3. Magnet Studies - Part II.

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1. Introduction.

In the method for increasing the focusing of ion beams proposed by Courant, Livingston, and Snyder, the field between two hyperbolic poles was considered. For high values of the field gradient it is necessary to add a third pole (the neutral pole) to obtain the desired linearity of the field. Recently, Sigurgeirsson has proposed a change in the disposition of the hyperbolic poles which might give some advantages especially with regard to the influence of the saturation of the poles while, at the same time, the focusing properties of the field are essentially retained. Figure 1 shows 4 hyperbolic poles together with those parts of the field which are utilized according to Courant, Livingston and Snyder, and Sigurgeirsson, respectively.

In view of the desirability of obtaining quantitive information about the actual magnetic fields intended for such focusing methods, we have undertaken some measurements using a model which has been constructed according to the proposal by Sigurgeirsson. Preliminary tank measurements were made with pole pieces which had been shaped to fit into a yoke, with the result that a field could be produced which was linear within 2 - 3%, inside the region occupied by the vacuum chamber.

2. Experimental Method.

The yoke of the magnet was made from 10-mm steel sheet of unknown carbon content. The sheets were torch-cut and stacked together with paper insulation. Adjacent sheets were then welded together at a few points on the outside; the welding has a negligible effect on the eddy currents. Only the surfaces facing the pole tips were machined. An accuracy of 0.02 mm was attempted, but this was not quite attained, so that the gap in the yoke shows variations in length slightly in excess of 0.02 mm.

The coils were wound from cotton-insulated copper band with cross-section 2 x 5 mm; each coil has 350 windings. Without any forced cooling the coils can be loaded with 50 amp for an indefinite time.

The pole-pieces, shown in figure 2, were machined from Swedish steel. The following average analysis was supplied by the steel plant (Ragnäs bruk, Sweden):
C max 0.05%, Mn traces, Si 0.02%, P_{max} 0.07%, S_{max} 0.005%. Slabs of thickness 12 mm were first machined roughly to the desired shape and then bonded together with Araldit, before the final machining was carried out. The direction of rolling was, in all cases, parallel to the direction of the field. After the final machining the two pole pieces were clamped together by brass holders and wedged into position in the gap of the yoke. We are not able to give exact figures for the tolerances finally obtained, but it is to be expected that an eventual deviation from the desired shape would most probably be found in a lack of parallelism between the upper and the lower pole piece.

Figures 2a and 2b show the pole pieces which have been used for the measurements. In the first case the poles are a rectangular hyperbola and its asymptotes, in the second case two rectangular hyperbolas with the same asymptotes.

The magnet was excited by a DC generator capable of giving 300 volts and 150 amp. In most cases the current in the magnet rose to its maximum value in somewhat less than 1 second, roughly linearly with time, and then decayed to zero.

The results of the measurements will be referred to a three-dimensional system of coordinates x, z, Θ. Near the middle of the pole pieces only the components along the x- and the z-axis differ from zero.

In the vertical line of symmetry (x = 0) we have

$$\frac{n}{R} = \frac{1}{B_C}\frac{\partial B_z}{\partial z},$$

where B_C is the value of the field at the centre, and $\partial B_z/\partial z$ is measured for any value of z. To map out the field for a given value of B_C measurements of $\partial B_z/\partial z$ were made with a differential coil, consisting of two nearly identical coils which were wound in opposite directions and connected in series.

To determine the variation of "n" with B_C for a given location of the differential coil (in practice near the centre) $\partial B_z/\partial z$ was measured as before by the differential coil and B_C was measured by the same two coils in the same position but switched in the same direction. In this way relative values of "n" were obtained. Further details of the measurements are given below and also the method by which relative values of "n" were adjusted to absolute values.

The general method of measurement is explained in fig. 3. The rise of the magnetic field with time is shown and also the differential coil, C, connected through a switch, S, to the galvanometer, G, which is used as a ballistic instrument with small damping. When the switch, S, is opened at the time, t, the deflection of the galvanometer will show the field or, when a differential coil is used, the gradient of the field, which existed at the time, t. The sequence of events is shown schematically in the block diagram. K is a key which is operated by hand; when K is pressed, an electronic arrangement, E1 magnetizes the generator by a current pulse of square form and variable height, which results in a current pulse through the magnet with a rise-time determined by the time constants of generator and magnet. The same electronic arrangement operates S through a delay mechanism. By varying the delay time between the pressing of K and the opening of S, readings corresponding to different fields can be obtained.

The accuracy, which can be obtained in this way, is limited for two reasons. In the first place, the result is obtained by reading a ballistic deflection, which can hardly be done to better than 1%; secondly, the value of the field, for which S is opened, shows small variations from one operation to another. For these reasons the method was changed so that the galvanometer could be used as a zero instrument.

In Figure 3d, C_1 is the differential coil with winding area S_1 and resistance r_1, C_2 is a reference coil with resistance r_2 and winding area S_2, which actually consisted of a few windings of a thick copper wire round the yoke of the magnet. C_1 and C_2 are connected in series with a variable resistance r; the galvanometer is shunted across the coils in series with S, which is operated as before. The resistance, r, is varied until the galvanometer shows no deflection. Let B_1S_1 be the flux through C_1 and B_2S_2 the flux through C_2 at the moment when S is opened; one then has the relation

$$\frac{B_1S_1}{r_1} = \frac{B_2S_2}{r+r_2} ,$$

$$\text{or, taking } S_1 = S_2, \quad \frac{B_1}{B_2} = \frac{r_1}{r + r_2} \longrightarrow \frac{r_1}{r}$$

since r_2 is very small compared to r.

When the switch, S, is opened at some specified current through the magnet, B_2 is constant. The field can, then, be mapped out by placing the measuring coil at various positions in the field, and B_1 is obtained in relative units as the reciprocal value of r. The value of r varied from about 300 ohms to about 3000 ohms and r could usually be determined with an accuracy of 1 ohm.

Some care had to be taken to keep the temperature of the measuring coil, which was wound from copper wire, sufficiently constant. When air was blown on the coil by a small fan it was easy to keep the temperature of the coil constant within 0.5° C.

In the differential coil the core of each coil was about 4 cm x 0.5 cm, the cross-section of the winding area was 0.4 cm x 0.4 cm and distance between the coils about 0.4 cm. Two sets of coils were used for most of the measurements, one with 100 windings per coil and a total resistance of 6 ohms and one with 1000 windings per coil and a total resistance of 600 ohms. A third coil with somewhat smaller dimensions was used near the apex of the lower pole piece in Fig. 2a.

The coils were connected to a galvanometer which had two coils on the same frame with a resistance of 4 ohms and 1000 ohms respectively. The advantage of this type of instrument is that the damping can be varied within very wide limits without serious changes in the sensitivity.

By the zero method, only relative measurements can be made but, at the same time, the important advantage is obtained that the exact timing of the switch S is unimportant. For a given location of the measuring coil in the field the ratio B_1/B_2, between the flux through the differential coil and the flux through the yoke, does vary somewhat when the field is changed, but the variation is so slow that the fluctuations which actually occured in the timing of the switch, S, were without importance. The variation in the ratio B_1/B_2 with the field implied, further, that it was not possible to bring the galvanometer to a complete standstill. When the resistance, r, had been adjusted to balance, the galvanometer actually showed a small deflection from its equilibrium and back again, when the field was switched on. This was, however, without influence on the accuracy of the measurements.

For measurements of the field gradient by a differential coil only a limited accuracy in the determination of the location of the coil in the field is required, because the deviations from linearity are within a few percent as long as only the region of the field near the middle is considered.

3. Results.

Figure 4 shows the gradient $\partial B_z/\partial z$ for the pole pieces shown in Fig. 2a. The ordinates are 1/r, where r is the compensating resistance in Fig. 3d. For a field at the centre of 4500 gauss, the field is linear within the accuracy of measurement over the whole range occupied by the vacuum chamber. For a field at the centre of 8500 gauss, the gradient shows a decrease of about 2% with increasing z, for fields below 4500 gauss (not shown in the figure) the gradient shows a very slight increase with increasing z. The regions of the field near the pole pieces, as shown by dotted lines, could not be explored, but the extrapolations would appear reasonable.

Near the upper pole piece the gradient shows a decrease which might indicate that a still better result could be obtained with a somewhat more acute shape of the upper pole piece.

The results of measurements of "n" are shown in Figure 5 in arbitrary units, the value of "n" for a weak field being put equal to 100. For the pole pieces in Fig. 2a, a variation in "n" of about 2% is found at the centre; for the fringing field at a point at the end of the section a somewhat larger variation was found. It may be remarked here that a variation in "n" of about 2% is not far from the limit set by the mechanical tolerances. As mentioned above, we have no definite figures for the tolerances of the present model, but if 0.1 mm is assumed as mechanical tolerance in the distance of 4.8 cm between the upper pole piece and the apex of the lower pole pieces, then this alone would result in a variation in "n" of 0.2%.

To convert the relative values of "n" in Fig. 5 to absolute values, the vertical distance between the poles at the centre was 4.8 cm, so that

$$\frac{n}{r_o} = \frac{1}{B_c}\frac{\partial B_z}{\partial z} = \frac{2}{4.8} = 0.41 \text{ cm}^{-1}$$

A further set of measurements was made with the poles shown in Fig. 2b. The result for "n", measured at the centre, is shown in Figure 6; the decrease in "n" at 17000 gauss, which is the highest value of the field at the centre, is about 7%. Figure 7 and 8 show $\partial B_z/\partial z$ in relative units as a function of z and x, respectively.

The geometry of the poles, in this case, gives

$$\frac{n}{r_o} = \frac{2}{5.0 + 7.5} = 0.16 \text{ cm}^{-1}$$

4. Conclusion.

The deviations from linearity, which have been discussed here, arise partly from the fringing field and partly from the saturation of the steel. For a given configuration of the poles a reduction in the nonlinearity can be obtained by pole-face windings. Disregarding for the moment all economic considerations, the deviations from linearity can be reduced to any desired amount by extending the hyperbolas and by increasing the radius of the machine, the lower limit of the nonlinearities being finally determined by the mechanical tolerances and by inhomogeneities of the steel. It would appear, however, that the limit set by mechanical tolerances is so low (about 1 or 2 in 1000) that the amount of nonlinearity, which finally must be introduced, is determined mainly by economic considerations.

The stray fields at the ends of a magnet sector remain to be taken into consideration; the experimental material here is rather meagre and must be supplemented by further measurements.

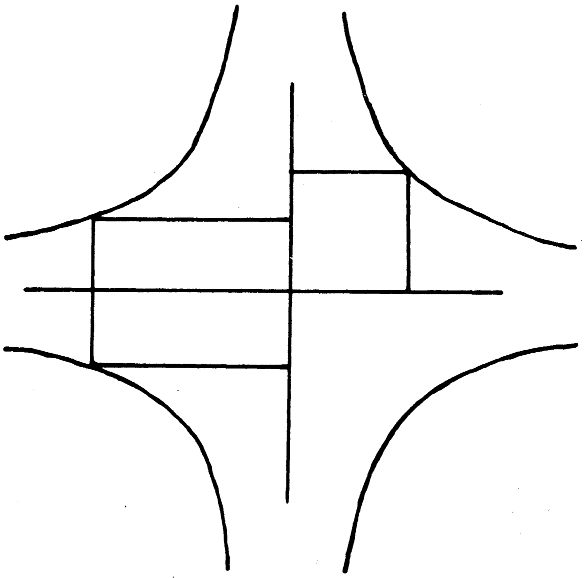


Fig 1

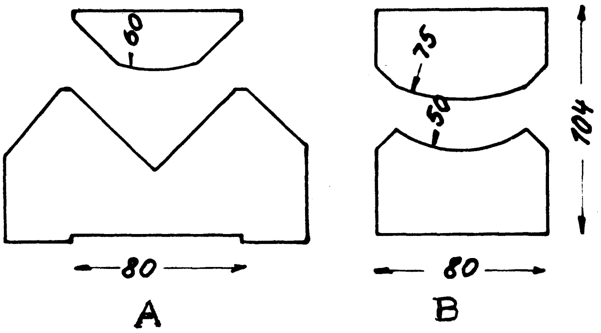
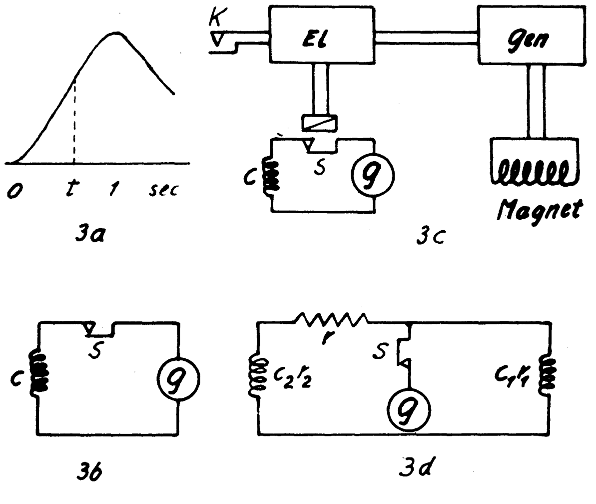


Fig 2



3a

3c

3b

3d

Fig 3

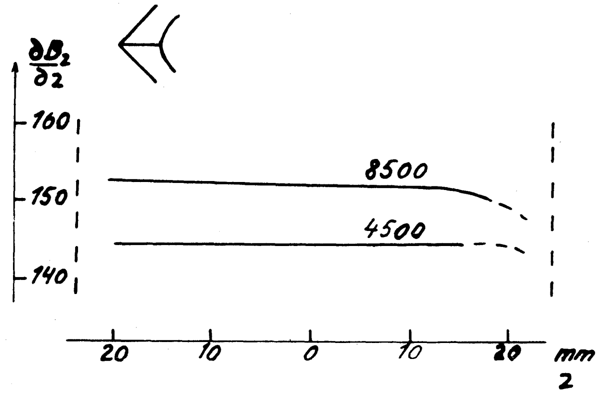


Fig 4

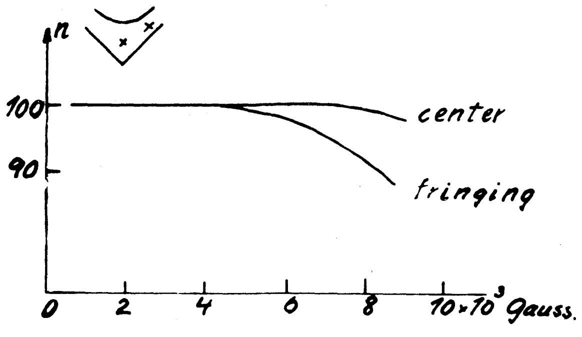


Fig. 5

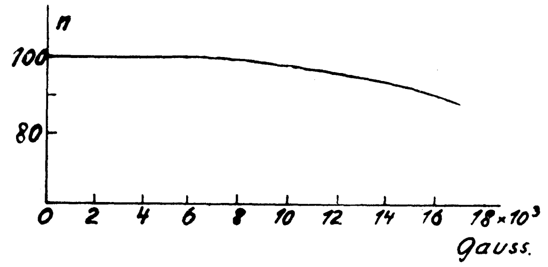


Fig. 6

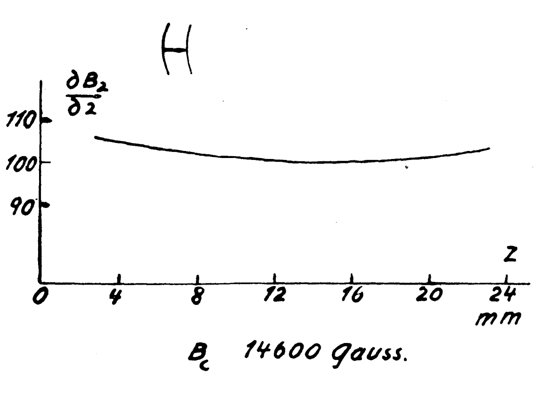


Fig. 7

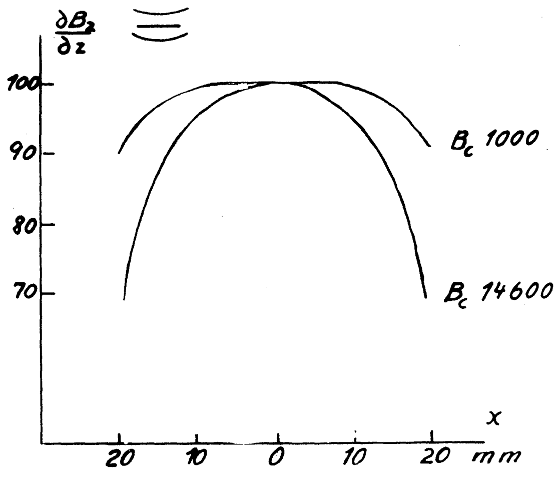


Fig. 8