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PRELIMINARY DATA FOR MAGNET DESIGN

by

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INTRODUCTION:

As a basis for preliminary estimates of the amount of iron required for the synchrotron magnet, and for preliminary specifications of the magnet power supply, a rough, one-fifth scale, magnet model has been built and tested. Measurements have been made on the distribution of magnetic flux in the median plane of the magnet gap and at various locations in the magnet structure. From these measurements a possible set of magnet specifications has been worked out and tabulated.

DESIGN OF MAGNET MODEL

The magnet model was constructed from 19 mil (about 1/2 mm) laminations left over after construction of the betatron at the Michelsen Institute. It has a 2 cm air gap and was designed for a field gradient of 1 percent per centimeter. (If this magnet were scaled up by a factor of five and then arranged on a circle of radius 100 meters, it would have an n-value of 100).

The core of the model is made up as shown in Fig. 1, of 250 laminations 174 by 80 mm, 500 laminations 130 by 64 mm, and 500 laminations 50 mm wide 250 of which had an average length of 45 mm and the other 250 of which had an average length of 109 mm. The latter 500 laminations had one end cut at a small angle to form the pole pieces. The laminations were stacked as indicated in Fig. 1 which shows the arrangement of one layer with solid lines, and the next layer with dotted lines. The completed stack of laminations was clamped between wood bars 5 cm square in cross section. The total thickness of the clamped lamination stack was 122 mm.

The winding for this magnet consisted of 220 turns of cotton covered wire 3 mm in diameter. It was made in four coils 4 turns high by 10 turns in the radial direction and two coils 3 turns high by 10 turns in the radial direction. These coils were wound on a form and were thin enough that they could be inserted through the gap of the magnet structure. They were held in place by wooden wedges.

Single pickup loops were wound around the magnet core at locations indicated by the numbers 1 to 8 in Fig. 1. Between the 80th and 81st lamination and between the 170th and 171st laminations, fibre spacers 1 mm thick were inserted. These spacers were arranged so that loops could be inserted to link the central 90 laminations at all of the 8 positions of the complete pickup loops.

For measurement of fields in and around the magnet gap a search coil was constructed on a 5.56 mm diameter form using 0.063 mm overall diameter insulated wire. This coil had 64 turns in one layer and two layers of 50 turns each. The computed area turns for this coil are 41.5 cm^2. A check with a fluxmeter against a calibrated search coil gave a measured value of 41.3 cm^2. The resistance of the search coil is about 15 ohms.

MEASUREMENTS

Most of the measurements were made with both a-c and d-c excitation of the magnet. D-c measurements were made by reversing a 10-ampere current through the magnet coil and reading flux change on a Cambridge fluxmeter. A-c measurements were made at the same peak magnet current (7 amps r.m.s.) using a vacuum tube voltmeter or anoscilloscope. Measurements of the same quantity made by fluxmeter, vacuum tube voltmeter, and oscilloscope generally agreed within about 2 percent. The measured field at the center of the gap for excitation by 2200 ampere turns is 1370 gauss.

Fig. 2 is a plot of the measured distribution of field in the median plane of the magnet gap at the center of the model. The integrated area under this curve is 1.57 times the product of the pole width and the field at the center of the gap, so that we can expect the leakage flux in the regions of the magnet free from end effects to be about 57 percent of the flux in the gap. For a 100 meter radius the n-value indicated by this curve is about 118. The difference between this value and the design figure of 100 is attributable partly to the distribution of B in the iron and partly to inaccuracies in construction.

Fig. 3 shows the measured distribution of field in the median plane around one end of the model. Contours are plotted at which the field is a particular fraction of the field at the gap center, far from an end. The leakage pattern at the end is similar in character to that on either side of the pole so that the total leakage flux can be expected to be roughly proportional to the perimeter of the magnet pole. In this model the total perimeter of the pole is 344 mm whereas the model length is 122 mm. We can thus expect the total leakage flux to amount to $\frac{344}{2 \times 122} \times 57 = 81$ percent of the product of field at the center of the gap and gap area. These predictions of leakage flux are supported by flux measurements quoted below.

The measurements of flux were made at locations 4, 5, 6, 7, and 8 with the magnet configuration shown in Fig. 1. The magnet pole was then moved to the position indicated in Fig. 4 and measurements were made at all eight positions. The change in position of the pole structure made no significant change in the field pattern in the median plane or in those flux measurements which were made at both locations. The results of the flux measurements on loops which linked only the central 90 laminations were as follows. They are quoted in terms of the product of field at the center of the gap and area of the 90 lamination gap face.

Position of flux loop	Ratio of flux to effective gap flux
1	1.12
2	1.43
3	1.52
4	1.54
5	1.52
6	1.50
7	1.50
8	1.47

The figures in the second column are in good agreement with the figure 1.57 obtained from integration of the field distribution.

The results of the flux measurements on the loops which linked all 250 laminations were also converted to multiples of the product of field at the gap center and the complete gap area. They are as follows:

Position of flux loop	Ratio of flux to effective gap flux
1	1.26
2	1.61
3	1.81
4	1.84
5	1.84
6	1.83
7	1.83
8	1.81

These figures agree well with the 81 percent total leakage computed from the pole perimeter.

POSSIBLE POLE SHAPE

The flux measurements, quoted above, provide a basis for a preliminary design of the magnet pole. If the field at the center of the gap is, for example, 12,000 gauss, the average field at the pole face will be 12,000 x 1.12 or 13,400 gauss. Near the corners of the pole, the fields will be much higher - how much must be resolved by more refined analysis and model measurement. If, now, the average flux density in the pole is to be maintained, its cross section must increase with distance from the gap. At a distance of 0.75 gap widths from the gap (position 2 on Fig. 1) the pole width must be 1.43/1.12 times its width at the gap. Further applications of the flux data given above yield a pole shape of the sort indicated by the solid lines in Fig.5. For convenience in construction and coil assembly a compromise form is indicated in the same figure by dotted lines. Similar contouring should be included at the ends of the magnet sections.

The edges of the gap shown in Fig.5 have been contoured to extend the useful region as far as possible in the radial direction. This contour has been scaled from that used at the edge of the gap of the Cosmotron magnet. Since the geometry of this magnet is very different from that used in the Cosmotron, this contour is probably not correct and should be considered as only a first approximation, useful only during the design of magnet models.

Even with the contoured gap edge, the n value on the median plane will experience changes of one or two percent about three quarters of a gap width from the edge of the gap. If the average gap width is 10 cm and 15 cm of good field are required in the radial direction the poles must be 30 cm across.

POSSIBLE MAGNET STRUCTURE

For the purpose of estimating costs and power a possible magnet cross section is shown in Fig. 6. The coil design is based on a figure of 300 amperes per sq. cm peak current density in the copper. It is assumed that 50 percent of the coil cross section is copper, the remainder being occupied by insulation and mechanical supporting structure.

The coil design shown is the simplest possible. If this coil consists of three layers of equal thickness as indicated in the figure, it can be fabricated externally and inserted, layer by layer through the magnet gap. This coil is inefficient in two ways. First, it is not designed to have a minimum perimeter and so to require a minimum amount of magnet steel. This was not done because a coil with minimum perimeter of the type indicated would have a radial extent of about 26 cm and a vertical extent of only 13 cm for each half of the winding. The external winding would be rather difficult to support mechanically and the radial extent of the iron return would be increased with a possible increase in interference with emergent beams of high energy particles. The compromise coil has a perimeter only 6 percent longer than that of the coil with minimum perimeter. Secondly, the coil is inefficient because there is a space in the magnet window which is not occupied by magnet windings. Both of these inefficiencies are absent in a winding which fills the window and whose return windings are shaped around the magnet end to return externally in a winding whose form bears no necessary resemblance to the main winding (as, for example, in Dahl's n100 Engineering Study of May 26, 1953). The choice of a specific coil design will, no doubt, follow from a cost analysis of the two possibilities.

In Fig 6 we have indicated three possible ways for arranging the turns of the winding.

MAGNET PARAMETERS

The important magnet parameters derived from this model study are collected below. Also included in the tabulation are the factors by which the parameter in question must be multiplied if the gap length is changed from 10 cm to "a" cm. For comparison we have included similar results derived from analysis or electrolytic tank measurements by Lien (KPL/5) and Widerøe (RW/6). The figures quoted by these authors have been scaled to a magnet with a 10 cm gap by using the scaling factors included in the table. The most important difference between the present magnet and those sketched by Lien and Wideröe is in the width of the pole considered necessary to give the necessary useful aperture in the radial direction.

In the following table t_0 is the time taken to go from zero to peak magnetic field. It is assumed that approximately the same time will be required to reduce the field to zero. N is the number of turns in the magnet winding and a is the mean gap length.

General	Present Study	KPL	RW	For gap length "a" multiply by
Orbit radius (m)	86	86	86	1
Maximum field (gauss)	12000	12000	14000	1
n	100	100	440	1
Magnet Geometry				
Gap length (cm)	10	10	10	a/10
Pole width (cm)	30	15	18 (approx)	a/10
Useful vertical aperture (cm)	9	9	9	a/10
Useful radial aperture (cm)	15	?	?	a/10
Iron cross section (sq.m)	1.01	0.24	0.54	$(a/10)^{7/4}$ approx
Total azimuthal magnet length (m)	542	520	540	1
Weight of iron (1000 kg)	4300	1000	2300	$(a/10)^{7/4}$ approx

	Present Study	KPL	RW	For gap length "a" multiply by
Coil Geometry				
Maximum current density (amps/cm^2)	300	340	290 (230 in return winding)	1
Copper cross section (sq.cm)	325	330	425 (540 in return winding)	a/10
Winding packing factor	0.5	0.47	0.5	1
Weight of copper (1000 kg)	350	350	570	a/10
Electrical Characteristics				
Ampere turns	100,000	115,000	123,000	a/10
Magnetic stored energy (1000 joules)	13000	10000	32000	$(a/10)^2$
Energy dissipated per cycle (1000 joules)	$4100t_o$	$5800t_o$	$4900t_o$	(a/10)
Resistance (ohms)	$6.2\times10^{-4}N^2$	$6.6\times10^{-4}N^2$	$5.3\times10^{-4}N^2$	(10/a)
Inductance (henry)	$2.6\times10^{-3}N^2$	$1.5\times10^{-3}N^2$	$2.1\times10^{-3}N^2$	1

(The inductance quoted under KPL is his final value. He quotes an average inductance over the cycle corresponding to $2.2\times10^{-3}N^2$)

Time constant (sec)	4.2	3.2	4.1	(a/10)
Initial voltage	$260N/t_o$	$130N/t_o$	$210N/t_o$	(a/10)

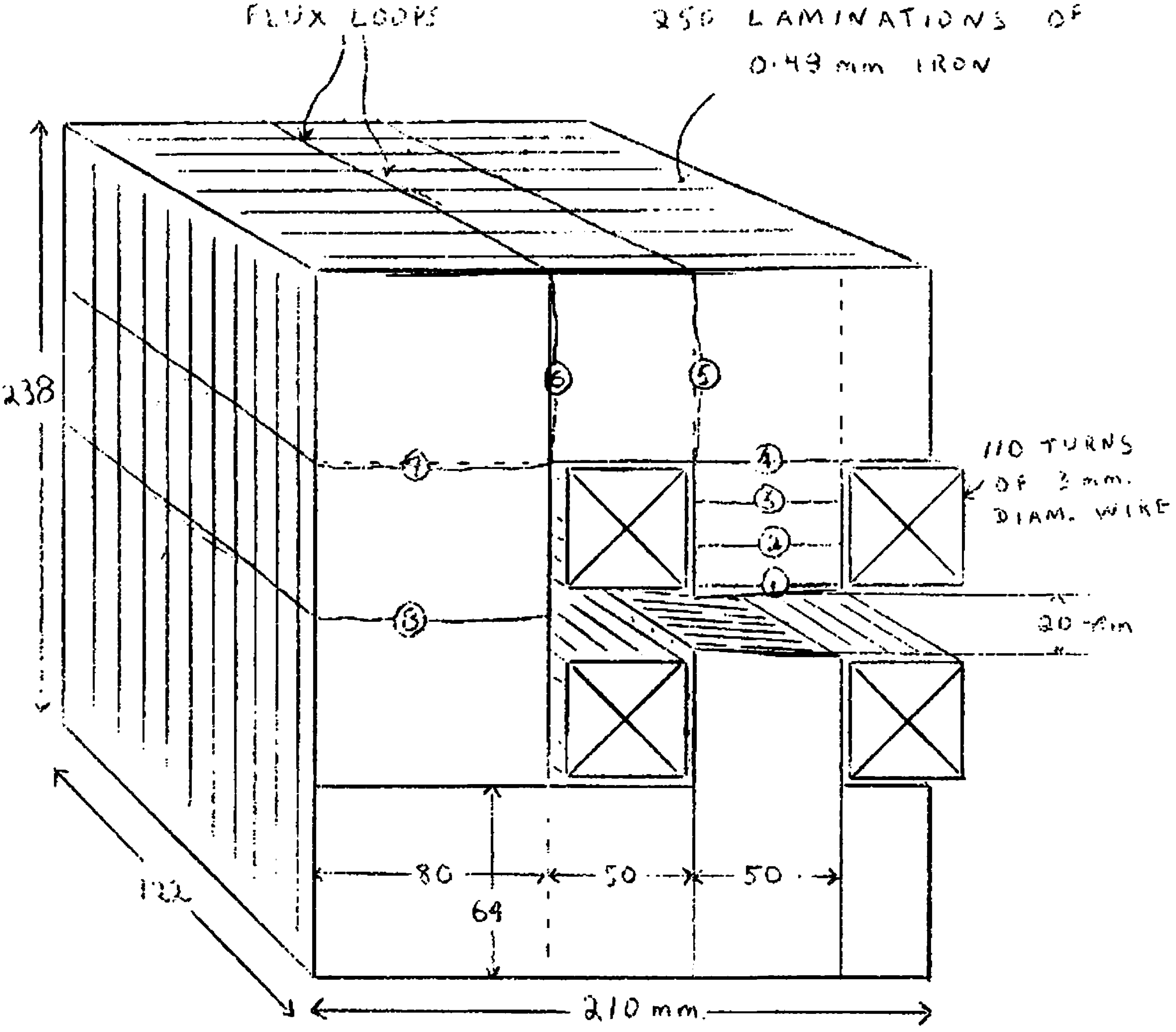
FLUX LOOPS
250 LAMINATIONS OF
0·48 mm IRON
238
6
5
7
4
3
2
1
8
110 TURNS
OF 3 mm.
DIAM. WIRE
20 mm
80
50
50
64
122
210 mm.

FIG 1

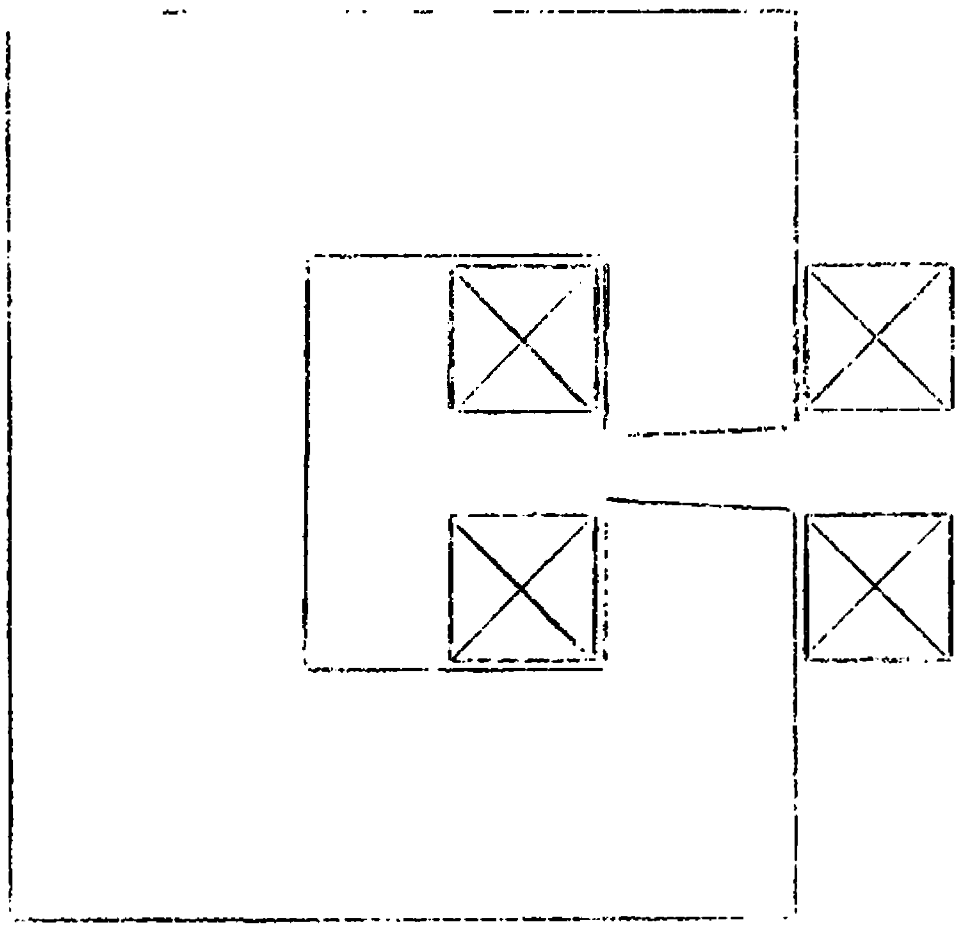

FIG 4

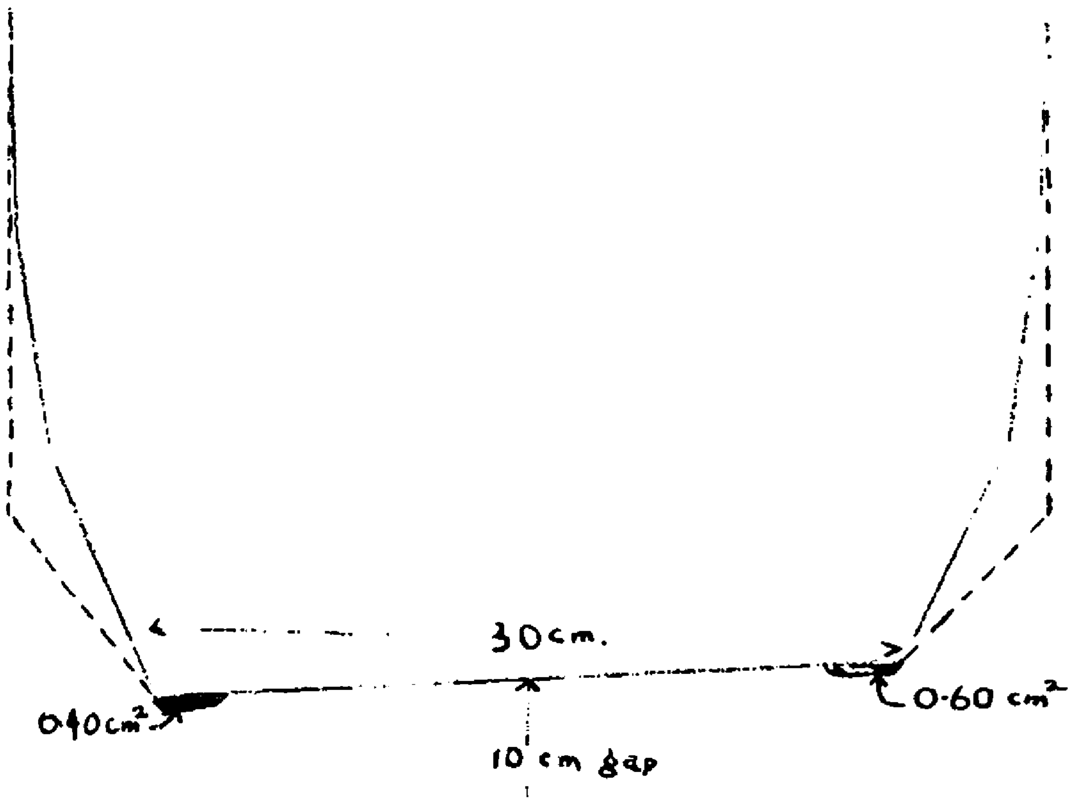

FIG. 5

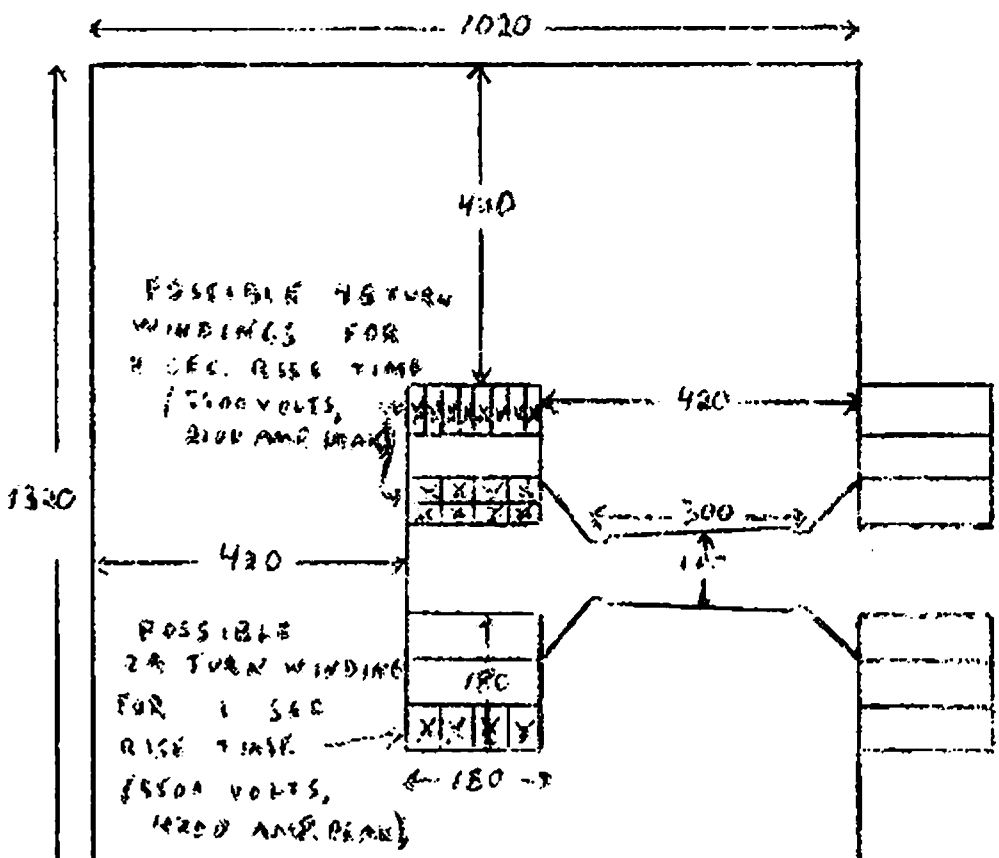
1020
1320
430
420
420
300
180
POSSIBLE 48 TURN WINDINGS FOR ½ SEC. RISE TIME
POSSIBLE 24 TURN WINDING FOR 1 SEC RISE TIME

FIG. 6