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THE HARWELL VARIABLE ENERGY CYCLOTRON

by

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Chilton, Berkshire

March 1965

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ABSTRACT

A description is given of the more important features of the Variable Energy Cyclotron being built for the Atomic Energy Research Establishment by staff of the Rutherford Laboratory, Chilton. This cyclotron will be used mainly for studies in radio and radiation chemistry, metallurgy, and solid state physics.

The cyclotron is a 3-ridge A.V.F. machine, with 70" diameter pole and maximum central field of 17 kg. A single dee is fed by an amplifier and coaxial line resonator, and up to 100 kV peak dee volts will be obtainable. The frequency can be varied from 7.6 to 23 mc/s, and studies of harmonic operation have been made so that particles can be accelerated over a wide range of energy and charge to mass ratio. The energy range will be about 8 N^2/A to 78 N^2/A MeV (where N = ion charge and A = atomic weight) except that protons will be limited to 50 MeV. In order to facilitate the acceleration of heavy ions, source development has been undertaken (which we hope will lead ultimately to axial injection), and good pumping has been provided. Probes at 120° intervals have been built in as a permanent feature, so that setting up under various operating conditions can be achieved quickly.

An extraction and beam handling system has been designed, which will enable the beam to be transported into one of seven positions, situated in three independent shielded target rooms.

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March 1965

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CONTENTS

1. Introduction

The design and construction of the Variable Energy Cyclotron, being built by the Rutherford Laboratory for A.E.R.E. Harwell, has proceeded substantially along the lines indicated in the paper presented to the Los Angeles Conference in April 1962.[1] Approval to build the machine was obtained on the very day that the paper was presented; at the present time (February 1965) installation of major components is well under way, with the expectation of external beam early in 1966.

Having chosen a pole diameter of 70", a considerable effort has been made to provide as versatile a machine as possible within this limitation. Not only is it required to accelerate a range of heavy ions, but also lighter ions down to energies of a few MeV only. The maximum energy which can be achieved will be about 78 N^2/A, and the minimum (using third harmonic operation) about 8 N^2/A. The maximum proton energy will however be limited to 50 MeV, though the minimum can probably be extended by using H_2^+. High extracted currents are required, and the target of 100μA of 50 MeV extracted protons remains, though it is now clear that this will not be easy to achieve.

To meet demand for versatility, fairly extensive diagnostic equipment has been built into the machine, and attempts have been made to design in such a way that modifications to components which are likely to be developed (such as ion source, centre region, and extractor) can be made without undue difficulty. A subsidiary programme of orbit calculation, and measurements on the 22" model[2,3] has been carried out to aid our understanding of beam optics and familiarity with diagnostic equipment; in this way it is hoped to obtain versatile operation of the machine in a reasonably short time after start up.

A general impression of the layout of the machine, and of the building which contains it, may be obtained from Figs. 1 to 5. Apart from the deflector design, these differ only in detail from what was visualized at the time of the Los Angeles Conference.

The main components of the machine will be considered in the following sections. The account will be mainly descriptive; a more detailed treatment, with more emphasis on basic design considerations will be found in the companion papers.[4-8]

2. Magnet and Trim Coils

The magnetic field is provided by a 180 ton magnet, with horizontal gap. The azimuthally varying field is provided by three flat ridges, the edges of which are bounded by arcs of circles. The ridges are $4\frac{3}{4}$" deep, and the minimum gap is $7\frac{1}{2}$". The locus of the maximum of the field makes an angle of 50° to the circumference at the radius of the maximum orbit. The central field is 13.5 kg for protons, and 17 kg for heavier ions.

There is an 8" axial hole in the magnet, and the ridges extend in to a radius of 4". In the centre is an 8" dia. plug, with three 2" radial slots which go to the centre. The ion source tube enters from above through one of the slots, the other two preserve the three fold symmetry. In this way the ion source position can be moved radially along the slot, or azimuthally by rotating the plug. Furthermore, the plugs can be moved axially to adjust the centre field. The design and performance of this plug are described by Trew.(8)

The magnet yoke was cast in fourteen pieces from dynamo steel. The ridges were cut from 5" rolled plate, oriented such that the grain direction was the same in each. The magnetic survey has indicated that the magnet is homogeneous, the first harmonic error at the maximum beam radius being 3g at 13.5 kg and 10g at 17 kg.(4) The magnet excitation is provided by four double-layer pancake coils on each pole. The pancakes are wound from 1.6" x 1.25" hollow copper conductor, and insulated by taping with epoxy impregnated glass tape during winding. The coils contain a total of 144 turns and carry a current of up to 3820 amps.

One unusual feature of the magnet is two 9" holes in the side yoke. With the aid of a window in the tank, these enable a view along the dee edge to be obtained.

Variation in field shape for different particles is provided by a set of 12 trim coils, each containing 4 or 5 turns top and bottom, and capable of carrying up to 1400 amps. The field change per coil pair which can be obtained is about 300 gauss. In addition, there are three sets of harmonic coil in each valley, capable of producing first harmonics of 20 gauss (centre coils) and 60 gauss (outer coil). Besides correcting errors the outer coils can be used to produce a small harmonic to aid extraction, and the inner coils can be used for trimming the injection conditions.

The main trim coils are constructed of mineral insulated cable with a hollow inner conductor; this is similar to that used at Berkeley[10] except that it is finally squared to a section of side ½". In this way it was possible to obtain a better packing fraction for the final pancake, which was made by forming the conductor into coils, locating these accurately on a grooved copper plate, and brazing the whole assembly at 750° with Sil-fos brazing foil in a reducing atmosphere. The whole assembly is screwed to the pole face, so that the outer side of the copper plate forms the r.f. surface opposite to the dee, as may be seen in fig. 4.

The valley coils are separately wound from conductor of circular section with outer diameter 0.4"; these are held together with tack welds and mounted on individual plates; these sub assemblies are then bolted on to the trim coil plate. The whole assembly is shown in fig. 6.

The production of a suitable conductor was not easy, since both a large area of inner conductor, and also a central hole sufficient to enable the heat developed to be removed without excessive water pressure were necessary. Photographs of the conductors used are shown in fig. 7.

Many difficulties were encountered in the construction of these coils and the first braze attempt resulted in disaster; ultimately however two assemblies were produced.

When installed, the coils reduce the available gap between the poles from 7½" to 6¼".

3. Power Supplies

The magnet is powered by a 308 kW motor-generator set, consisting of motor and two generators on the same shaft. This is stabilized to a few parts in 10^5 in current; the signal from a 1 volt shunt is compared with a Zener diode reference, and the generator field controlled by means of an Amplidyne.

The circular trim coils are fed from solid state rectifier units; the specification calls for currents up to 1440 amps, with a stability and ripple content of less than $\pm$ 3 amps. Stability is achieved with the aid of a D.C.C.T., Zener reference source, magnetic amplifier and flux reset transductor; the maximum power which can be delivered per unit ranges from 32 to 66 kW. Valley coil units supply up to 250A with $\pm$ 1A stability.

4. Radiofrequency System

The accelerating system consists of a single 180° dee and dummy dee. The dee, which has a nominal internal aperture of 1.8" and an overall height of 3" is supported on the inner of a quarter wave coaxial line system which forms the resonator.

The diameters of the outer and inner lines of the resonator are 75" and 50" respectively, and the resonator is tuned by a moving short. The active length of the resonator from the low-frequency position of the short to the end of the dee is 20ft. The resonator will tune over a frequency range of 23 to 7.6 mc/s, and it is designed to handle sufficient power to provide 100 kV peak dee voltage over this range.

The dee is of sandwich construction; the top and bottom members each consist of a pair of 0.036" copper skins, between which spacers and water-pipes are secured by means of a copper-silver eutectic furnace braze. Carbon linings protect the inside from being struck by the beam. The resonator lines are made from rolled copper-clad steel, and the shorting plate makes contact with the inner and outer of the line through domed silver contacts which are held in position by pneumatic pressure. From the shorting plate to the inner and outer there are 432 and 576 contacts respectively.

Opposite to the dee is a dummy dee, which consists of two horizontal water cooled copper bars of diameter ½". The dummy dee is supported on the side plates of the vacuum tank, and both dee and dummy dee can be moved to vary the central gap from 1" to 2". The decision to have a dummy dee was made after experiments on the 22" centre model indicated that the field concentration thereby produced is beneficial for harmonic operation.

Power for the resonator is provided from a Marconi 250 kW transmitter type BD 272, driven by a Rhode & Schwartz synthesizer. The output from the transmitter is fed through a balanced-to-unbalanced transformer, along a coaxial line of length 55ft. which passes through the vault wall and into the resonator through a coaxial alumina insulator, where it excites the resonator by capacitive coupling to the inner line. The present coupling is not continuously adjustable, but is chosen to give the minimum variation in the coupled impedance over the working frequency range.

The dee and resonator system is kept on tune by servo controlled capacitive trimmers, and the dee voltage is monitored and designed to be constant to 0.1% by a feedback loop connected into the lower power stage of the amplifier.

Further details of the radiofrequency system are given in the companion paper by Jones and Payne.(5)

5. Ion Source

The ion source is mounted at the bottom of a vertical tube, which enters the vacuum tank through the vertical hole in the magnet yoke. The tube is mounted eccentrically in a cylindrical plug of diameter 5", which is itself eccentrically mounted in a further plug of diameter 8". By rotating both these plugs, the source can be moved 3" radially, and a sufficient extent azimuthally to scan the region between dee and dummy dee. As explained previously, the magnetic circuit at the centre is completed by a plug with three radial slots, as may be seen in fig. 5.

In the first instance a filament source similar to that used at Berkeley will be used for light ions, and a cold cathode source of heavy ions. These sources, and future plans for axial injection, are described by Bennett.(7)

A moveable puller electrode is mounted in the dee mouth opposite to the ion source. The face opposite to the ion source slit contains a rectangular slit which concentrates and collimates the beam from the source; the precise dimension of the slit will be chosen when experiments on the centre region now being down on our 22" cyclotron(2) are completed. The puller can be moved along and perpendicular to the dee axis; it is mounted on a thin plate which slides on the lower face of the dee, and can be withdrawn from the machine via an airlock at the end of the resonator. (The mounting is essentially the same as for the "beam probe" described in a later section.)

6. Extraction system

The beam will be extracted by means of an electrostatic system, basically similar to that in operation at Berkeley.(11) (The proposal outlined in the Los Angeles paper(1) has been abandoned.) Ions will enter the deflector after crossing the $Q_R = 1$ and $Q_R = 2Q_V$ resonances, where the value of Q_R is about 0.85. Precise conditions for optimum extraction are not known, but it is expected that a small coherent radial oscillation (to enhance turn separation) will be applied by suitable adjustment of the outer valley coils.

The deflector consists of two independent electrostatic channels, which are disposed as shown in fig. 1. The reason for providing two channels is that some accommodation can be made for the change in orbit shape at high fields, where saturation reduces the flutter and makes the orbit more nearly circular. The ridge orientation was chosen so as to permit extraction with the minimum deflector voltage; this orientation was fortunately the most convenient for providing compensation for the change of orbit shape using only two channels.

The earthed electrode of the first channel consists of a tungsten strip, which is held in water cooled supporting members made of copper. Dissipation on the leading edge of this electrode (the septum) is the factor which limits the current which can be extracted from the machine; it therefore needs very careful design, which will probably be modified after the operational characteristics of the machine are determined experimentally. The first six inches of the septum can be removed, and it is expected that various designs and materials (e.g. tungsten and water-cooled copper) will be tried before the best design is found. The other channels are machined accurately to size from copper, and are water-cooled. The height of the good field region of the extractor electrodes is 0.7".

Both ends of each electrode can be moved independently from the control room (8 controls) and can be set within an accuracy of 0.005". The minimum gap between electrodes is expected to be about 0.2", and the maximum field strength about 120 kV/cm. The vertical section of the second channel is curved, to give additional radial focusing. In this way divergence which occurs in this channel is made very small.

After leaving the deflector, the beam will pass through an iron magnetic channel, and pass through a hole in the vacuum tank into the beam handling system. Compensation for the harmonic produced by the channel will be provided either by iron mounted on the opposite side of the magnet, or by a special sector coil mounted in the tank.

During commissioning a "temporary target box" will be fitted to the corner of the tank from which the beam will emerge. This will be fitted with a controlled moveable platform and a horizontal bar (moveable in the vertical direction) which will allow collimating blocks, probes, etc. to be used to explore the beam. A standard remote handling tool has been adapted to be vacuum tight and to use non-magnetic materials; this will enable various blocks etc.to be moved, connected up, and taken in and out of the vacuum tank through an air lock.

7. Beam Handling

After leaving the tank the beam will pass in succession through a steering magnet, a quadrupole pair, a bending magnet, a further quadrupole pair, a switching magnet, and then through yet a further quadrupole pair into one of seven positions in the target rooms. The object of the beam handling system is to get all the beam into any one of the target positions. No attempt at energy selection will be made.

The disposition of the beam lines is shown in fig. 8 and the table gives properties of the quadrupole and bending elements. The switching magnet, described by Hansford in a separate paper[9], is rectangular in plan with semi-circular ends; it can be rotated about the centre of one of the semi-circles, and is set so that the angle of rotation is equal to half the angle through which the beam turns.

(Table on next page)

TABLE 1

Element	Bending angle	Maximum field, kg.	Aperture
Steering Magnet	$\pm 1\frac{1}{2}^{\circ}$ at max. field	17 kg.	4"
Bending Magnet	75°	15 kg.	4"
Switching Magnet	$\pm 19\frac{1}{2}^{\circ}$, $\pm 53\frac{1}{2}^{\circ}$, $\pm 73^{\circ}$	15 kg.	4"
	Length of pole, inches	Maximum field gradient, kg/inch	
Quadrupole 1	14	1.58	5"
2	14	1.58	5"
3	14	2.35	4"
4	15	1.36	4"
5	15	1.36	4"
6	15	1.36	4"

The large aperture of the initial elements should make it easier to cope with extracted beams possessing a range of optical properties. The strength and position of the quadrupoles were determined after extensive studies with the analogue described by Hansford.(12)

The beam pipes are made of aluminium,and individual sections can be insulated to enable the current striking them to be monitored; a series of iron shutters similar to those in use at Oak Ridge are mounted in the shielding wall between the vault and the target rooms. Shut off valves are provided at the positions shown, and a fast shut-off valve upstream from the bending magnet, triggered by pressure rise, will protect the main vacuum system against bursts in the target rooms. Instrumentation in the beam lines will be described in the following section.

8. Probes and Instrumentation

Provision has been made for three "beam" probes at 120° intervals round the machine. These will be operated from the control room, and various types of head can be fitted. Three independent electrical and water cooling circuits will allow the use of 'three finger' and 'differential probes'. In addition there is provision for a high power users probe, and a phase probe which can replace the users probes or one of the beam probes. The probes are disposed round the machine as shown in fig. 1.

The mechanical design of the probes has not always been simple. Beam probe No. 3 is straightforward. Probe No. 2 comes in over the deflector, the head is therefore offset from the shaft, and it needs to be rotated before being inserted or withdrawn. Further, the motion is limited when the deflector is in position. Beam probe No. 3 is the most troublesome. This has to be driven from the far end of the resonator, and is consequently long and awkward to remove. It runs along rollers in the inner of the resonator, and the end is located in a slide in the dee.

The provision of three probes should enable the orbit centre to be determined rapidly, and a quick check to be made of the beam loss with radius.

The "temporary target box" which will be inserted at the exit to the tank has already been described in the section on extraction.

In the beam lines, "flip in" scintillators for quick viewing of the beam will be provided. These will be in "standard boxes", on which probes etc. can readily be mounted if desired. In addition, pairs of slits, which can be traversed across the beam in two directions at right angles will be mounted at the exit from the machine, downstream from the machine, and after the bending magnet. These will be used for emittance measurement, by scanning with a slit downstream the beam which passes through a slit upstream, as a function of distance from the beam axis. The slit system after the bending magnet will enable estimates of energy spread to be made.

9. Vacuum

The volume to be evacuated is about 20,000 litres with a total surface area of greater than 10^6 cm^2. The main pumping is by means of two Leybold DO 30,000 oil diffusion pumps with chilled water-cooled 36" Edwards chevron baffles, giving a total baffled speed of about 25,000 litres/sec. These are connected at the corners of the tank, as may be seen from figs. 4 and 5, giving good pumping of the dee gap. A good vacuum is necessary when accelerated multicharged ion, otherwise charge exchange causes excessive attenuation of the beam.(13) In addition, there is an Edwards 24" pump at the end of the r.f. resonator. A flexible system of pipework is provided with an 8" roughing line to the tank and resonator and separate 4" backing lines to each diffusion pump, so that with the appropriate valves in the plant room combination of Kinney pumps and/or Roots Blower may be used for roughing as desired. A separate small pump system is attached near the bending magnet and used to evacuate the external beam lines.

Vacuum seals are made with butadiene acrylonitrile rubber; for the main tank seals this is of diameter 5/16". In order that the corner posts as well as the side plates of the vacuum tank may be removed, it is necessary to use demountable T-joint seals at the corners. This arrangement is similar to that described by Verster.(14) Extensive tests were made on a model in order to find the optimum dimension, and it is now found that a reliable seal can be quite simply made.

10. Controls

The control system is conventional, its functioning and merits will most usefully be described after some operating experience is obtained.

11. Shielding

Wall and roof thicknesses in the vault were estimated by application of the neutron attenuation curves given by R. H. Thomas to data (experimental and theoretical) on the neutron yield and energy spectrum for the two extreme conditions of a 1 mA beam of 50 MeV protons on a heavy target and 24 MeV deuterons on a beryllium target. Ducts and gaps in the doors were designed according to the rules established for reactors, the thermal neutron flux being assumed equal to the fast flux at the walls.

Further details on the vault and door design are given in the companion paper on the building by Harbert.(16)

12. Acknowledgments

The main contributors to the various aspects of the design are listed below.

Magnet: J. H. Coupland was responsible for the magnet and trim coil design, which was based on experimental work of K. J. Howard, D. H. Trew and P. H. Beckett. Engineering support was provided by P. T. Clee and J. Condliffe.

R.F.: E. J. Jones was responsible for the r.f. system; electrical design was done by H. E. Payne, C. R. Walters and B. J. Wood (who specialised in the servo controls), and mechanical design by W. Holland and B. W. H. Edwards.

Deflector: The electrical design of the deflector was by T. C. Randle, A. E. Thorp was responsible for the mechanical design.

Ion Source: J. R. J. Bennett is responsible for ion source design and development, with contributions from H. E. Walford, and mechanical support from J. Condliffe who designed the source positioning mechanism.

Probes: The mechanical design of the probes was done by A. E. Thorp.

Beam Handling: The basic design of the system was done by R. N. Hansford, with contributions from P. T. Clee (mechanical), J. H. Coupland (quadrupoles and steering magnet) and P. S. Rogers (beam measurement devices).

Vacuum: J. H. Coupland was responsible for the overall design in association with K. J. Howard, P. T. Clee was responsible for engineering aspects.

Controls: Most of the general controls for the cyclotron, including interlocks, as well as cabling, wiring, etc. was the responsibility of D. J. Woodington, who also contributed with K. J. Howard to the magnet and trim coil power supplies.

Water circuits: P. T. Clee was responsible for the water circuits, L. J. White carried out the detailed design.

Theory: Orbit and deflector calculations were carried out by A. R. Mayhook, under the guidance of W. Walkinshaw.

Engineering: The project engineer was A. G. Hewitt, who was in charge of the design office responsible for engineering aspects of the design, including liaison with contractors, financial control, programming, etc.

Members of Engineering Division A.E.R.E. contributed substantially to a number of components, in particular the design of bending and switching magnets, the water system, and the stabilized ion source supply.

Much of the detailed engineering design was carried out either in our design office or at their own premises by the staff of T.D. & T., Reading and Portsmouth Aviation, Portsmouth.

In addition, we gratefully acknowledge the contribution of many visitors. The influence of R. Burleigh from Berkeley who worked with us in the formative stages will be evident to the discerning critic. Other visitors from the U.S.A. who contributed to the project were R. Worsham, A. L. Garren and J. R. Richardson. D. J. Clark was on our staff for two years, and clarified a number of basic aspects of the design and operation.

W. B. Powell of the University of Birmingham has been a consultant since 1962; he has attended a number of our design meetings and has contributed many useful ideas.

Contributions from Rutherford Laboratory staff not working full time on the project include those of F. M. Russell and R. Billinge, who have helped to clarify the extraction problem.

Finally we should like to acknowledge constant help and encouragement from W. Walkinshaw, Head of Applied Physics Division, and P. Bowles, Chief Engineer.

13. List of Principal Contractors

We are indebted to the many firms who have contributed to the cyclotron by supplying various (often unconventional) components; some of the larger contributions are listed below.

Magnet:

Castings supplied by Edgar Allen, Sheffield.

Machining, ridges, and vacuum box by Foster, Yates & Thom, Blackburn.

Copper for coil conductors from Yorkshire Imperial Metals, Leeds.

Main magnet coil wound by G.E.C. Witton.

Mineral insulated cable was supplied both by Pyrotenax, Hebburn and Smiths (Industrial Instruments) London.

Trim coil assemblies by A.E.R.E. workshops, brazed in furnace at Edgar Allen's, Sheffield.

Power Supply:

Motor generator set supplied by Crompton-Parkinson, Chelmsford.

Solid state rectifier units from Brentfords, Crawley and Gresham Transformers, Feltham.

R.F.:

Transmitter from Marconi, Chelmsford.

Resonator from Wm. Neills, St.Helens (copper work partly sub-contracted to Robinson's, Stockport).

Short mechanism and push rods by A.E.R.E. workshops.

Deflector:

Deflector construction by Graviners, Gosport.

Deflector electrodes by A.W.R.E. Aldermaston, Smith's Jig & Tool, Colnbrook and Metpresco Engineering, Feltham.

Power supply by Miles Hivolt, Shoreham.

Beam Handling Equipment:

Bending and Switching magnets by Lintotts, Horsham.

Quadrupoles by N. Taylors, Parkstone.

Moveable shield plugs by Hall Engineering, Shrewsbury.

Vacuum Equipment:

Diffusion pumps from Leybold, Cologne and Edwards, Crawley.

Roots blower, backing pumps and valves from General Engineering, Manchester.

Header valves, Fairlede Engineering, Chatteris.

Ion Source:

Ion source, and mechanism for moving it by A.E.R.E. workshops.

Probes:

Probes by A.E.R.E. workshops.

Cooling:

The cooling system was installed by Alden's, Oxford.

Controls and Cabling:

Main power cabling installed by B. French, Kidderminster.

Control cabling installed by Read and Partners, London, S.E. 1.

Control room suite by Wm. McGeoch, Birmingham.

Electronic control equipment was supplied by C and N, Gosport, Calne Electronics, Chippenham, and S. Devall, Greenford.

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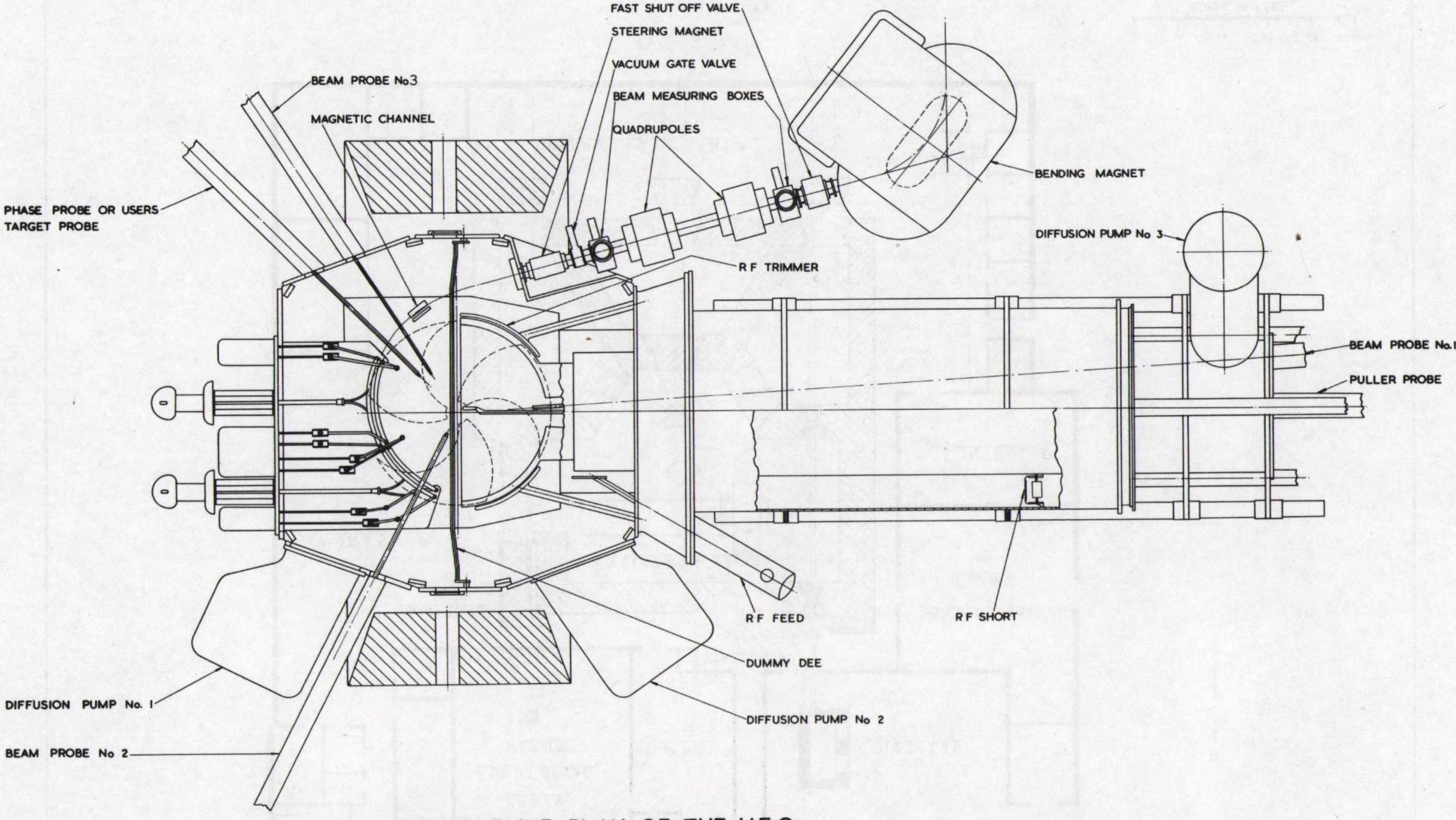
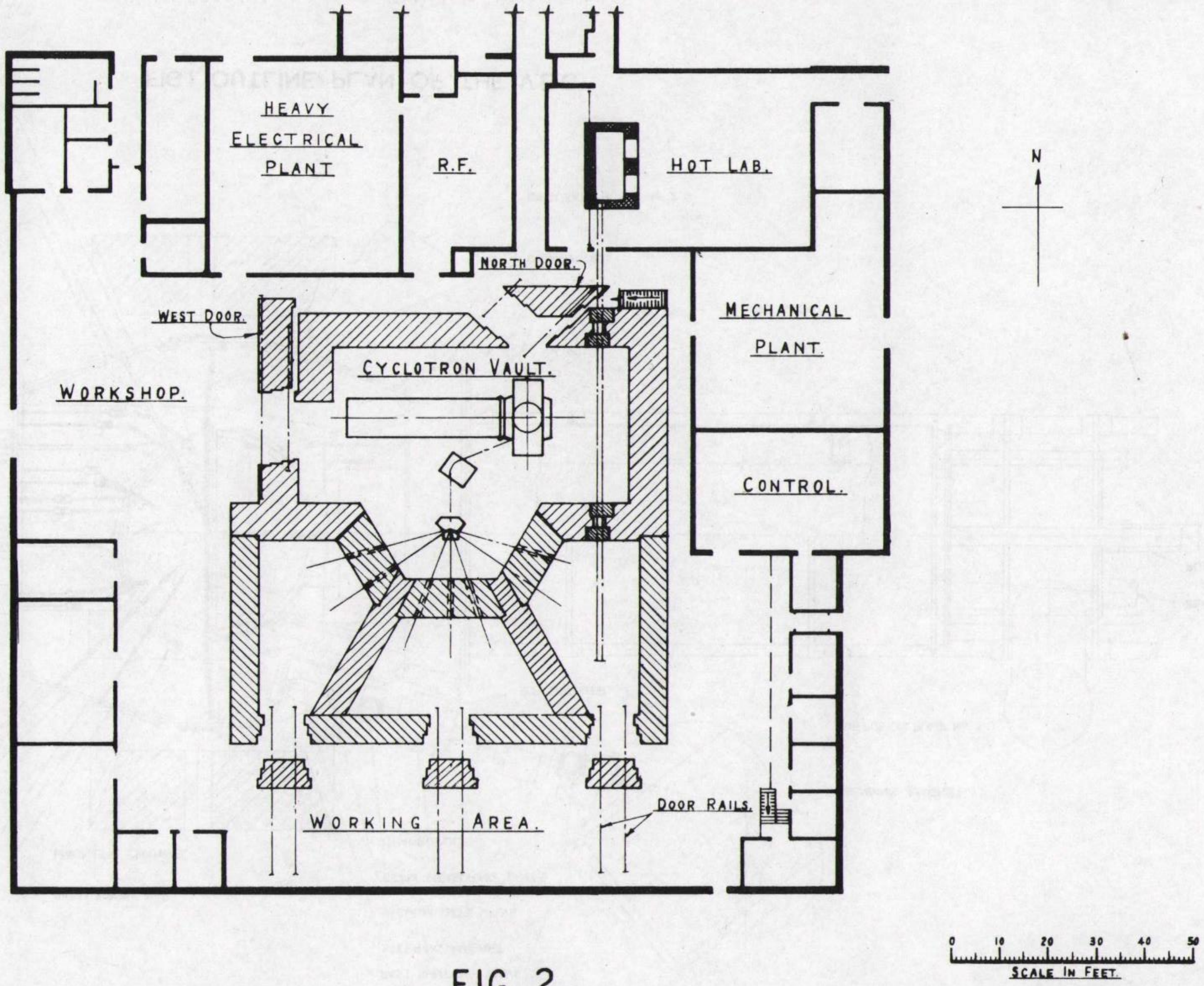
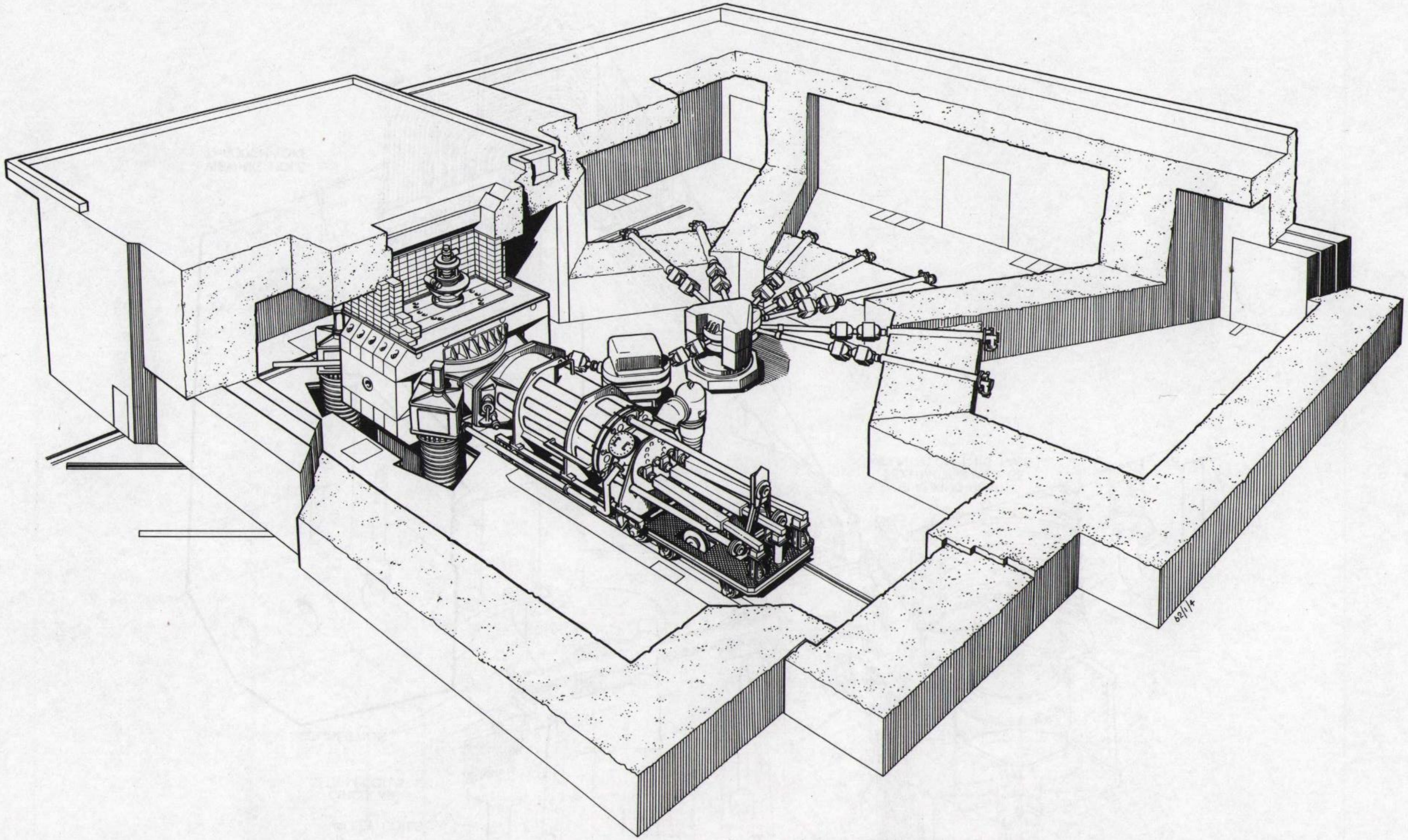


FIG.I. OUTLINE PLAN OF THE V.E.C.



HEAVY
ELECTRICAL
PLANT
R.F.
HOT LAB.
N
NORTH DOOR.
WEST DOOR.
MECHANICAL
PLANT.
CYCLOTRON VAULT.
WORKSHOP.
CONTROL.
DOOR RAILS.
WORKING AREA.
0 10 20 30 40 50
SCALE IN FEET.

FIG. 2.



CUT-AWAY VIEW OF VAULT, SHOWING CYCLOTRON & BEAM TRANSPORT SYSTEM
FIG.3.

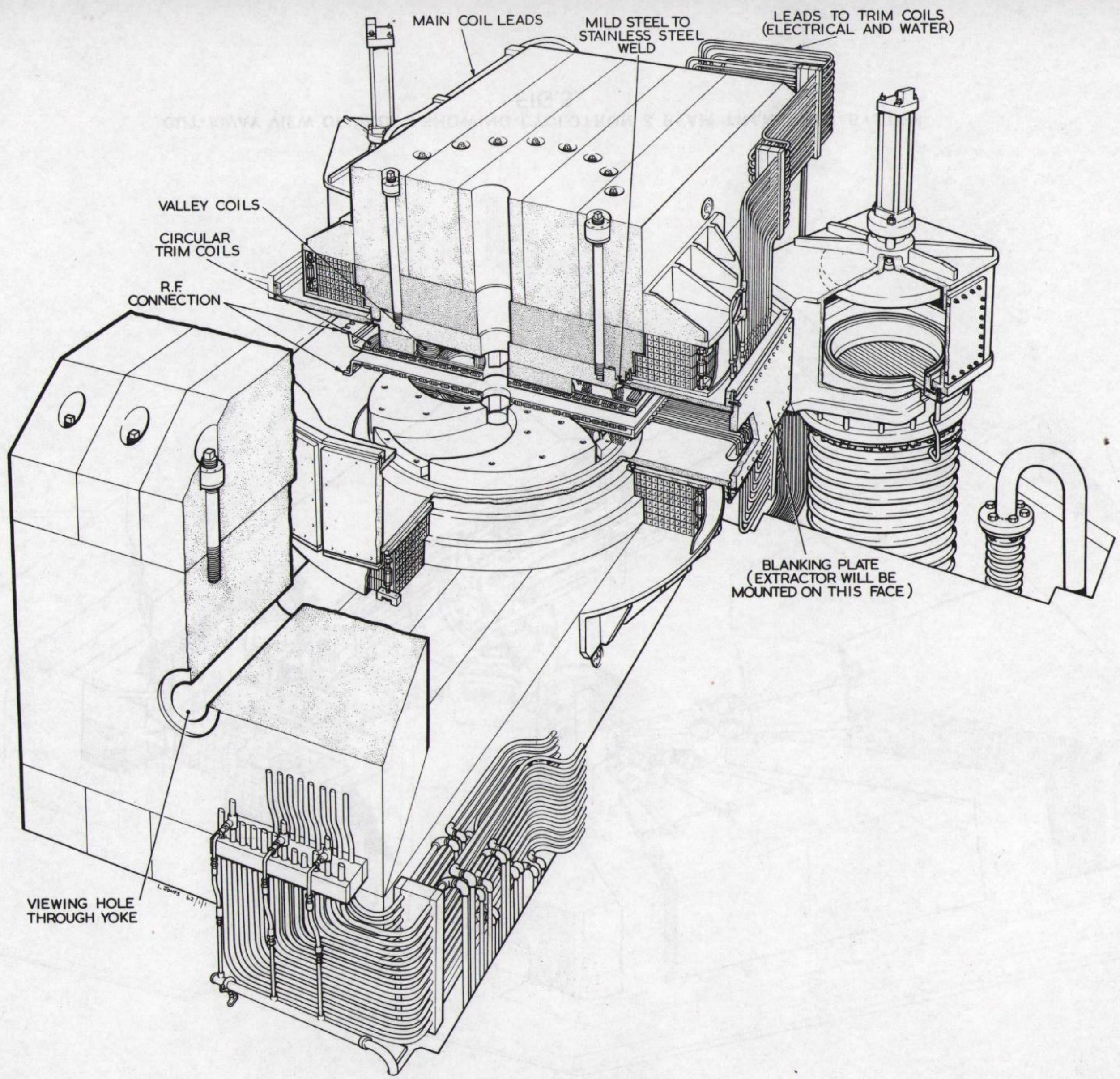


FIG.4. V.E.C MAGNET ASSEMBLY

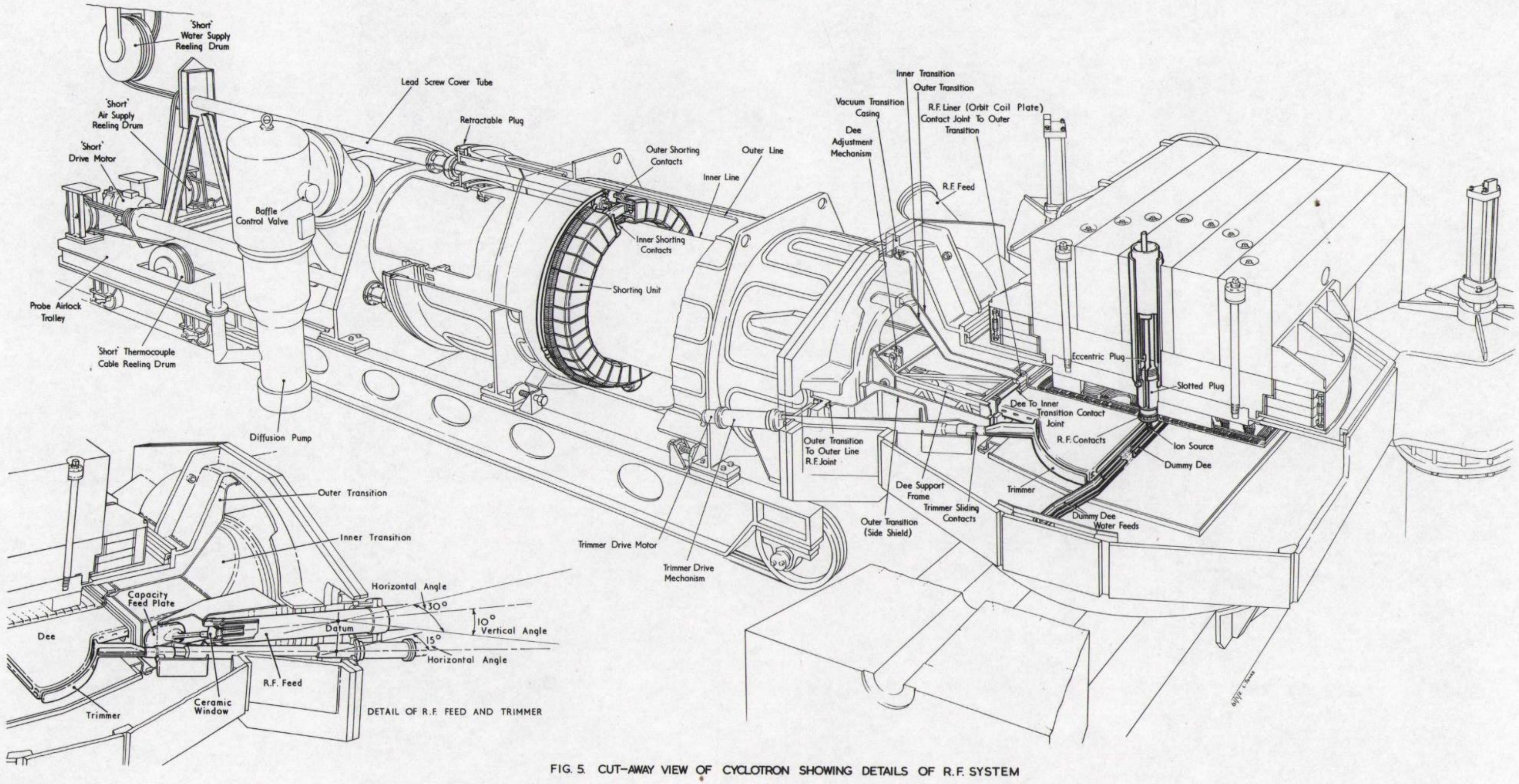


FIG. 5. CUT-AWAY VIEW OF CYCLOTRON SHOWING DETAILS OF R.F. SYSTEM

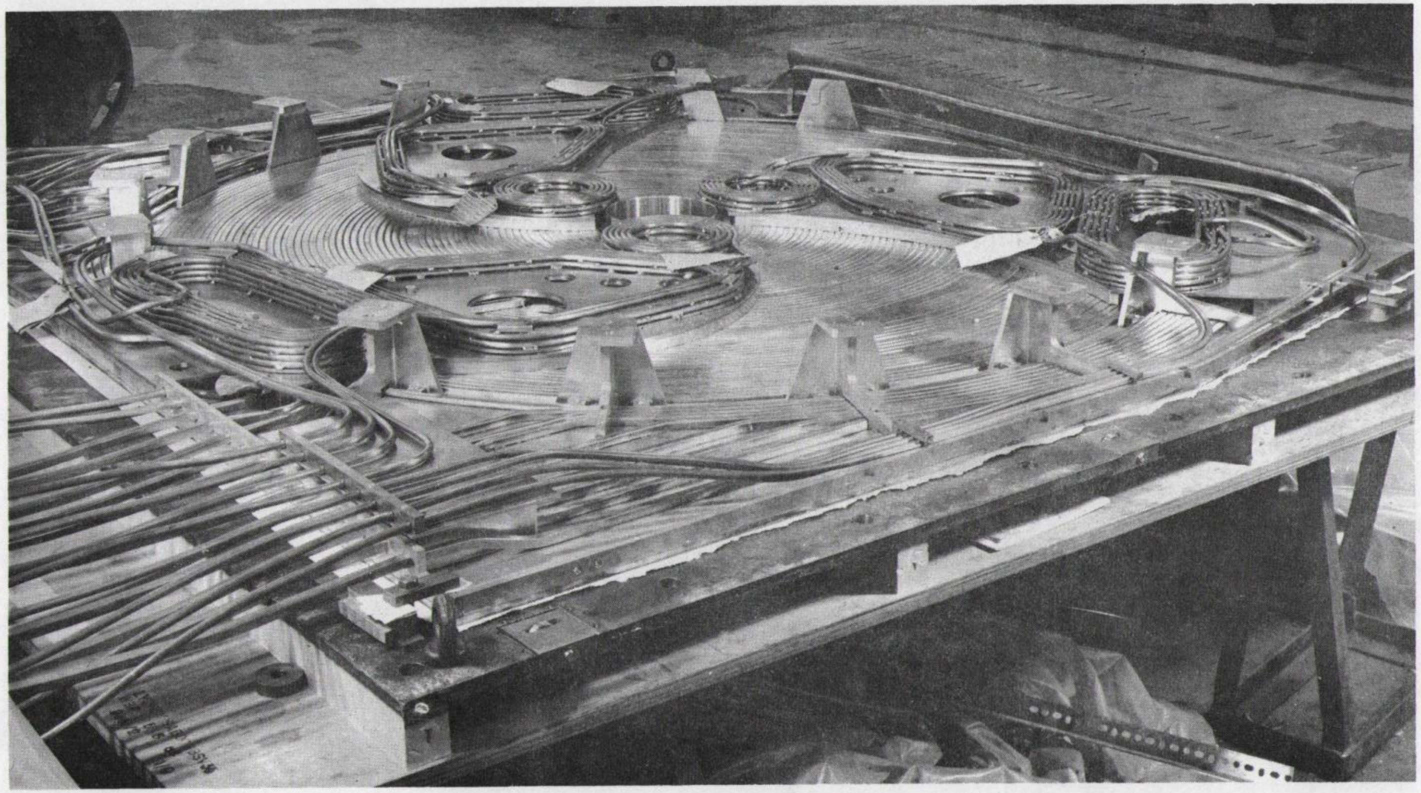


Fig. 6. Completed trim coil assembly.

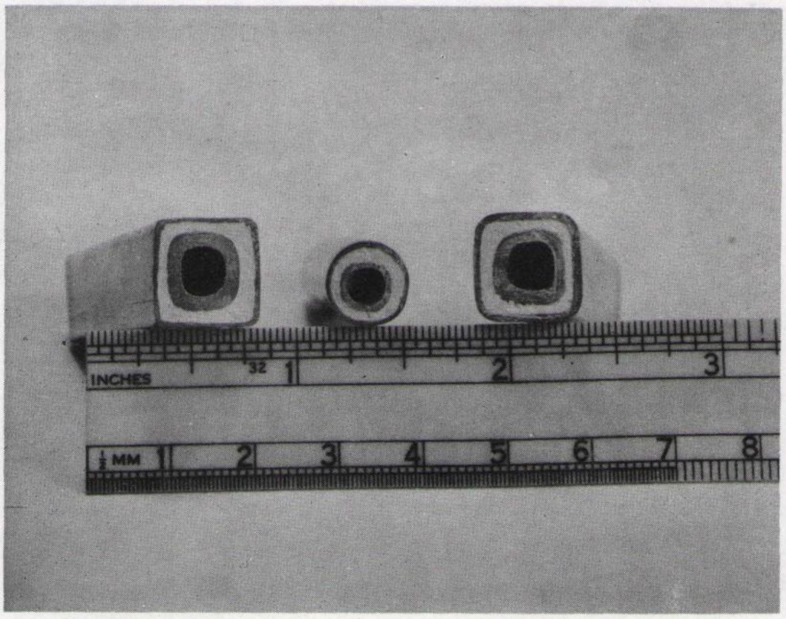


Fig. 7. Photograph of conductors used in the trim coil assembly. (These specimens, taken from conductor ends, show rather irregular inners; the field errors introduced however are negligible).

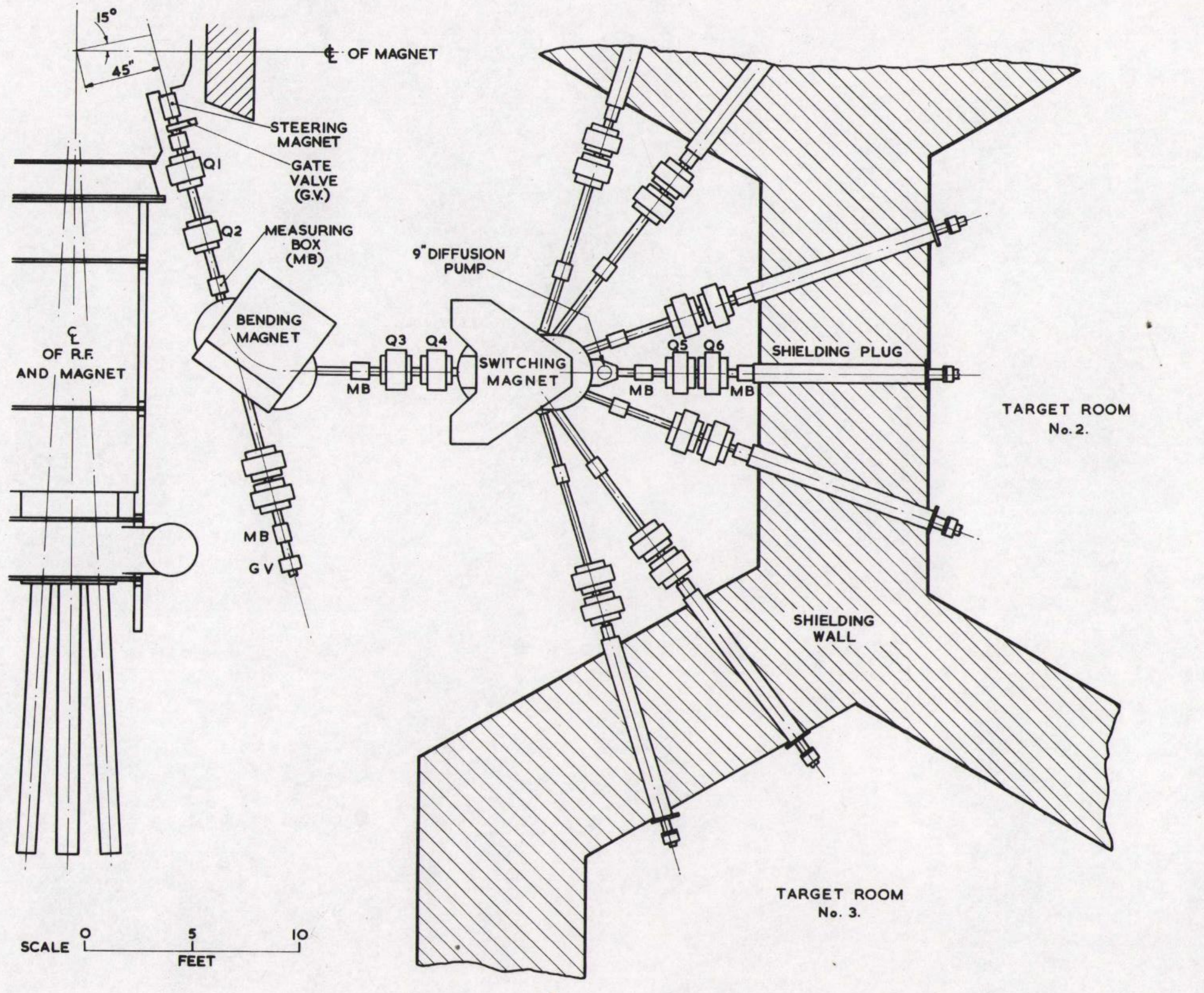


FIG. 8 THE BEAM TRANSPORT SYSTEM.