Nimrod Maintenance Handbook

Editor: B. G. Loach

INTRODUCTION TO MAGNET

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INTRODUCTION TO MAGNET

I FOREWORD

This document is intended as a simple introduction to some of the design considerations and requirements for the Nimrod magnet. Reference to the reports dealing with the detailed design are given on page 6. Photographs show various stages of construction of the magnet (Figs. 17 to 20).

Nimrod is the type of accelerator known as a constant gradient proton synchrotron. Protons are injected into a vacuum vessel and are bent into a roughly circular path by the magnet. After injecting for a time corresponding to a proton executing several hundred turns round the machine, the power is switched on to the r.f. accelerating cavity. This increases the energy of the protons and the magnetic field must be correspondingly increased to keep the protons within the radial limits of the vacuum vessel. The magnetic field shape in the magnet gap must also be controlled in order to ensure that the protons are focused both vertically and radially within the vacuum vessel.

II RADIUS OF MAGNET

Nimrod was designed as a 7 GeV (7×10^9 eV) accelerator. Practical considerations of magnetic flux density in steel determined the peak field as 14 kilogauss (kG), giving a nominal radius as 61.62 ft. or 1878.1 cm. Table I gives the value of field for different proton energies in Nimrod and the corresponding energising currents.

TABLE I

I (A)	B (kilogauss)	T (GeV)
2000	3.7	1.4
3000	5.6	2.4
4000	7.4	3.4
5000	9.3	4.4
6000	10.7	5.2
7000	12.1	5.9
8000	13.4	6.7
9150	14.6	7.3
10500	15.6	7.9
12000	(16.4)+	(8.3)+

\+ estimated values

III CURRENT AND VOLTAGE REQUIREMENTS

To contain oscillations of the protons within the vacuum vessel, a magnet aperture of 11 in. vertically by 45.5 in. radially was required. This determined the current and voltage requirement for the magnet, viz.:-

$$NI = H_o g + H_s L \quad .... \quad (1)$$

$$V = NA\,(dB/dt) + RI \quad .... \quad (2)$$

where N = the no. of turns on the magnet coil
I = the magnet current
H_o = the magnetic field strength in the gap
g = the vertical magnet gap
H_s = the magnetic field strength in the magnet steel
L = the path length of the flux in the steel
V = the magnet voltage
A = the effective area of flux linking the coils
dB/dt = the rate of change of flux density in the gap ($= \dot{B}$)
R = the resistance of the magnet winding

To give easy access to the vacuum vessel and to allow easy extraction of particles from the machine, a C-shaped magnet was chosen. This, together with the requirement for 8 field-free straight sections for injecting, accelerating and extracting devices gave the following, for N = 42, dB/dt = 20,000 gauss/second (G/s):-

$$I \simeq 9{,}150 \text{ A}$$
$$V \simeq 16{,}000 \text{ V}$$

IV MAGNET COMPONENTS

The main components of the magnet are:-

(1) Sectors (336 in number)

(2) Polepieces (336 pairs)

(3) Straight section boxes and coil shielding

(4) Energising coils

1. Magnet Sectors

(a) Design

The purpose of the sectors is to act as a 'yoke', i.e. a return path for the magnetic flux in the magnet gap. The sectors should have:-

(i) A small reluctance (impedance to magnetic flux) to cut down coil current requirements: especially at high fields.

(ii) A low coercive force so that with zero energising current the remanent magnetic field is low.

(iii) Low hysteresis loss because the magnetic field is pulsed.

(iv) High resistivity to cut down eddy current effects and losses.

For these reasons, an annealed mild steel containing about 1% silicon was used. Sectors were made up from steel sheet $\frac{1}{4}$ in. and $\frac{1}{8}$ in. thick, selectively taken from different billets.

A cross-section and plan of a sector are shown in figure 1. There was some tapering of the sector (as shown) to obtain a better packing factor. The build-up plates were added to increase the effective cross-section of steel at critical points.

(b) Position of sectors in the yoke

It can be shown [1] that a variation of magnetic field strength around the magnet ring can lead to radial oscillations of the protons (effective aperture loss): viz: variations of ± 4 parts in 10^4 can lead to a loss of 1 in. in aperture.

The sectors could not be made to give this tolerance in field. They were therefore measured relative to a 'standard' sector and put in the appropriate position in the magnet ring, the octants being equalised for the following parameters:-

(i) Remanent field

(ii) Field at 200, 600, 10,000, and 14,000 gauss

(iii) Weight of steel

The sectors were placed in position on the foundation to a tolerance of .010 in. in plan, using optical alignment techniques.

2. Polepieces

The magnet polepieces are used to give the correct magnetic field shape in the magnet gap. They are connected to the magnet sectors as shown in figure 2.

(a) Requirements for Magnetic Field Shapes

Vertical and radial focusing in a constant gradient synchrotron like Nimrod is achieved as follows. Consider the magnetic lines of force in the magnet gap to be slightly curved as shown in figure 3. A proton, which for some reason is off the median plane, sees a radial component of field in a direction which will move it back to the median plane. A field with curved lines of force as shown, is one which has a decreasing strength with increasing radius; it may be produced by a magnet whose gap increases with increasing radius.

Considering the focusing radially; a particle, with charge e and momentum p in a magnetic field B, will move in a circle at radius R, such that:-

$$P/_{e} = BR \qquad .... \quad (3)$$

A proton at too large a radius must see a product (BR) which is too great and it will then be forced toward its proper radius, i.e. BR must increase with radius. A normalised gradient 'n' may be defined as $-(R/B)(dB/dR)$ and this must lie between 0 and 1 to get both vertical and radial focusing.

These focusing forces lead to vertical and radial oscillations known as betatron oscillations. The necessity to avoid working with these frequencies close to one another and to the rotational frequency of the protons leads to further restriction on 'n'. The nominal working value of 'n' for Nimrod is 0.6, or about 1% change in field per foot radially. The design requirement was for a good field (i.e. correct n-value) region at injection of 36 in. radial width.

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(1) See references: page 6

(b) Design of Polepieces

The detailed design of the Nimrod polepieces is discussed in references (2)(3) and (4). Briefly, the necessary useful aperture at injection and low fields is obtained by using shims at the radial edges of the polepieces: figure 4 demonstrates the effect. The design at high fields incorporates 'saturable edges'.

Although an aperture of 36 in. is required at injection, the beam shrinks due to the decrease of the radial amplitude of focusing oscillations. (Typically the beam at 7 GeV may be four inches wide). The good field region, therefore, may be allowed to shrink as the magnet field increases. The assumption was made that 14 in. of good field would be required above 5 kG to allow for steering of the beam and for targetting and extraction.

Referring to figure 5, the radial edges contain a reduced amount of steel and therefore begin to saturate when the flux density reaches about 5 kG/cm^2. This reduces the amount of flux to be carried by the sectors at high fields and hence reduces saturation and the current requirement in the energising coils by about 5%.

This saturable edge technique produces a polepiece which is effectively shorter in the radial direction and produces field and 'n' shapes (Fig. 6) which change with the amount of saturation, i.e. with the field value. These shapes are corrected using 'crenellated' shims. Referring to figure 7, the effective magnetic surface at low fields is close to A. As the field increases, the flux density in E increases causing saturation in E and the effective magnetic surface drops successively to C and D. This produces a 'shim' effect and produces corrections as in figure 8. By putting the correct amount of material in E, the saturation in the 'edges' may be matched by the crenellated shims and correction obtained at all field levels.

In Nimrod, four basic shapes of lamination are used, as shown in figures 9 and 10. Laminations 1, 2 and 3 successively saturate as the field increases and produce a correction to match the saturation effects.

(c) Manufacture and Installation

The centre 40 pairs of poles in each octant are of the type described in (b). The laminations, which are of .020 in. thick, 4% silicon steel and .030 in. thick, 1% silicon steel, were stamped and then stuck together with insulating glass cloth and hot cured epoxy resin.

The polepieces were carefully aligned in the sector gaps to the following tolerances:-

Radial and azimuthal tilts - 50% of poles within ± .001 in.
80% of poles within ± .002 in.
95% of poles within ± .003 in.

Radial position - All poles within ± .005 in. with respect to the sectors.

The high tolerance on the radial tilt is required because .001 in. radial tilt on the pole produces about .020 in. shift in the magnetic median surface.* Consideration of variations around the machine show that this may lead to a loss of vertical aperture of about 1 in.

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*This surface is defined with reference to figure 11. One must first define a geometric plane (perhaps horizontal) in which one wishes to work. A magnetic median surface may be defined with reference to this plan by joining points in the magnetic field at which the radial component of field parallel to this geometric plan is zero.

3. Straight Sections

The design of the straight sections was required to give the following characteristics:-

(i) As small a magnetic field as possible in the straight section.

(ii) A correct effective octant length L defined as

$$B_o L = \int B \, dl$$

where B_o = magnetic field in the centre of an octant

dl = incremental distance along the theoretical ideal closed orbit path of the proton

The absolute value of L is much less critical than variations of L around the machine. A few inches constant error in L for all octants is permissible but differences between octants of 0.2 in. may lead to a loss of aperture of about 1 in.

(iii) The magnetic field shape, i.e. the contribution to the average 'n' value in the machine, should be correct.

(iv) A mechanical arrangement to allow the easy extraction of secondary beams from the straight section.

The three components making up the straight section are:-

(1) Straight section box

(2) Coil shielding

(3) End polepieces

These were designed together, using models.

The shielding effect of the boxes and coil shielding is illustrated in figure 12. Flux is bypassed from the centre region of the straight.

(a) Straight Section Boxes

For the long straight sections, the design is governed mainly by the requirements of the r.f. cavity. Other long straights are foreshortened on the outside of the box but the steel is replaced as shown in figure 13. The short straights are determined mainly by the inflector box.

(b) Coil Shielding

The elements making up the coil shielding are indicated in figures 13 and 14.

(c) End Polepieces

In order to get a more constant value of L as the mean field in the machine rises, the end polepieces are tapered in the azimuthal direction (Fig.15). They were therefore made from $\frac{1}{4}$ in. thick steel of the same type as used in the sectors. Some crenellated shims were used as shown in figure 15.

The predicted average 'n' value, taking into account the appreciable effect of the straights, was found to be best using 28 pairs of Mk I polepieces (in the centre) and 12 pairs (6 pairs at each end) of Mk II polepieces per octant (Fig. 10).

V MAGNET COIL

As indicated in section III, the magnet coil consists of 42 turns, placed as shown in figure 2. The conductors, which are high conductivity copper, are insulated by glass tape and bitumen based varnish (Spec. No. P.S.120-013 refers).

The arrangement of the connections to the octant coils is indicated in figure 16.

Clamping of the longitudinal conductors and end conductors is achieved by means of air bags pressurised to 25 lb/in^2. Three narrow bags, stretched the length of the throat longitudinal conductors, are placed between the upper and lower sets of conductors. These bags clamp the conductors against the lower and upper faces of the coil aperture. Two wide bags in front of the conductors press the conductors back into the throat of the magnet. A similar arrangement is used for the lip conductors.

The end conductors are held also by air bags. Three narrow bags clamp the conductors in a vertical direction, and one wide bag clamps them in a horizontal direction. To allow for extra coil movement (and end conductor movement) due to large temperature changes, e.g. when the coil cooling water drops below a pre-determined figure, solid paxolin packers are used which can be released manually when required.

The maximum amount of movement observed when the magnet was being pulsed was at the ends of the upper lip conductors, which had an upward movement of the order of .018 in. at each pulse.

VI MAGNETIC SURVEY

A measurement of the magnetic field in the whole of the magnet gap was undertaken for the following reasons:-

(i) To see that the field was sufficiently good to be used for acceleration

(ii) To determine corrections required by the pole face windings

(iii) To measure fringe fields, i.e. fields to which the protons are not subjected during acceleration but through which scattered and extracted particles may pass.

(iv) To detect unwanted ferromagnetic material

The following characteristics were measured:-

(a) Remanent field values along the nominal radius of the machine

(b) Remanent field 'n' values in the whole working area of the magnet

(c) Pulsed field levels on the nominal radius of the machine for fields from 300 to 15,000 G

(d) Pulsed field 'n' values for fields from 300 to 15,000 G

(e) Fringe fields at large radial distances from the magnet gap

(f) Fields around the straight sections

(g) Magnetic median surface positions at remanent and pulsed fields

The results of the survey are given in NDN 100/10. These indicate that some correction of 'n' was required at injection and up to 2,000 G, but that otherwise the field was sufficiently good to allow acceleration to full field.

Some extraneous mild steel was also detected and removed.

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REFERENCES

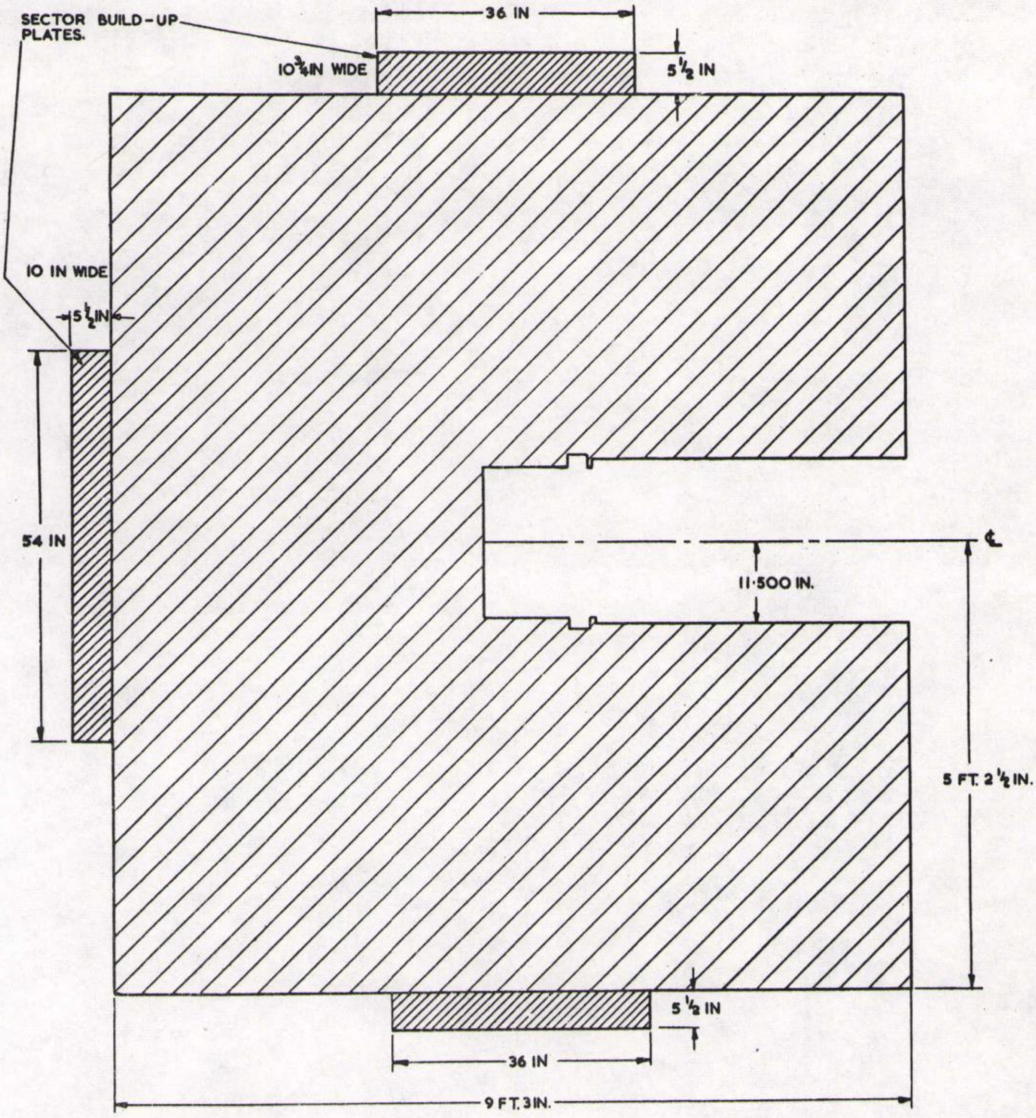
(1) A.E.R.E. GP/R 2181 - Some Parameters of the 7 GeV Proton Synchrotron Magnet. J.J. Wilkins and A.J. Egginton, 1957.

(2) NIRL R/6 - Design of Fringing Shims for Magnet Poles. J.J. Wilkins and A.H. Spurway, 1961.

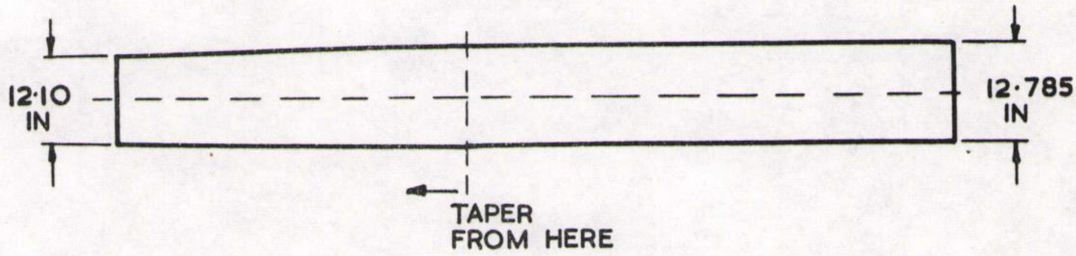
(3) NIRL R/33 - The Nimrod Magnet: Saturable Fin Polepieces. J.J.Wilkins and D.A.Gray.

(4) NIRL R/44 - Nimrod (A 7 GeV Proton Synchrotron): Part 1. Edited by B.G.Loach and B. Southworth.

LIST OF DIAGRAMS

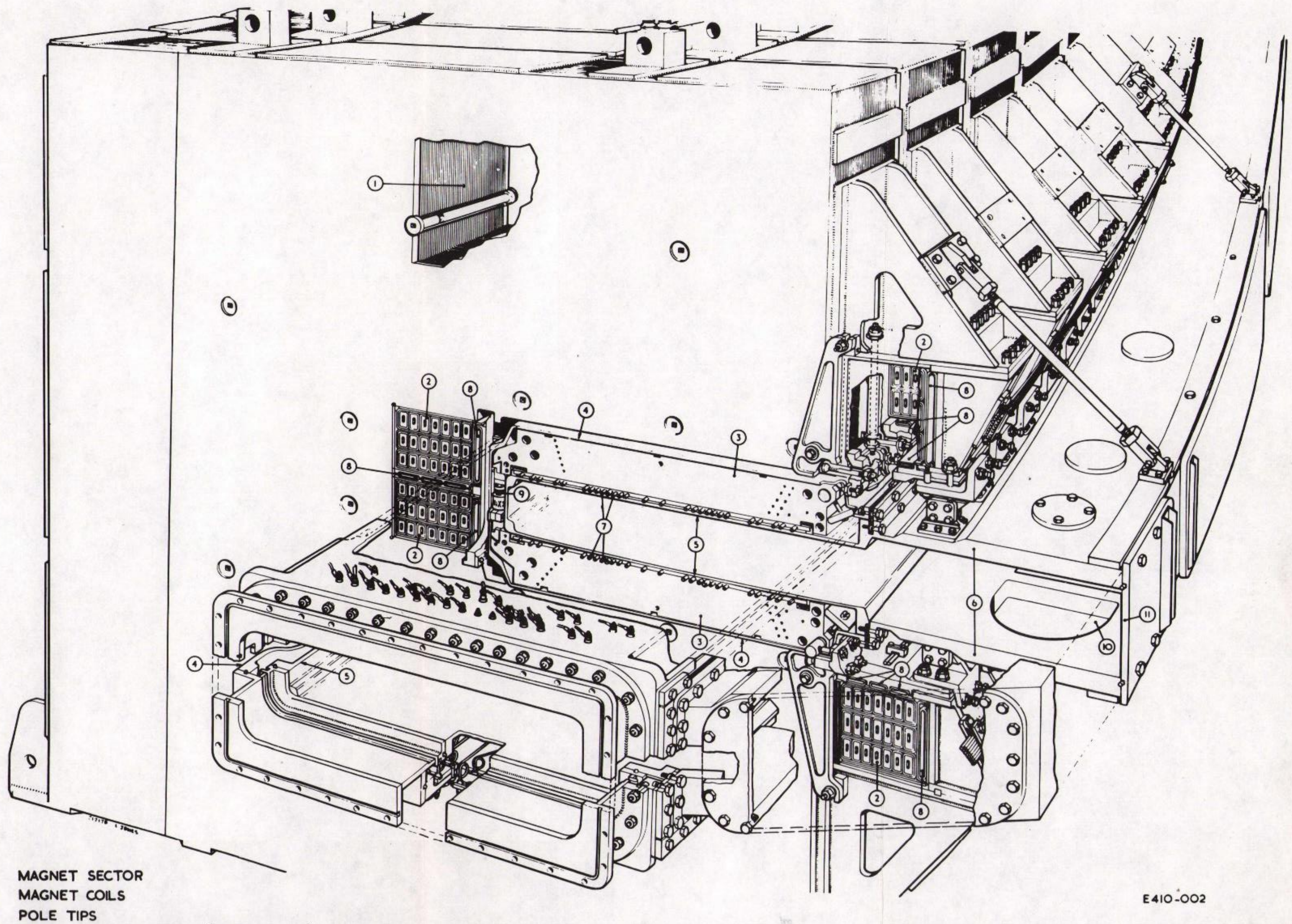


(a) Cross section

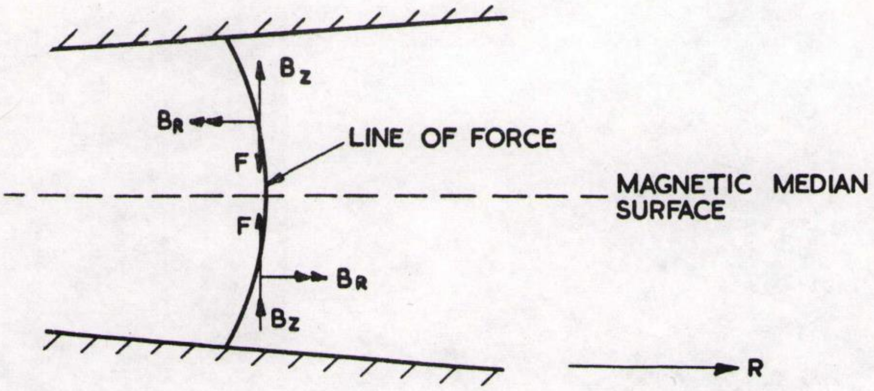


(b) Plan

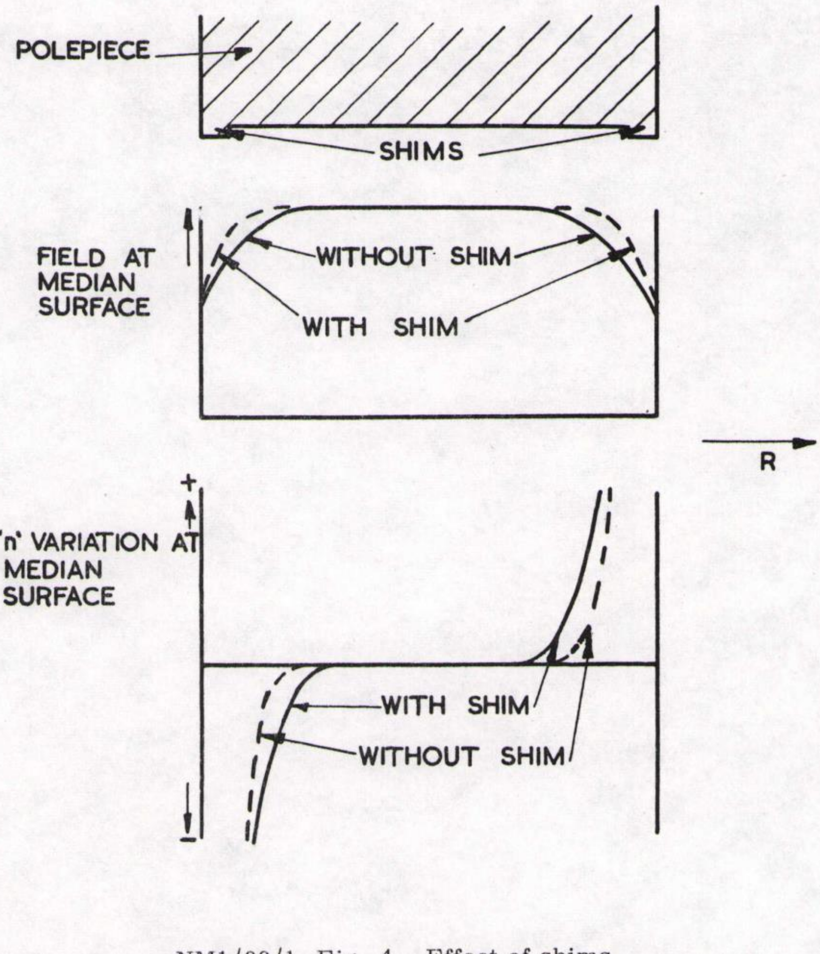
NM1/00/1 Fig. 1. Magnet sector.



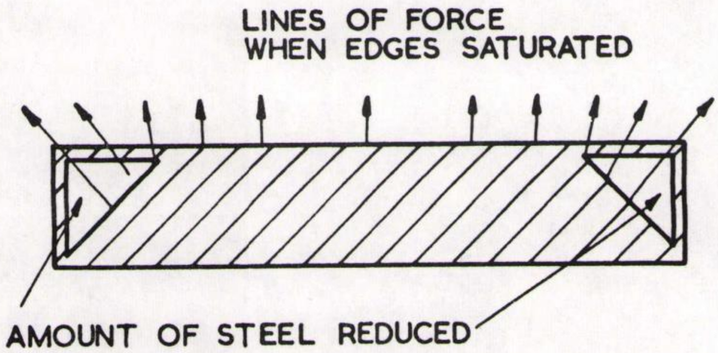
NM1/00/1 Fig. 2. Pictorial view of typical cross section through magnet octant.



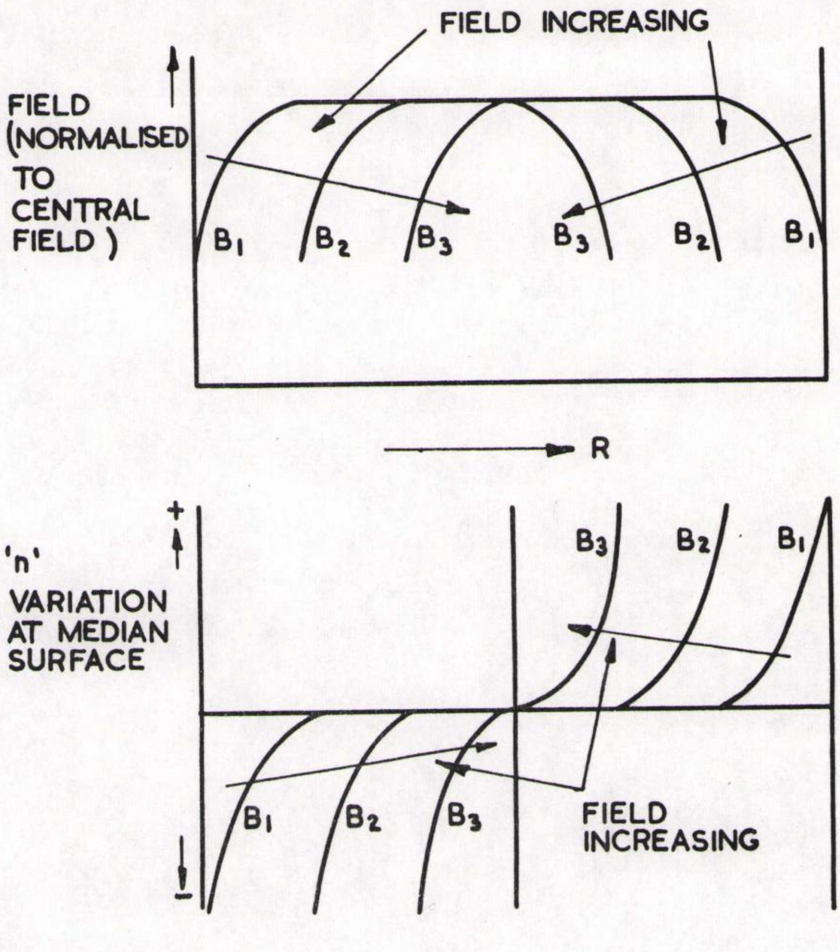
NM1/00/1 Fig. 3. Vertical focusing.



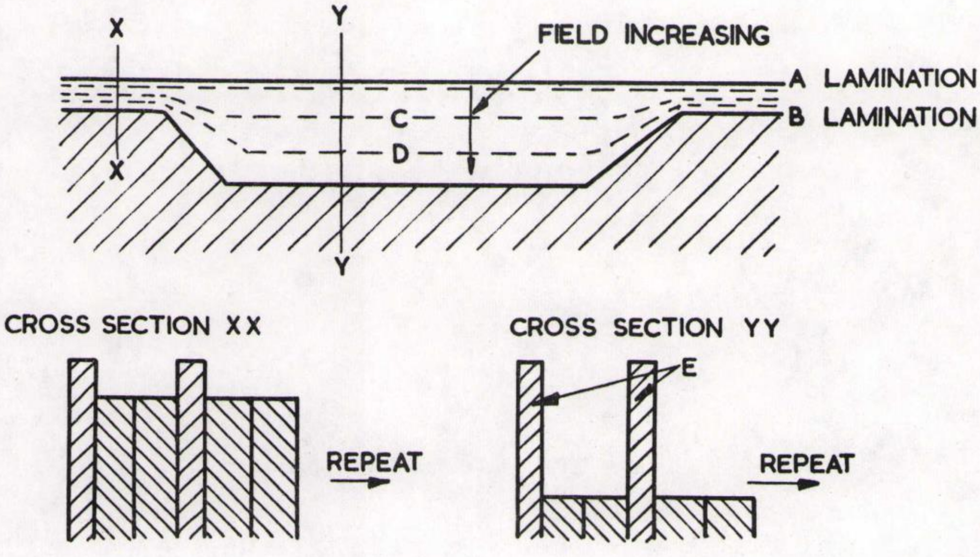
NM1/00/1 Fig. 4. Effect of shims.



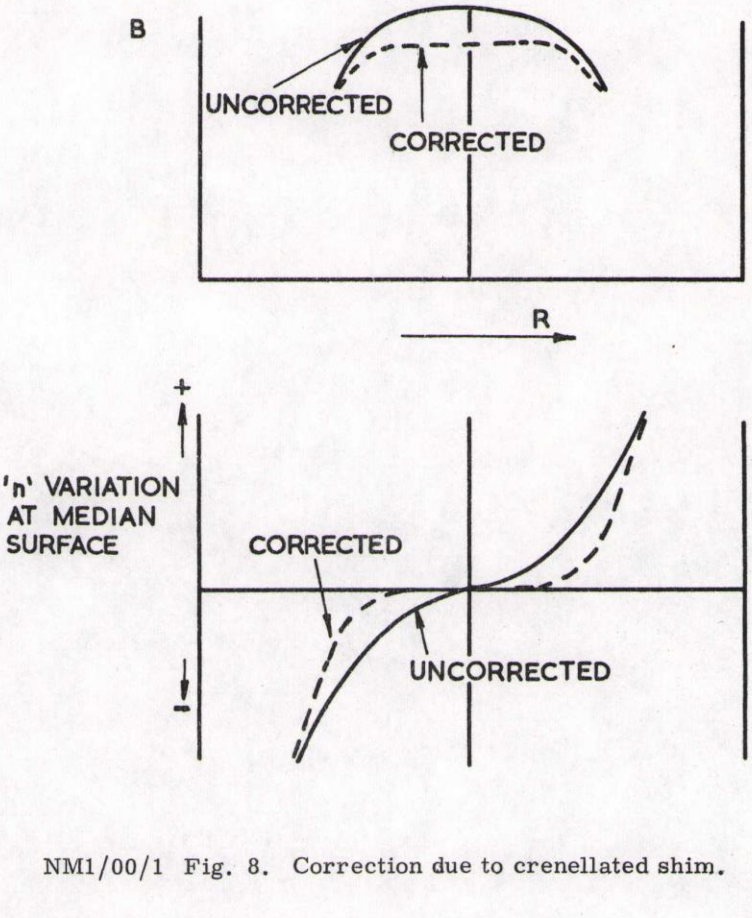
NM1/00/1 Fig. 5. Saturable edge polepieces.



NM1/00/1 Fig. 6. Field and gradients with saturable edge polepieces.

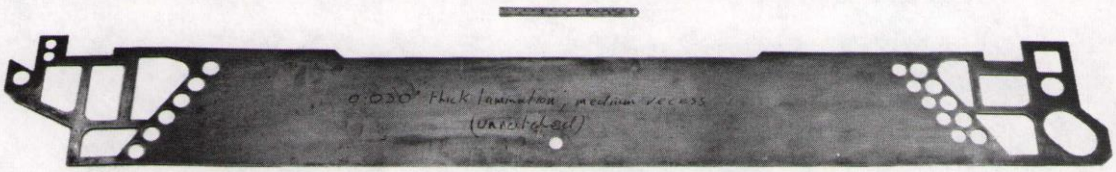


NM1/00/1 Fig. 7. Crenellated shims.



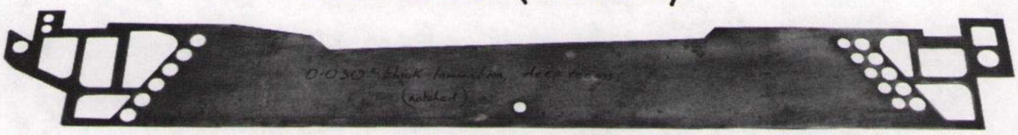
NM1/00/1 Fig. 8. Correction due to crenellated shim.

O·O2O IN. THICK LAMINATION
(NOTCHED)



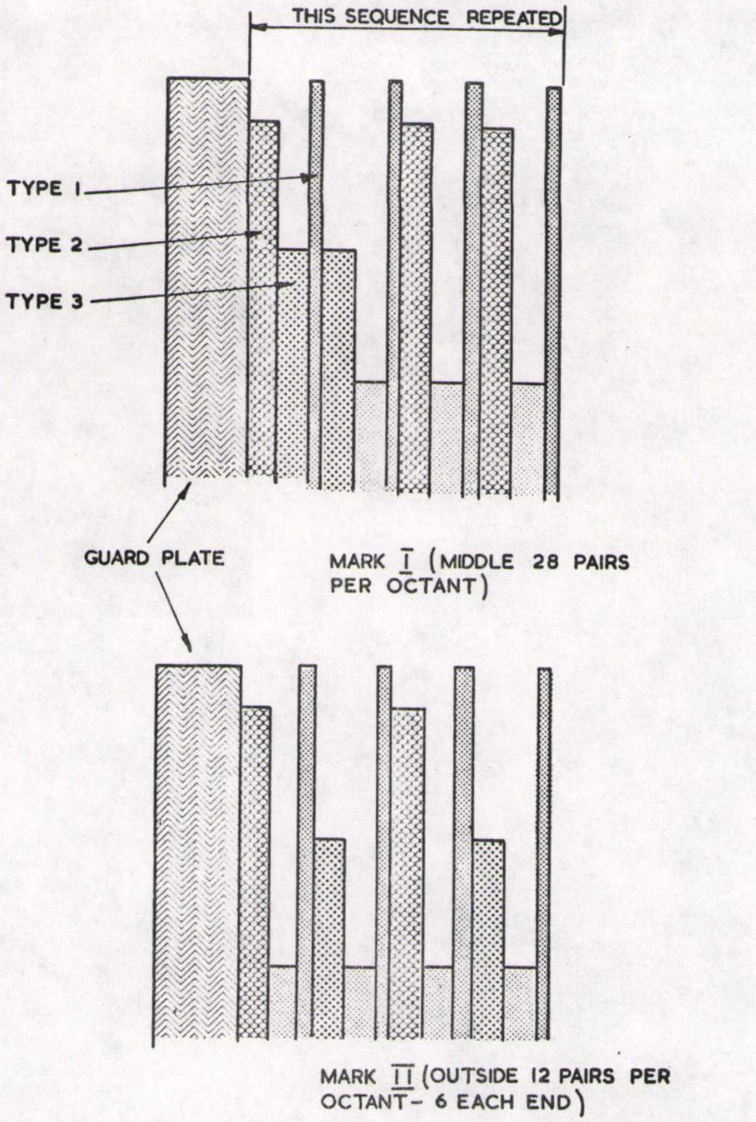
O·O3O IN. THICK LAMINATION
MEDIUM RECESS (UNNOTCHED)

O·O3O IN. THICK LAMINATION
DEEP RECESS (NOTCHED)

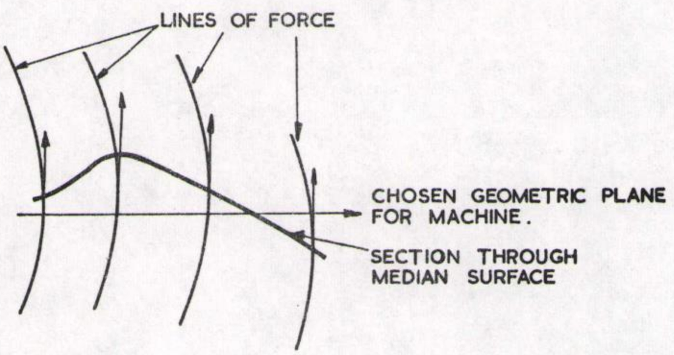


O·O3O IN. THICK LAMINATION
SHALLOW RECESS (UNNOTCHED)

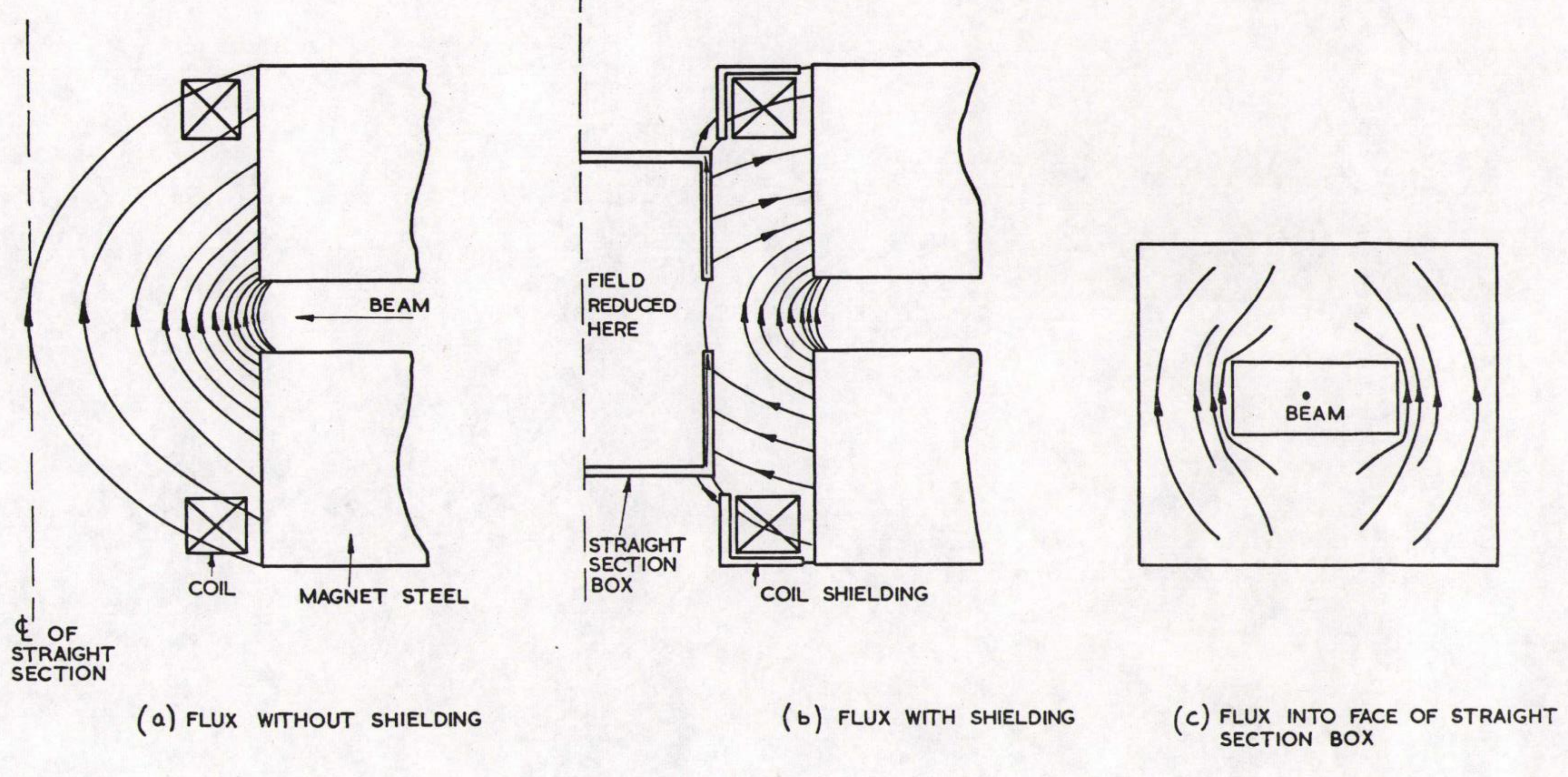
NM1/00/1 Fig. 9 Polepiece laminations.



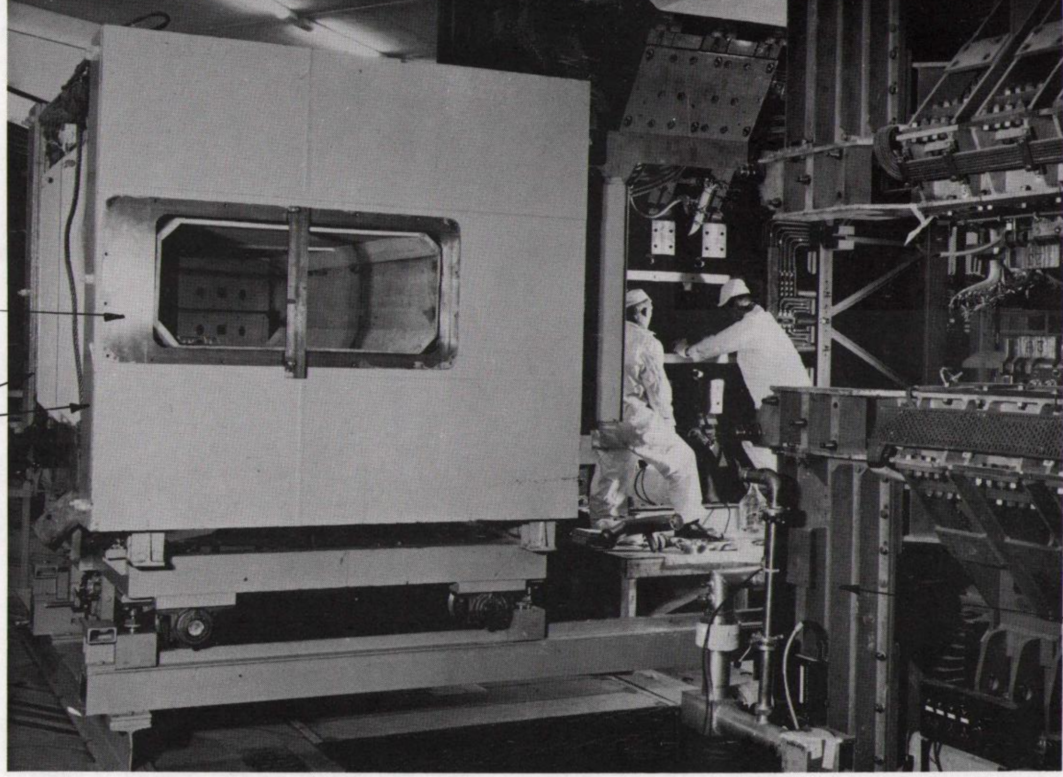
NM1/00/1 Fig. 10. Cross sections through centres of polepieces.



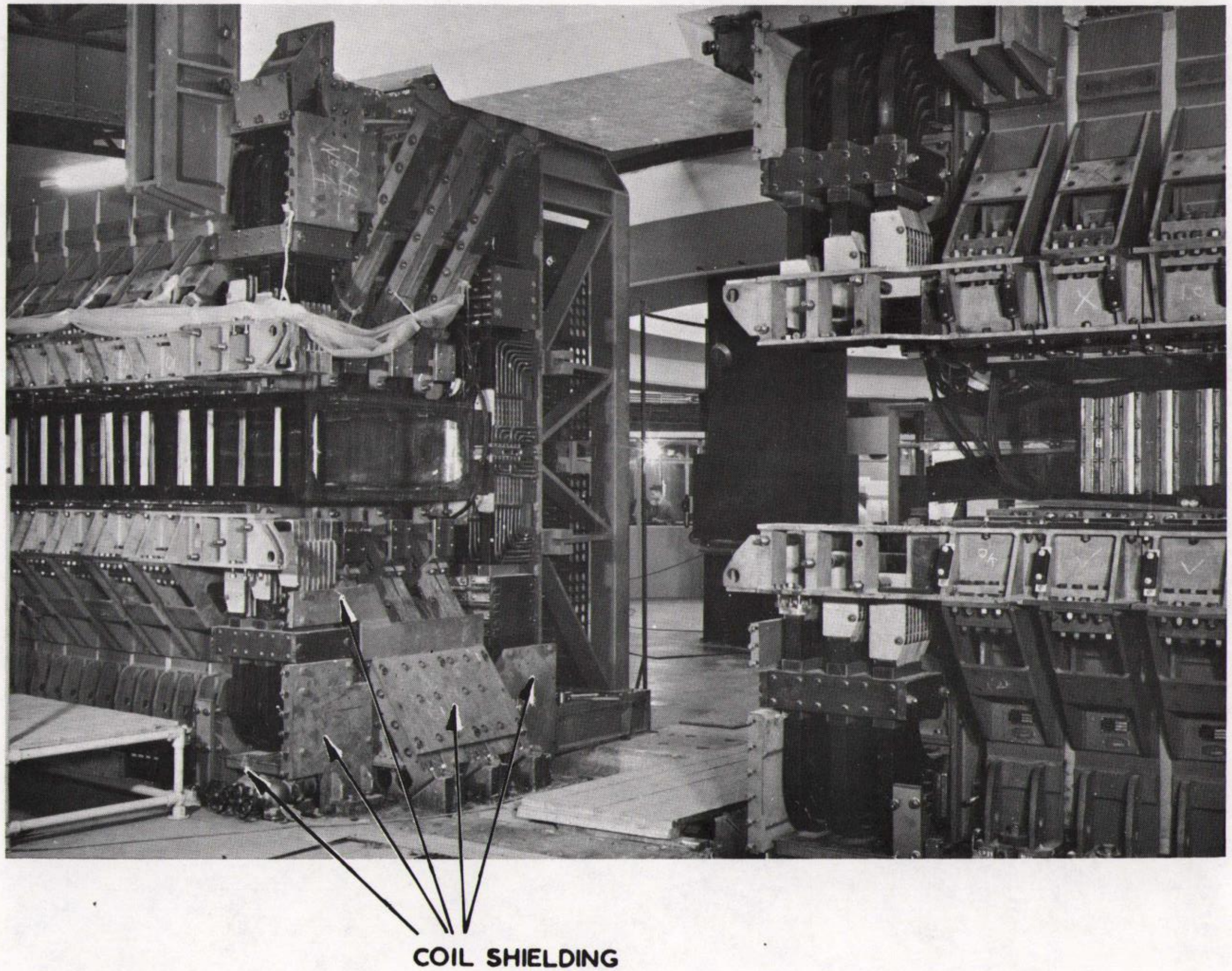
NM1/00/1 Fig. 11. Magnetic median surface.



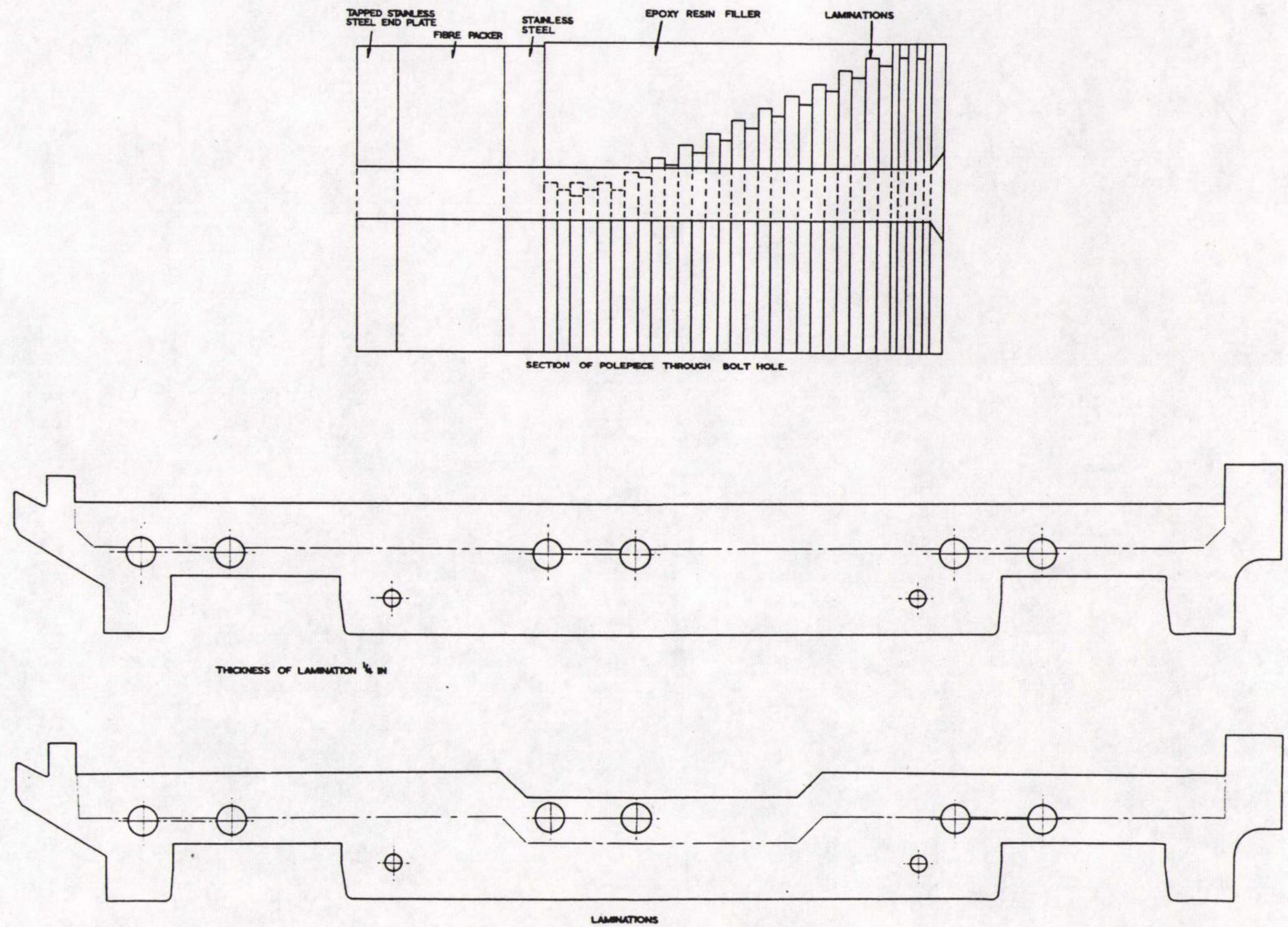
NM1/00/1 Fig. 12. Straight section shielding.



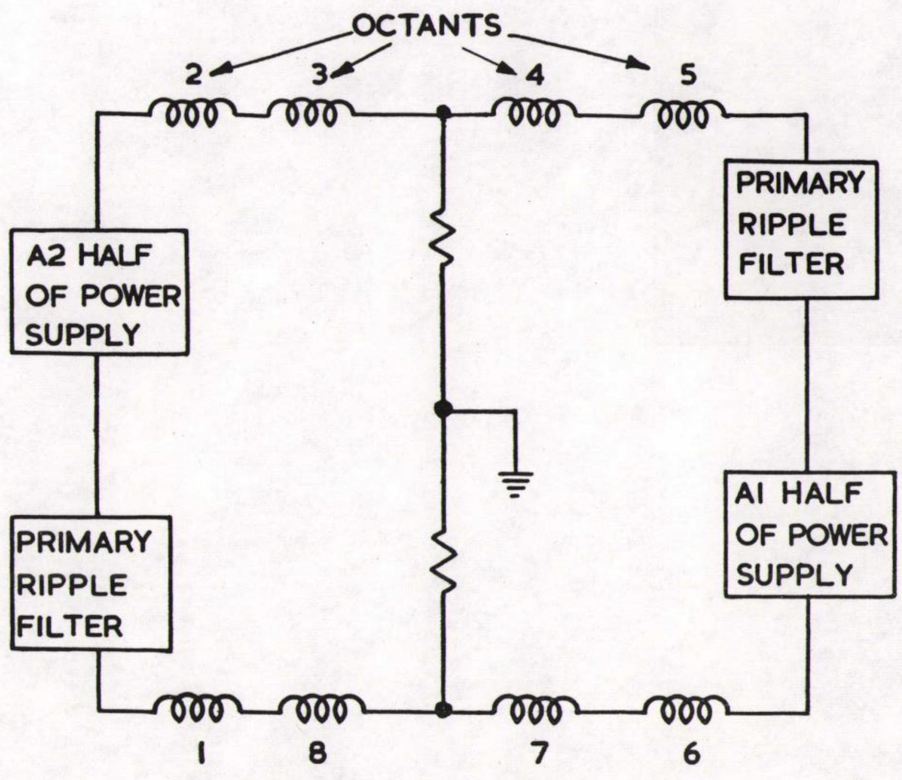
NM1/00/1 Fig. 13. Straight section box and front coil shielding.



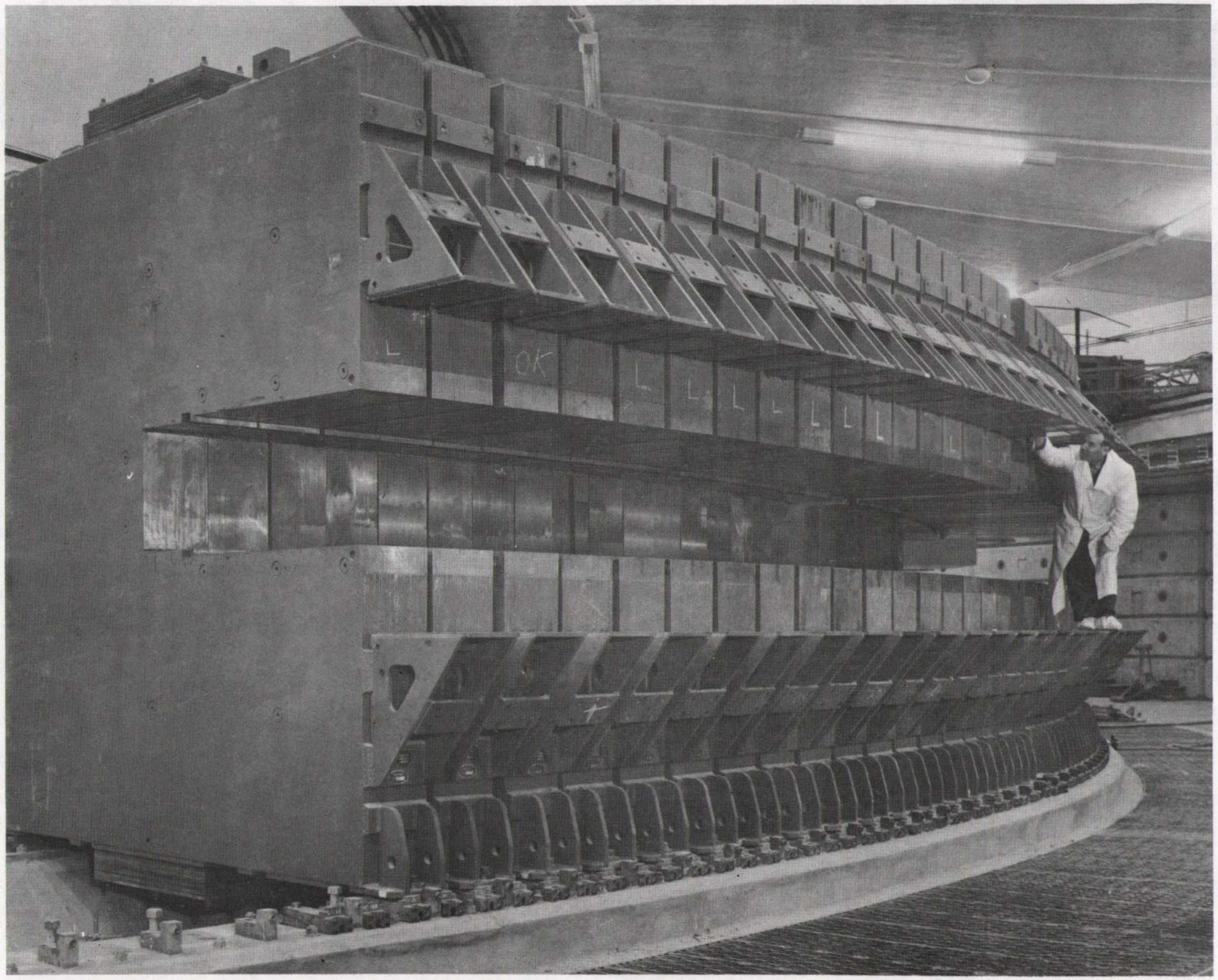
NM1/00/1 Fig. 14. Coil shielding.



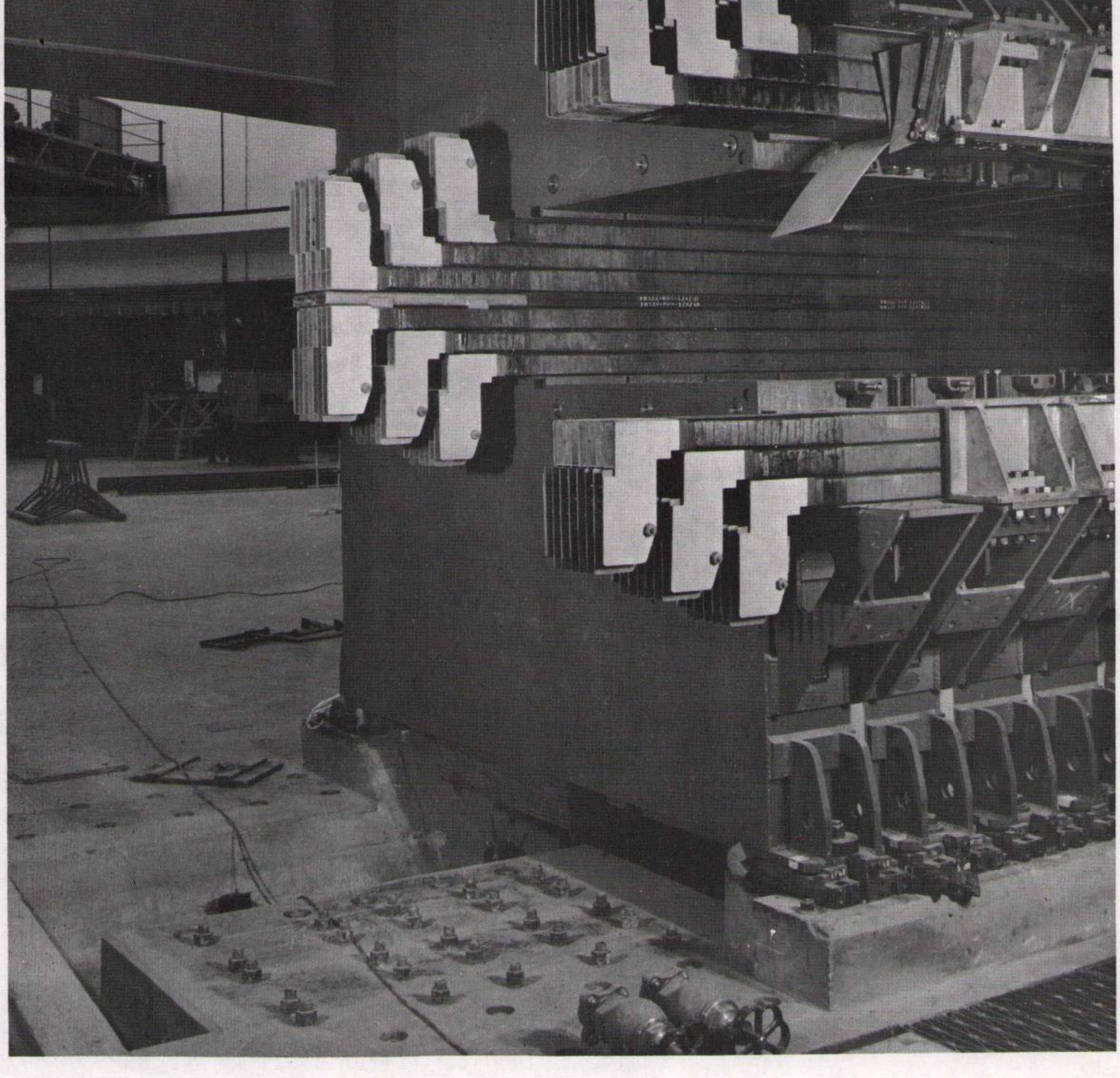
NM1/00/1 Fig. 15 End polepiece.



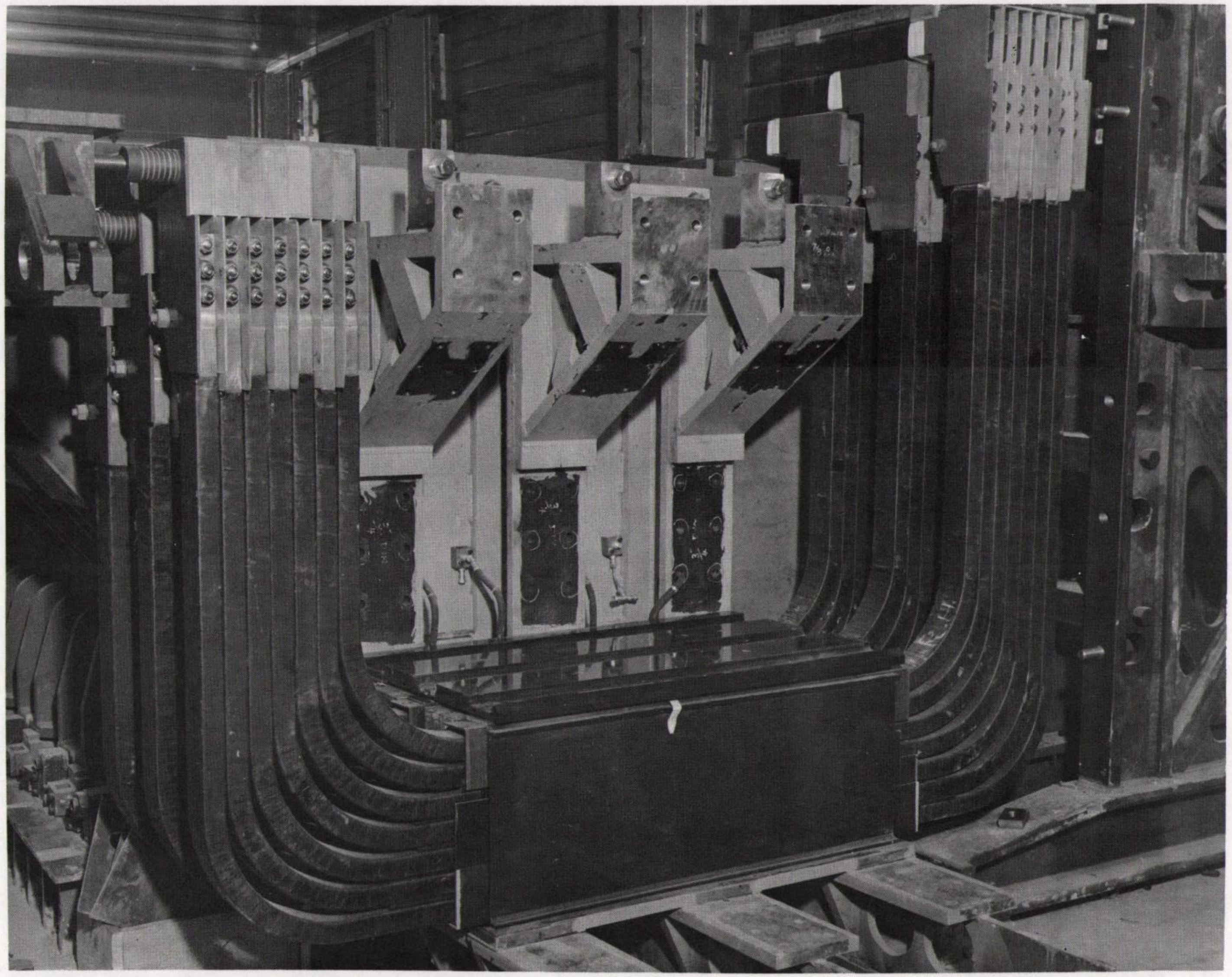
NM1/00/1 Fig. 16. Magnet octant connections.



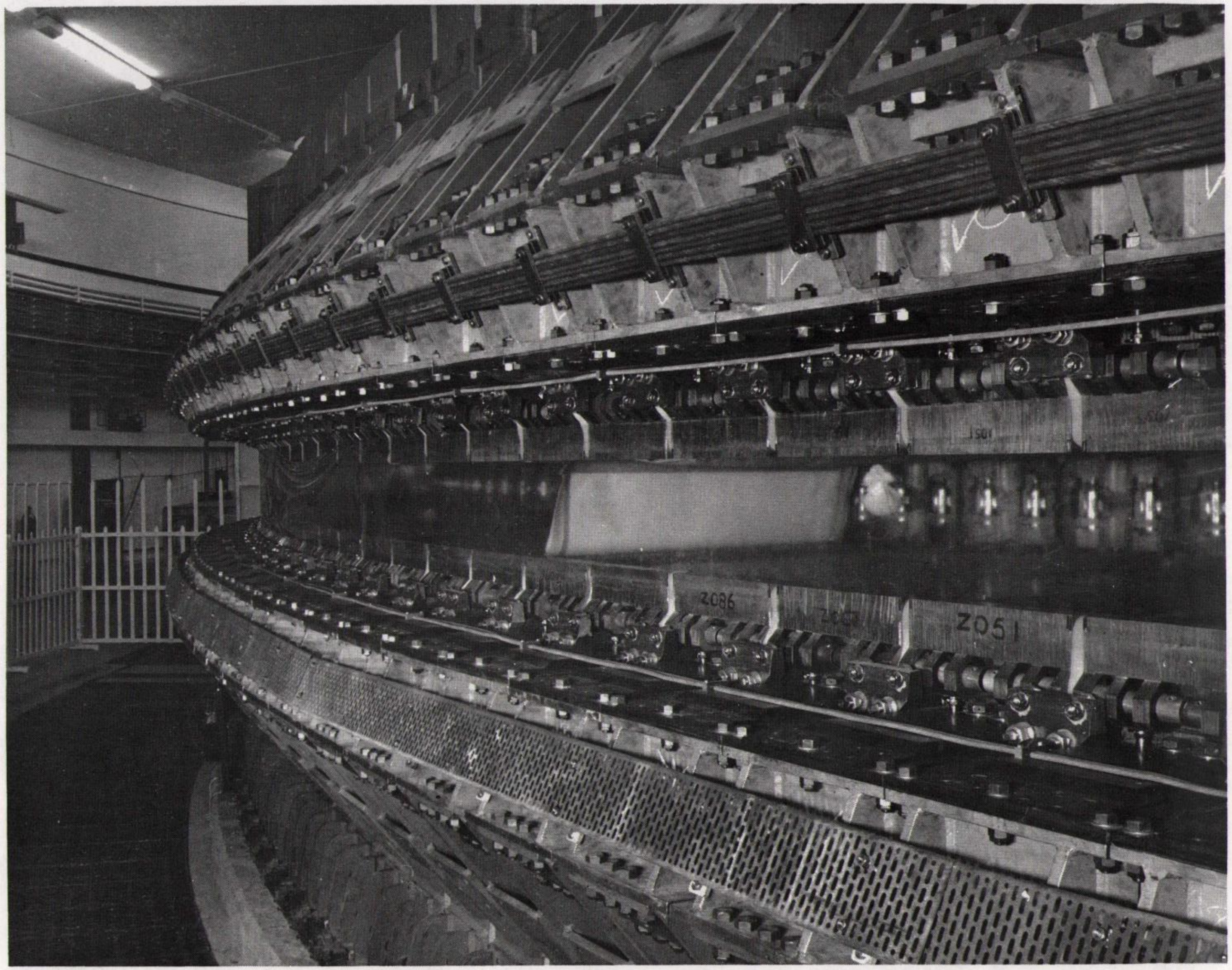
NM1/00/1 Fig. 17 Sectors in position



NM1/00/1 Fig. 18 Octant with longitudinal conductors



NM1/00/1 Fig. 19 End coil connections



NM1/00/1 Fig. 20 Polepieces installed in gap