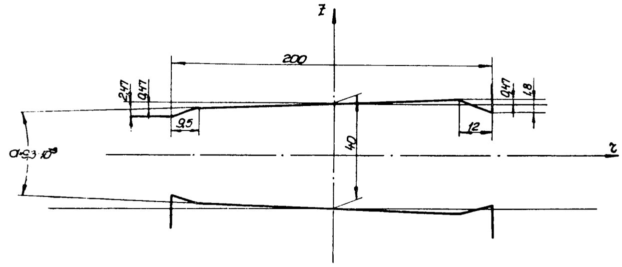



**Fig. 1.** Pole contour.

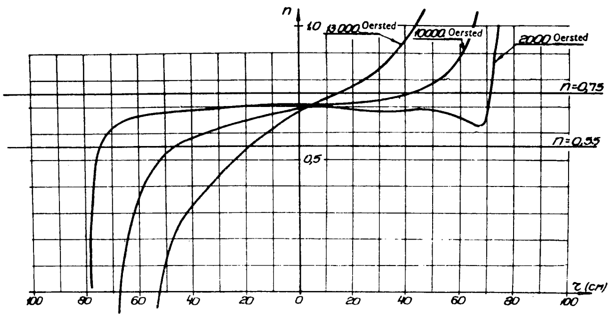



**Fig. 2.** Magnetic field index under static conditions.

The curves of fig. 2 illustrate the variations in field index n along the width of the electromagnet gap which were attained in the block with a field intensity varying from 2000 to 12,000 oersted. Measurements were made on the median surface and in the static field while the block was supplied with direct current.

If the field intensity in the center of the chamber $H_c$ was 2000 oersted the width of the useful field region, characterized by sufficient distance from resonant points ($0{,}55 < n < 0{,}75$), was of the order of 150 cm. An experimental curve of field distribution coincides quite well with the calculated values which were obtained with the assumption that $\mu = \infty$.

The width of the useful field region at $H_c = 10{,}000$ oersted was 90 cm., and at $H_c = 13{,}000$ it was 35 cm.

The use of windings, laid inside the chamber, made it possible to increase the useful field region up to 80 cm., at the field intensity of 13,000 oersted, which is quite sufficient at the end of acceleration.

The curves of fig. 3 give the value of the index at 150 oersted, which have been obtained at different values of residual field intensity before exciting the electromagnet. With a slow decrease in the current the value of the residual field was 43 oersted and in this case the dimension of the useful field region at the beginning of injection is inadmissibly small because of distortions, caused by the remanent field. Demagnetization of the electromagnet by supplying it with A.C. with attenuating amplitude made it possible to decrease considerably both the value of remanent field and its distorting effect, so that at the remanent field intensity of 3 oersted the width of the useful field region reached 150 cm. for $H_c = 150$ oersted.

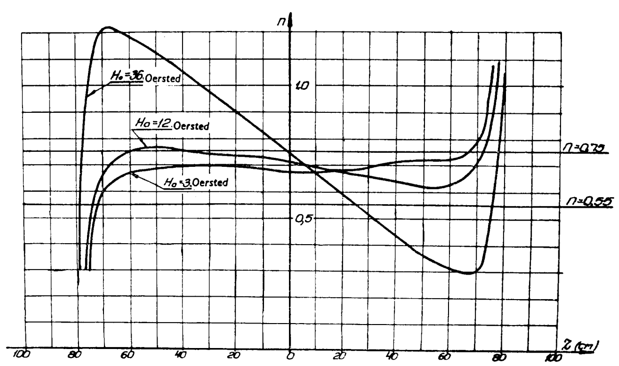



**Fig. 3.** Effect of demagnetization on field index.

To reduce the remanent field intensity in working conditions a special automatic apparatus was developed which was turned on during the interval between two cycles. This apparatus allowed us to vary the conditions of demagnetization and ensured its repetition with the necessary precision.

The demagnetizing system favourably affects the field distribution in the azimuthal direction, since, this system by decreasing the total value of remanent magnetization of the electromagnet naturally decreases the absolute value of the nonuniformity of the remanent field distribution in the azimuthal direction. This nonuniformity is caused by the varying value of the coercive force of the material of which individual blocks of the electromagnet are made.

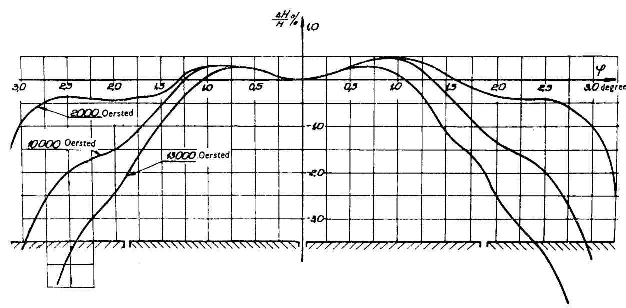



**Fig. 4.** Distribution of magnetic field in the azimuthal direction under static conditions.

The picture of magnetic field distribution in the azimuthal direction for the static field, which was obtained by testing a block of the accelerator electromagnet at different values of field intensity, is given in fig. 4.

The distribution curve contains insignificant harmonics of high period, which slightly influence the accelerating process. The cores of the electromagnet have special compensating windings which make it possible to compensate azimuthal nonuniformity of the first and second harmonics. The presence of two windings for each of these harmonics with 90° phase shift makes it possible to vary both amplitudes and phases of the correcting fields.

As homogeneity of the magnetic field in the azimuthal direction must satisfy severe specifications, it is necessary to take into consideration the magnetic field nonuniformity caused by the current leaks through cooling water. Because of this a scheme of connections of the electromagnet quadrants was so chosen that current leaks could not provoke nonuniformity of the first harmonic (fig. 5).

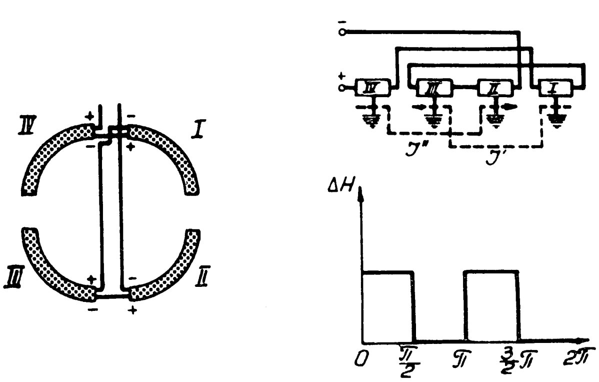



**Fig. 5.** Effect of leak currents.

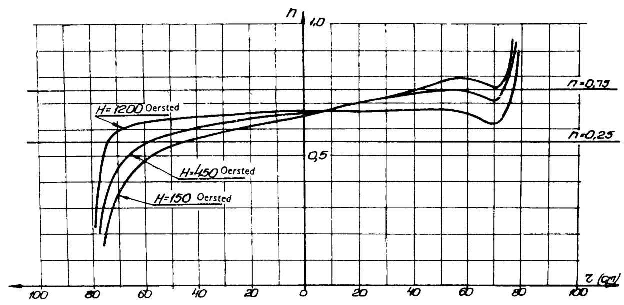



**Fig. 7.** Distortion of magnetic field index under dynamic conditions.

*3. Dynamic characteristics*

The study of the electromagnet blocks in dynamic conditions was carried out by supplying the windings from a special source which gave triangular current pulses with a rate of increase of field intensity of 3000-1500 oersted/sec.

As is evident from fig. 6, the azimuthal distribution of field intensity in dynamic conditions does not qualitatively differ from that in a static field. They only differ in somewhat enlarged amplitude of harmonics of high periodicity.

The curves of fig. 7 show the dependence of the magnetic field index on a geometric coordinate across the chamber of the accelerator with a rate of field increase equal to 3000 oersted/sec. In this case the remanent field is not taken into account.

In contra-distinction to the static field, where the curves $n = f(r)$ are approximately horizontal lines with practically constant $n$ value in the range of the entire width of the useful field region, the curves in dynamic conditions approach straight lines characterized by an angle of slope $\beta$ to the horizontal axis. The angles of slope decrease with an increase of the absolute value of field intensity but at a field intensity of 150 oersted they are almost independent of it (fig. 8).

The curve in fig. 8 gives the intensity distribution of an additional field $\Delta H_g$, caused by the dynamic effect. As is seen from fig. 8 the dynamic effect results in a lagging of the field intensity increase on the chamber edges in comparison with the central part, i.e. the distortions caused by the dynamic effect are opposite to the distortions caused by the residual magnetization.

It we assume that the dynamic distortion of the index is defined by the straight line of slope $\beta$ to the axis of abscissas it is not difficult to prove that for a compensation of this distortion it is necessary to attain on the pole surfaces a current the density of which $i$ increases from the centre to the periphery approximately according to the linear law

$$i = 0{,}8 \frac{H_c}{R} \frac{\delta}{2} \beta r \left[ 1 + \frac{3}{2} \beta \frac{r}{\delta} \right] \frac{\text{amp}}{\text{cm.}}$$

The surface current with variable density is easily approximated by irregularly placed conductors through which the same current passes changing in time in accordance with changes of $\Delta H_g$. The emf induced in the compensating windings during increase in the accelerator field intensity can be used as a supply source for these windings.

The general outlay of the compensating winding circuit is shown in fig. 9.

The necessary law for a time varying current has been obtained by a corresponding selection of inductive and active load.

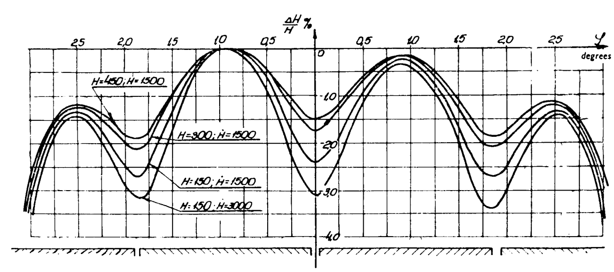



**Fig. 6.** Distribution of magnetic field in the azimuthal direction under dynamic conditions.

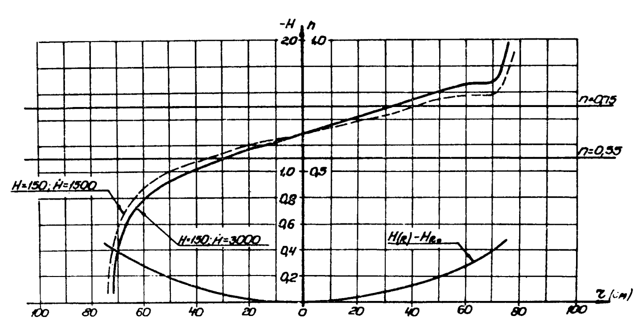
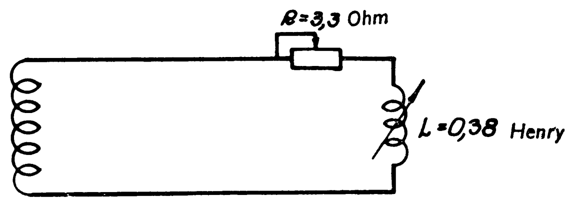



**Fig. 8.** Distortion of magnetic field index under dynamic conditions.




Scheme for compensating dynamic distortions

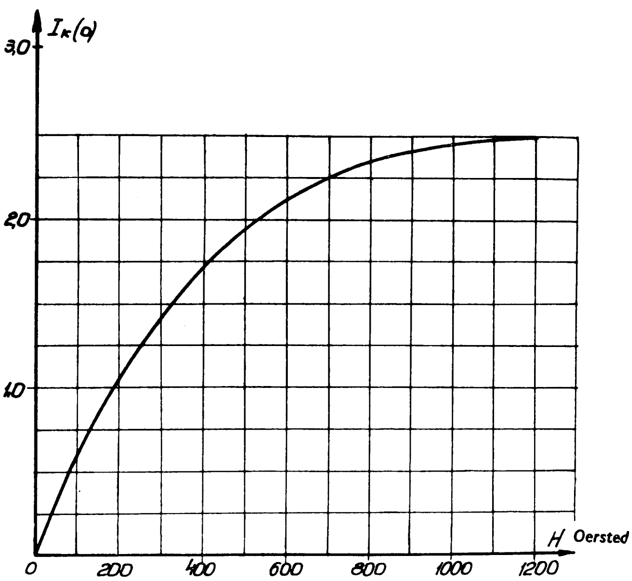



**Fig. 9.** Current in compensating winding

An experimental curve, $n = f(r)$, which was plotted with the compensating windings connected according to the above mentioned outlay, is shown in fig. 10. The methods developed for correcting the distortion of n by means of residual magnetization and dynamic effects make it possible to use to some extent the mutual compensation of an action of the residual magnetization and dynamic effect by changing the working conditions of the compensating units.

As is evident from the experiments carried out on a block, eddy currents in the structural part of the chamber have, due to the measures taken, an insignificant effect on the position of the surface of magnetic symmetry. The errors in the adjustment of the position of the pole surfaces in the radial direction have a considerably greater effect. The displacement of the median plane ($H_r = 0$) of the chamber due to these errors is estimated by the following equation.

$$\Delta Z = \frac{-\delta}{2} \, \frac{\alpha_1 + \alpha_2}{\frac{n\delta}{R} + \alpha_1 - \alpha_2},$$

where $\alpha_1$, $\alpha_2$ are errors in the radial angular adjustment of the top and bottom pole surfaces.

In the accelerator described the shifts of the poles of $\pm$ 0.2 mm. are rather significant.

Correction of the height of the median magnetic surface at the value $\Delta Z$ can be achieved by creating in the chamber a radial field of intensity $H_r$ defined by $H_r = \Delta Z \, n(Hc/R)$.

This field can be produced by currents on the pole surfaces facing the gap and running on the top and bottom poles, perpendicular to the chamber cross section in opposite directions. The necessary linear current density is

$$i_z = 0.8 \, \Delta Z \, n \, \frac{Hc}{R} \, \frac{\text{amp}}{\text{cm.}}$$

In addition to the correction of the dynamic distortions of n and the height of the median plane, it is convenient to introduce, by means of surface currents on the poles, a control of the index n for the purpose of finding out its optimal value especially at the beginning of the working cycle. For changing the index by $\Delta n$ it is necessary to have a surface current of linear density

$$i_n = \frac{\Delta n}{2,5} \, \frac{Hc}{R} \, \delta \, \frac{\text{amp}}{\text{cm.}}$$

In order to diminish the total number of the compensating winding conductors, placed on the pole surfaces inside the vacuum chamber (since the pole shoes form the vacuum chamber covers), and achieve correcting field pulses a scheme was used in the accelerator described (see figs. 11 and 12), allowing us to use all conductors for independent correction of the dynamic distortions of the index, the height of the median surface and the index itself.

Compensation of the dynamic distortions of the field index is carried out by adjustment of the R and L values

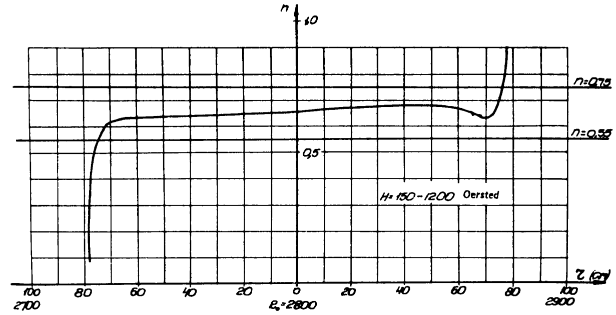



**Fig. 10.** Compensating of dynamic distortions of the magnetic field index.

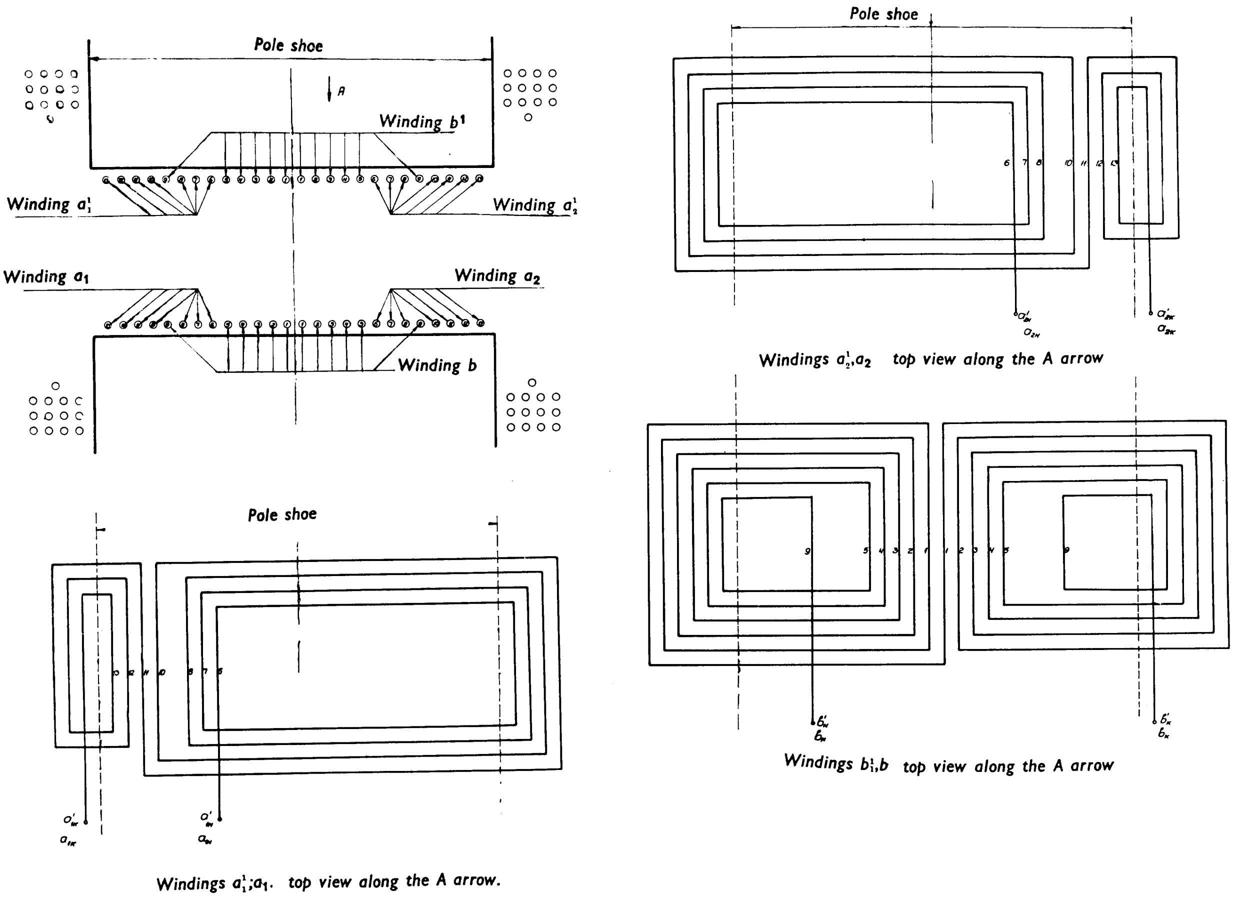
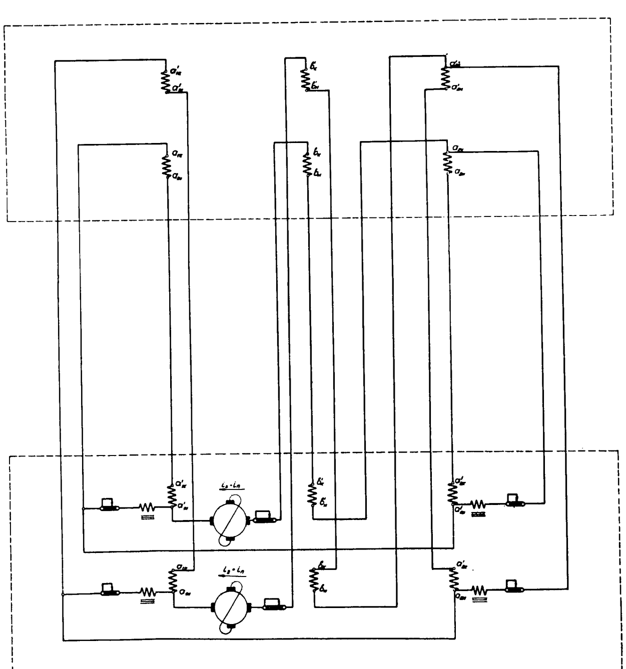



**Fig. 11.** Scheme and position of windings.



of the resistance and reactance coils, connected to the compensating windings. Regulation of the height of the median surface and the index value was attained through amplidynes, controlled as a function of the current of the exciting electromagnet.

The scheme presented in figs. 11 and 12 includes two opposite quadrants. Two such independent systems allow to produce correcting fields of the first harmonic with a regulated amplitude and phase.

Magnetic characteristics, which were obtained while experimenting with separate blocks, and methods of field correction developed as a result of these experiments, were fully verified during the test and adjustment of the assembled electromagnet of the Electrophysical Laboratory.

**Fig. 12.** Scheme of winding supply.