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SUMMARY. -

The transverse field around the compensator magnets is plotted by assuming two-dimensional conditions, and the consequence of the approximations are examined. It is shown that the effect of the external field which is due to the projection of the compensator and-windings produces an increase in compensator flux of more than 50 %, and an even larger increase in the screening effect which the compensator has on the main flux.

The flux intersecting different orbits through the magnets may vary by several percent, with similar components at right-angles to the main field and the orbit direction. A three-dimensional solution is recommended, and is entirely practicable in numerical terms.

(x) - Department of Electrical Engineering, Imperial College, London SW 7 (England).
(o) - Istituto di Elettrotecnica dell'Università di Roma.

I. - INTRODUCTION. -

In the transverse version of the "Adone" colliding-beam experimental apparatus the beam interaction region is subjected to a field at right-angles to the beam direction. The deflecting effect on the beam itself is neutralised by two compensating magnets which act in the opposite direction to the main transverse field, and these compensators need accurate adjustment to ensure that the total transverse flux to which the beam is subjected is small.

The problem which is examined here is that of estimating the field distribution around the compensator. Because of the departure of the electron beam from the axis of the vacuum pipe, the field is required both at points on the axis, and away from it. Off the axis the field has components in each direction in the plane at right-angles to the beam.

II. - BASIS OF ANALYSIS. -

Each compensator consists of an iron box fitting closely around the vacuum pipe (Fig. 1) and screening it from the main field. An internal winding (1) provides the reverse field inside the box, and an external winding (2) minimises the disturbing effect of the iron on the main field. Because the three external dimensions of the compensators are comparable, the field distributions are three-dimensional, and they can be treated only approximately by two-dimensional analysis. However a three-dimensional numerical computation would require more time than is available, and the present purpose is to gain as much information as possible from simpler, two-dimensional flux plots.

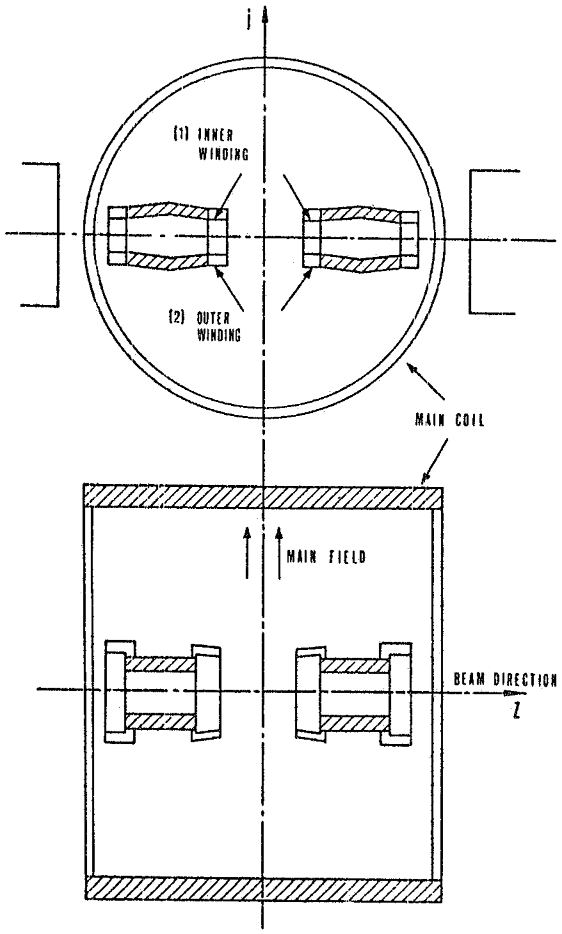

Fig. 1 - General arrangement.

We assume initially that the iron screens are unsaturated, and that the compensators are sufficiently remote from the iron plates at the ends of the main coil (producing the transverse field) to neglect any interaction between them. In other words, the magnetic pole distribution on the inner surfaces of the end-plates is specified and is uniform. The compensators are also assumed to be sufficiently remote from each other to examine their effects separately. These approximations are not necessary in making a numerical analysis, but the distances involved are sufficient to make any two-dimensional assessment of the interactions virtually meaningless.

A more serious omission is the neglect of the quadrupoles adiacent to the compensators, but outside the main field coil. These appear to be close enough to produce a very significant effect, but the separation distance is still sufficient to make a two-dimensional calculation of the interaction of dubious value. A further reason for ignoring the quadrupoles is lack of sufficient information about them.

The compensator windings are sufficiently thin to treat them as current sheets. These can be represented in a scalar-potential solution as discontinuities of specified magnitude(1).

III. - FRINGE FIELD DUE TO INTERNAL COMPENSATOR WINDING. -

The field sources consist of the main coil and the two compensator windings (one of which includes a fine-adjustment winding). These three sources can be treated by superposition, and we consider first the effect of the inner compensator winding (1) and, in particular, the field produced by its end-windings.

The ideal winding arrangement would give a uniform z-directed current on the inner, y-constant, surfaces of the flux screen, together with end-windings which likewise consist of uniform current sheets, but over the open ends (z-constant). Such a winding would produce a completely uniform field in the closed region bounded by the screen and coil, and zero field everywhere outside the compensator. However, vacuum-pipe access requires the removal of the end-windings from the z-constant planes to shapes which follow the pipe contour. This has the effect of "removing the lid" from the compensator "box" and allowing flux to "spill out" in the manner illustrated in Fig. 2, which shows the field in the x, z plane. The principal effect of this "opening out" of the winding is to produce a substantial increase in the amount of flux produced by the compensator, in the direction to the main transverse field.

The field plot which is shown in Fig. 2 has been obtained by separating the internal winding (1) into two parts. The first consists of the internal current sheets, together with the ideal and-windings, and this produces only the uniform internal field. The second component is that shown and, when added to the first, gives the total field due to winding (1). The relevant field sources are the actual end-winding, together with two current sheets which exactly neutralise the idealised end-windings and must therefore be placed on the end-surfaces of the compensator "box"; the two taken together (like the ideal winding) from a continuous current sheet. Thus the field sources used for the numerical solution in Fig. 2 consist of a uniformly-increasing potential discontinuity on the end-surface ACD, carrying a current chosen arbitrarily as 120 amperes, together with a similar current sheet AB along which the discontinuity falls linearly to zero. The position of the end-winding AB is different at the two ends of the compensator, but the differences can be ignored in comparison with the other approximations made, and the position shown is an average one. Because of symmetry only one quarter of the field need be considered.

No accurate two-dimensional solution is possible, particularly since the part AC only of the end surface is iron, whilst the remainder, CD, is open (on a plane draw through the beam axis). However, the current-sheet interconnections on the y-constant surfaces confine the field in the enclosed region so as to make it approximately two-dimensional, and we may, to a good approximation, treat CD, like AC, as an equipotential surface under the current sheet. This has the effect of over-estimating the external field, but only by a small amount since about 65 % of the flux emerges from AC and only about 35 % from CD.

The field boundary enclosing the region is assumed to be a flux line; this has negligible effect. Summing the "fringe" flux crossing the electron-beam axis up to this line, which is the region for which the two-dimensional approximation is a reasonable one, gives a total flux of 78 units (per unit length in the y direction), whilst the flux inside the compensator produced by the same m. m. f. is 135 units in the half-length. This result is obtained numerically by adding potential differences along the axis in the direction normal to it, but it follows also from the graphical flux plot. Hence the external flux crossing the axis is just under 60 % of the internal flux, when the effects at both ends are added.

The removal of the end-winding from the end surface thus gives a substantial increase in the compensator flux. If the inner winding (1) is designed to produce the required flux inside the compensator, and "leakage" is ignored, then the actual m. m. f. requirement will be some 35 % less than the design figure. But the flux will be distributed in the compensator iron in a much less uniform manner than with the ideal end-winding, giving a considerable increase in saturation near the ends.

The flux arrows point up the potential gradient in Fig. 2 since the potential needs to be reversed in sign to accord with Fig. 3.

IV. - FIELD DUE TO EXTERNAL COMPENSATOR WINDING AND MAIN COIL. -

The external winding (2), together with the main coil, produces

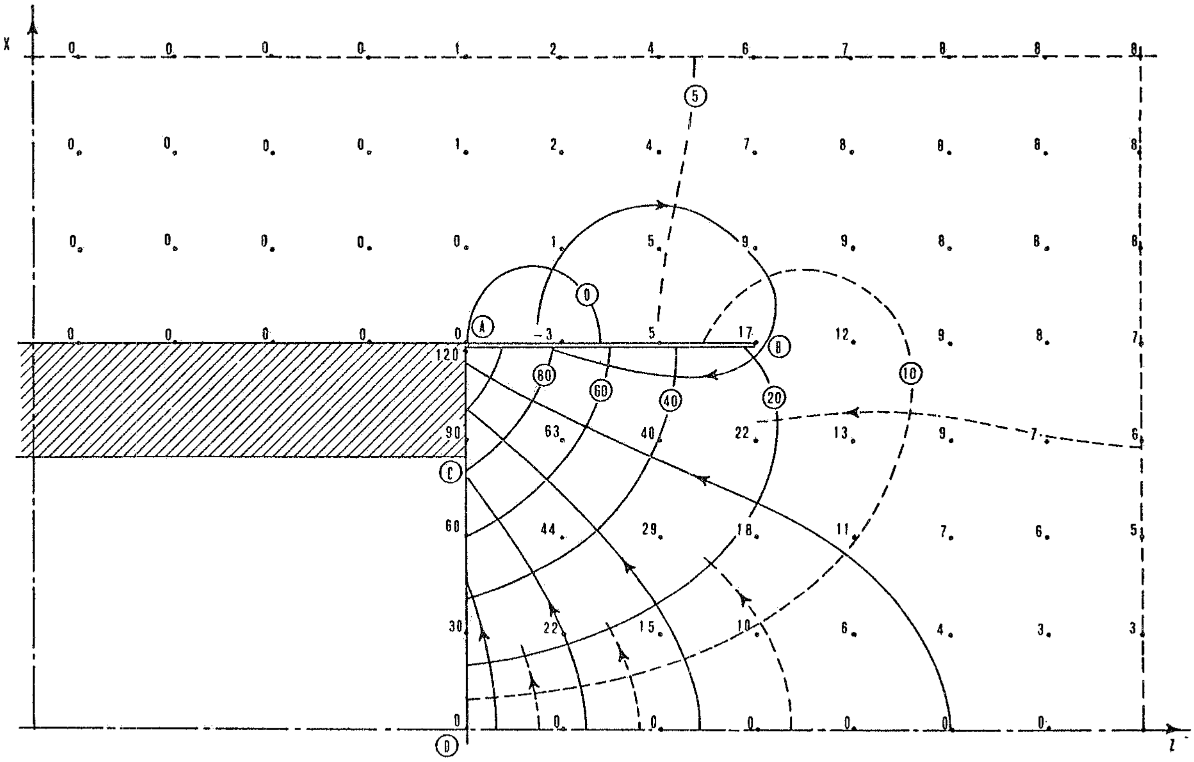

FIG. 2 - Field due to inner winding (1).

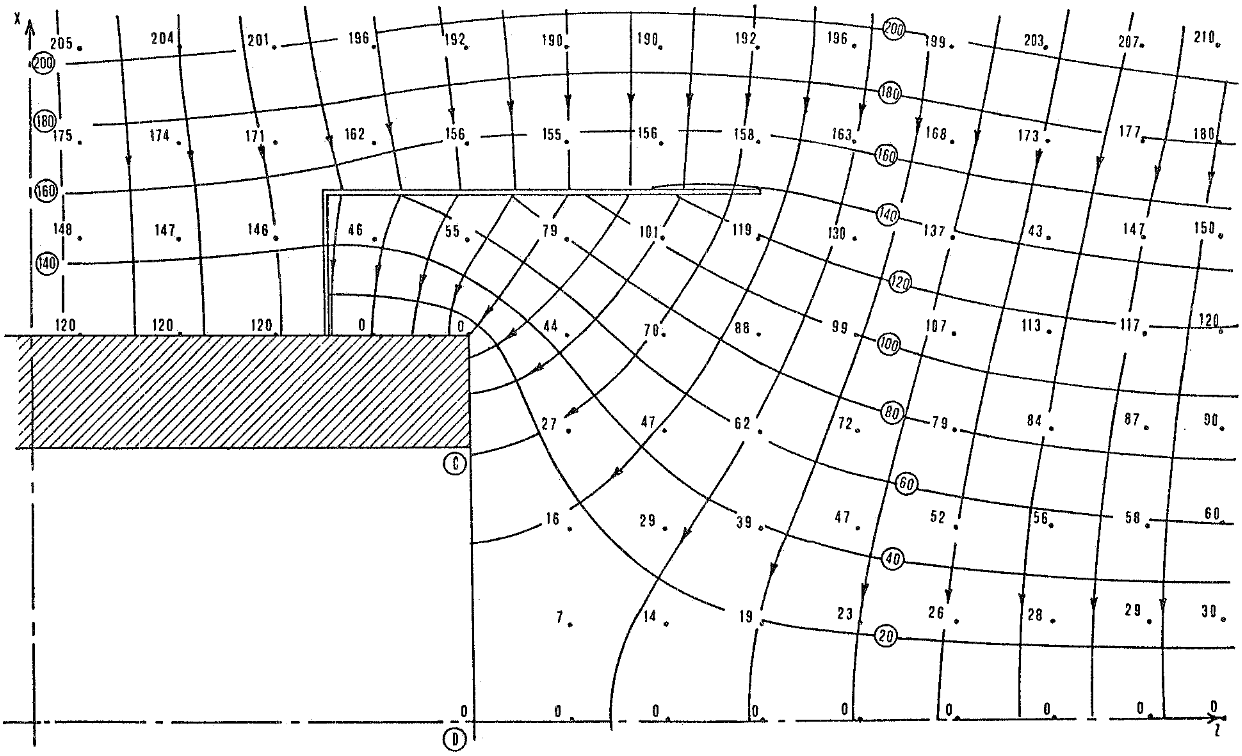

FIG. 3 - Field due to outer winding (2) and main coil.

a field in the opposite direction to that shown in Fig. 2, and because of this it is convenient to treat the two sets of windings separately. The flux-screening effect of the compensator causes a considerable distortion of the external, or "main field", as shown in Fig. 3, and reduces the amount of the "main flux" which crosses the beam axis. This further increases the relative proportions of the compensator flux (Fig. 2) to the main flux and in both respects the compensator has an effective magnetic length, in the z direction, which is considerably greater than the distance between the two end-surfaces of the iron.

The main coil is sufficiently close to one end of the compensator to intervene in one of the regions of interest but, since this (together with the iron end-plates) appears merely as a uniform-field source when viewed from all points inside it, the coil diameter can be increased to any required extent without influencing the field conditions immediately around the compensator. The same field plot can then be used at both ends, disregarding differences in end-winding position as before, and again only one quarter of the entire region need be considered. The coil merely introduces potential discontinuity which has no effect on the compensator side, whilst outside the coil the true field can be obtained by subtracting from the flux plot a uniform-field component H_c equal to the ampere-turns per metre of the coil.

The field which is shown in Fig. 3 is that obtained when the m.m.f. of winding (2), per unit width of the compensator (measured in the x direction) is the same as the m.m.f. per unit length of the main coil (also measured in the x direction). Under these conditions the compensator would not disturb the field at all in its centre portion, if its length, in the z direction, were sufficiently great. This particular winding m.m.f. ratio (which appears to correspond to one of this ratios studied earlier) makes the two-dimensional approximation reasonable because it provides the correct field termination at the external, y-constant, iron surfaces, just as the internal windings provided the proper tangential field at the internal iron surfaces in Fig. 2. Around the end of the compensator, where the three-dimensional effect is greater, the "box" formed by the projecting end-windings does help to maintain two--dimensional conditions, but these are now disturbed by the slot opening in a different way from before. The two adjacent iron surfaces, in y-constant planes, are no longer screened by appropriate current sheets, so that the flux entering the part CD of the end surface will mostly terminate on these surfaces, producing a y-directed field. This increases the reluctance of the relevant flux paths and reduces the flux density incident on CD. However, the flux density is comparatively small here, and the proximity of the two parallel iron surfaces means that the flux is likely to be distorted but not much reduced.

The field plot shows that the flux absorbed by the iron surface of the compensator, over half its length, corresponds to 9.2 mesh intervals in the uniform-field region, whereas the half-length of the compen sator iron in the z direction is 4. 5 mesh intervals. For this particular m. m. f. ratio the compensator thus screens its axis from the external field over a distance of twice its own length (measured over the iron). Notice that this effective length would be unity if the end-winding were placed in the ideal position on the end surface.

The screening action thus causes a considerable further increase in the preponderance of compensator flux (Fig. 2) over the main flux to which the beam is subjected. Again the increase in the intended effect is due to the removal of the end-winding to provide clearance for the vacuum pipe. Because of the opening on CD, in place of the continuous iron surface, the external flux is "drawn" into the compensator to some extent, so that the two-dimensional approximation over-estimates the effective magnetic length.

V. - CHANGE IN MAIN FLUX ACROSS VACUUM PIPE. -

In Fig. 2 the effect of the current sheets on the internal iron surfaces (in adjacent planes) is to keep the field at the entrance to the compensator iron approximately two-dimensional, with no y component, but this is not so in Fig. 3. In consequence there is a variation in the amount of main flux which intersects different electron orbits within the vacuum pipe, whereas the amount of compensator flux is virtually the same for them all.

The magnitude of the flux variation can be calculated only by making a three-dimensional field plot, but we can obtain some idea of its upper limit from the amount of flux intersecting CD in Fig. 3, which is about 8 % of the total flux entering the compensator iron. Some of this will intersect some electron orbits near the wall of the vacuum pipe, but none in the y-z plane in the centre of the pipe. Much of the flux tend to become y-directed in parallel x, y planes.

VI. - EFFECT OF SATURATION. -

Saturation in the compensator iron will tend to reduce the compensator flux and increase the amount of the main flux which crosses the vacuum pipe. The flux will not be uniformly distributed in the iron, because of the strong and-effects shown in Figs. 2 and 3, and since the two contributions combine in the magnetic circuit the tendency will be to produce considerable saturation at the ends. The extent of the saturation can, of course, be estimated for any given m. m. f. ratio by summing the flux contributions over the iron surface, and it is a simple matter to adjust the scalar potential boundary conditions at these surfaces to allow for it.

VII. - EFFECT OF COIL OPENING FOR VACUUM PIPE. -

The opening which has to be made in the main coil to admit the vacuum pipe creates a field disturbance in the immediate vicinity of one end of the compensator. This cannot realistically be taken into account without also including the adjacent quadrupole, and it is therefore ignored here. However the effect of the winding gap is easily incorporated in a two dimensional solution, by treating the gap as a long slit. It can be added to the uniform-coil solution by introducing an additional winding which consists of the displaced conductors, together with those which have to be added to the uniform coil in order to create the hole.

If the iron is ignored the field due to the additional winding can be calculated by integration, or simply by regarding the displaced and virtual conductors as equivalent to long lines, viewed from the centre-plane of the vacuum pipe. However, it is the interaction with the iron which is most important, since it is this which will produce variations in the amount of flux intersecting different orbits in the centre-plane.

VIII. - RECOMMENDATION. -

The two-dimensional analysis provides a means of assessing approximately the large increase in the ratio of the compensator to the main flux which results from the end-winding shape. But it is not capable of giving detailed and accurate information about the flux variations between orbits, nor the y-directed component of the field.

The two-dimensional approach can be pursued further, but in view of the uncertainly of the approximations which then have to be made a three-dimensional numerical solution is recommended if more information is required. The extension of the flux plots to three dimensions is essentially a matter of increasing the number of equations, and does not otherwise represent an increase in complexity. A programme taking no more than 10 minutes on a large computer will give a very much more detailed picture of the field distribution.

REFERENCES. -

(1) - C. J. Carpenter, Numerical solution of magnetic fields in the vicinity of current-carrying conductors, Proc. IEE 114, 1793 (1967).