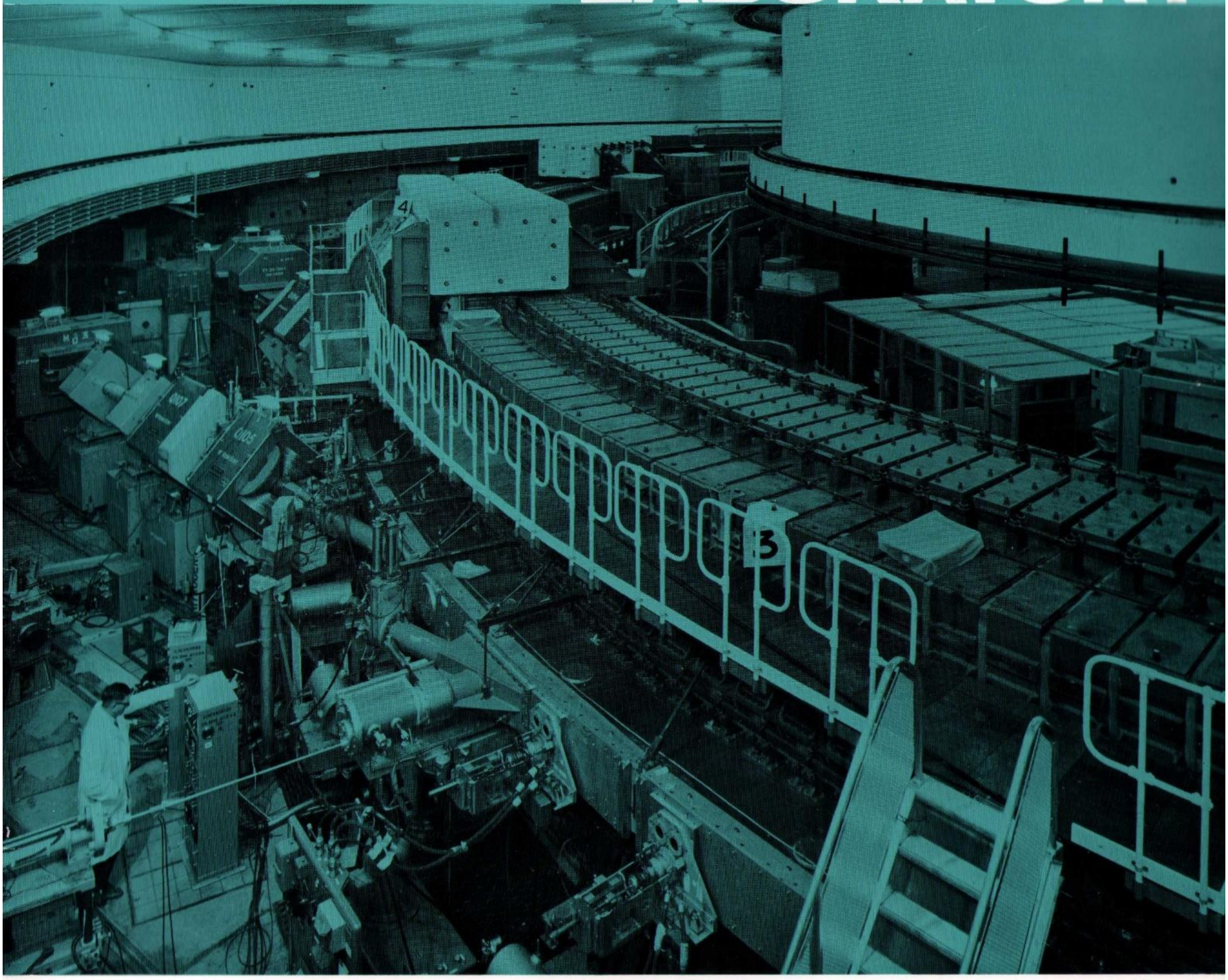
Science Research Council

RUTHERFORD LABORATORY



NIMROD

7GeV Proton Synchrotron

INTRODUCTION

The Rutherford Laboratory was founded in 1957 as a national research centre for nuclear science. It was particularly intended for the development and operation of nuclear research equipment for use by universities, where the size complexity or cost of the equipment was beyond the resources of the universities themselves.

The first machine in this category to operate at the Laboratory was the 50 MeV Proton Linear Accelerator which commenced nuclear research in April 1960. The second was the 7 GeV Proton Synchrotron Nimrod which reached full energy in August 1963 and started its programme of high energy physics experiments in February 1964.

In April 1965, the Science Research Council was set up with wide responsibilities for research in the physical sciences in its own laboratories, at universities and in collaboration with international organisations. The Rutherford Laboratory and its sister establishment the Daresbury Nuclear Physics Laboratory were transferred to the Science Research Council. The Council is now responsible for the entire national effort in pure nuclear science, by its support of these two Laboratories, nuclear research in universities and also by participation in the European Organisation for Nuclear Research at Geneva.

160 physicists from universities, the Atomic Energy Research Establishment and from the Rutherford Laboratory itself, now base their research on Nimrod and the Proton Linear Accelerator.

The name NIMROD – ("A mighty one in the earth" – Genesis 10, 8-9) has been given to the 7 GeV proton synchrotron

Injector

Energy of protons entering Linear Accelerator	0·6 MeV
Energy of protons entering Synchrotron	15 MeV
Linac output current	5 – 20 mA
Linac operating frequency	115 Mc/s
Estimated pulsed R.F. power dissipated	700 KW
Overall length of linac tank	46 ft
Diameter of Linac tank	8 ft
Number of pumps Mercury	4

Magnet Power Supply

Number of Motor-alternator-flywheel sets	2
Alternator ratings nominal	60 MVA
Alternator ratings maximum	79 MVA
Alternator ratings thermal	46 MVA
Weight of rotors	60 tons
Weight of stators	72 tons
Motor rating	5100 h.p.
Motor speed	970 r.p.m.
Flywheel diameter	10 ft 6 in
Flywheel weight	24 tons
Stored energy in each flywheel at 1000 r.p.m.	250,000 h.p. sec
Speed reduction during pulse	4%

Magnet

Beam radius mean	77·5 ft
Normal peak magnetic field at injection	300 gauss
Peak magnetic field	14,000 gauss
Useful magnetic aperture	9 in vertical 36 in horizontal
Number of magnet sectors	336
Weight of each magnet sector	19 tons
Number of turns in coil	42
Weight of magnet coil total	350 tons
Pulse rise time	0·72 sec
Pulse decay time	0·8 sec
Repitition rate of magnet pulse	28 pulses/min
Normal peak current in coil	9150 amps
Stored energy in magnet at peak field	40 megajoules
Number of protons accelerated	2×10^{12} per pulse

R. F. System

R F frequency at injection energy	1·4 Mc/s
R F frequency at peak energy	8·2 Mc/s
Weight of ferrite	12,000 lbs
Weight of cavity	20 tons
Peak R.F. volts per gap	7 KV
R F power dissipation	14 KW
Ferrite working temperature	25°C
D C bias winding ampere turns	7000

Vacuum System

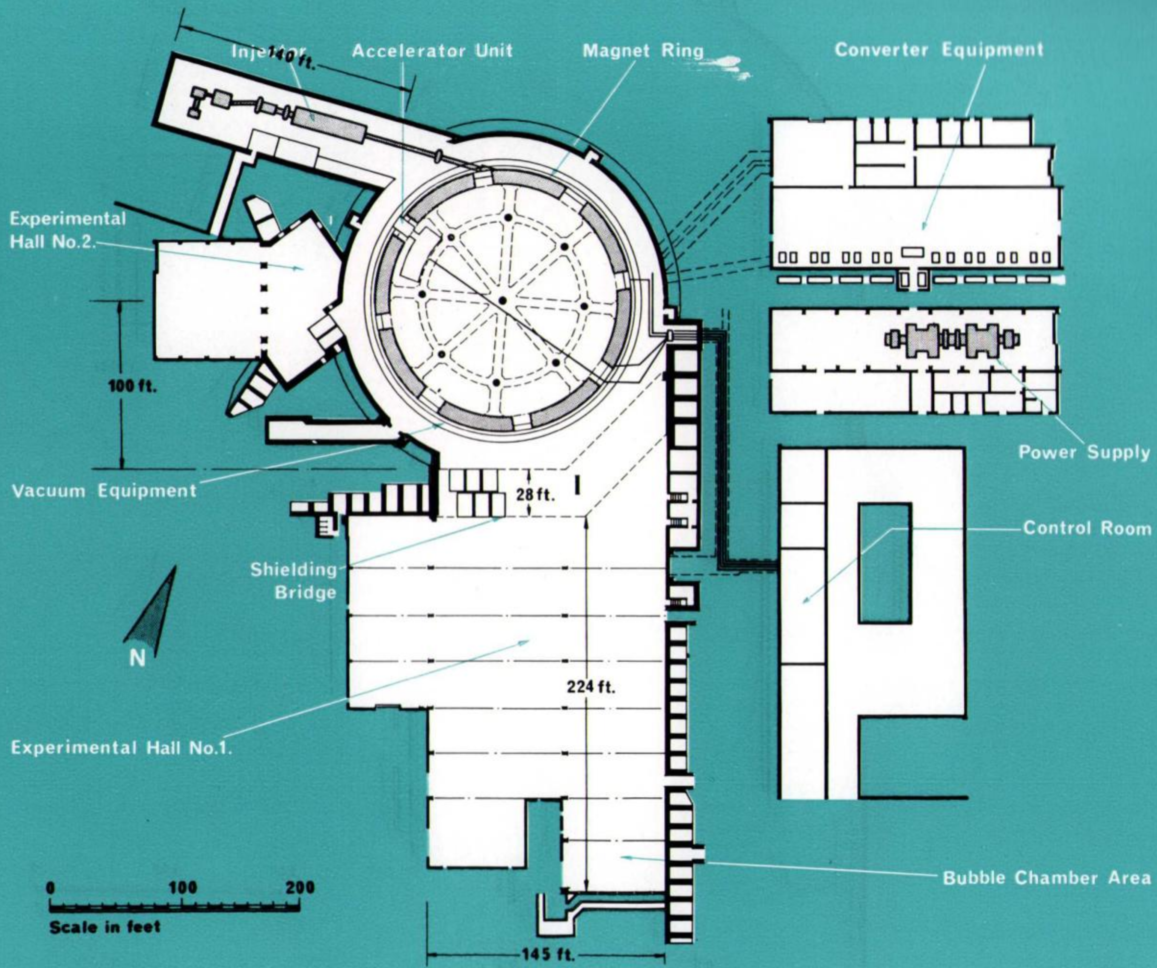
Beam aperture	$9\frac{1}{2}$ inches
Pressure in inner vessel	10^{-6} torr
Pressure in outer vessel	1 torr
Pumping volume of inner vessel	3500 cu ft
Number of pump units for inner vessel	40
Pump type	24 in oil diffusion
Vacuum vessel material	Epoxy glass laminate
Overall peak speed of diffusion pumps	200,000 litres/sec (approx)

General Parameters

Diameter of magnet building	200 ft
Weight of concrete in building	approx 100,000 tons
Radiation shielding wall thickness	30 ft of concrete (equivalent)
Roof thickness	16 ft of concrete (equivalent)
Distance travelled by particles during acceleration	100,000 miles

Crane Details

Injector room	8 tons	2
Magnet hall	5 tons	2
Magnet hall	30 tons	1
Experimental hall no.1	30 tons	2
Experimental hall no.2	20 tons	1
Alternator house	80 tons	1
Converter house	10 tons	1

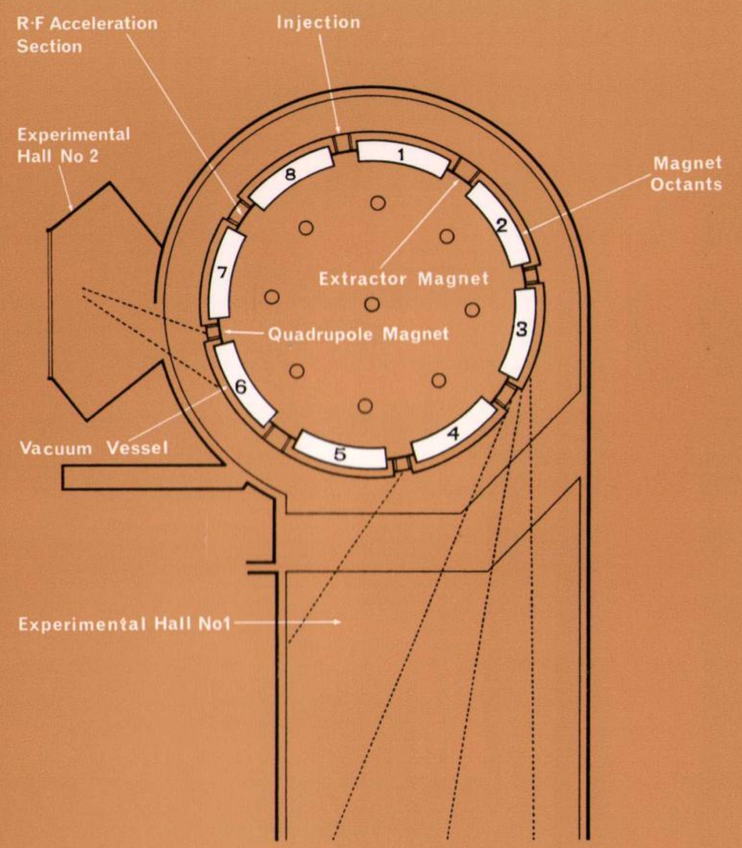


Nimrod Parameters

The main physical feature of NIMROD is a large ring-shaped electromagnét, 160 ft. in diameter, which weighs 7000 tons. A toroidal shaped evacuated chamber made from glass-fibre reinforced epoxy resin is situated between the poles of this magnet. A pulse of protons, given an initial acceleration to 15 MeV in a linear accelerator, is injected into this chamber and the protons are forced by the magnetic field into a circular orbit in which they receive an acceleration from a radio-frequency electric field once in each revolution. After approximately a million revolutions the protons reach their maximum energy; they are then either extracted from the vacuum chamber or allowed to bombard internal targets, the resulting secondary particles being channelled into an adjoining area where they are used for experiments. During the acceleration period, lasting about three-quarters of a second, the magnetic field strength and the frequency of the electric accelerating field have both to be increased steadily to confine the proton orbits to the magnet ring, and in such a manner as to maintain the delicately balanced stability in the motion of the protons. The whole machine is housed in a semi-underground circular building of reinforced concrete 200 ft. in diameter with a 16 ft. concrete roof on which a 20 ft. layer of earth is placed as additional radiation shielding.

Heavy currents up to 10,000 A with an applied voltage up to 15 kV are needed to energise the electromagnet during the short acceleration time. The power supply used consists of a motor-alternator set, incorporating flywheels connected to the magnet through a bank of rectifiers. This equipment supplies direct current of gradually increasing strength during the 0·72 sec acceleration period, and the current decays again to zero in a further 0·8 sec, ready for the next pulse. Energy is thus stored in the magnet during the current-rise period and is subsequently returned to the fly-wheels as the current is reduced again to zero. The amount of energy being shuttled to and fro amounts to some 40 megajoules. In this way, the flywheels act as a buffer between the load (the magnet windings) and the electrical supply.

The machine is designed to produce at least 10^{12} protons per pulse at a repetition rate of 28 pulses a minute. NIMROD is used for fundamental research into the physics of elementary particles.



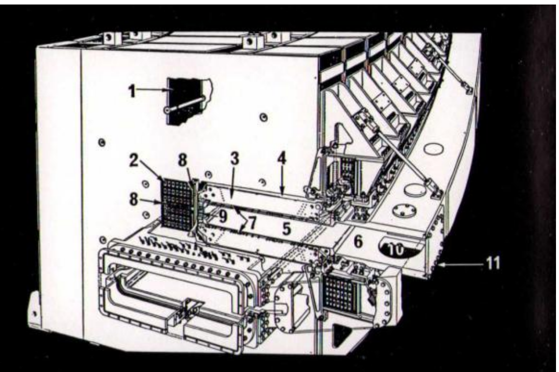
Magnet

The magnet comprises eight octants separated by straight field free spaces which accommodate the R.F. accelerating cavity, and various machine components. Each octant comprises 42 sectors the whole 336 sectors weighing 7,000 tons.

The 12½ in. thickness of a sector is made up from about 46 plates of 1 per cent silicon steel. The plates are annealed and flattened, cleaned and coated with insulation. The sector is held together by bolts and some edge welding. Finally the C-gap is machined to the final dimension.

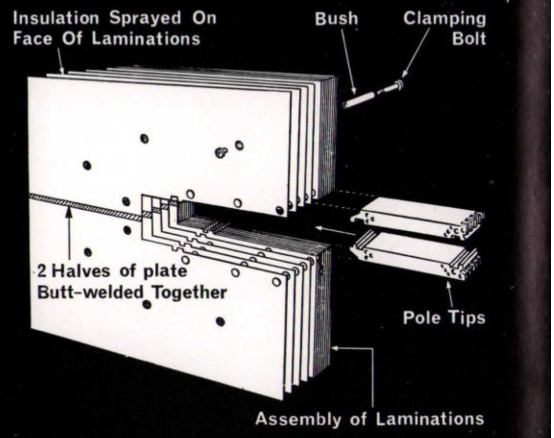
Each pole piece weighs 800 lb. and consists of a stack of about 450 steel laminations 0·020-0·030 in. thick. These accurately formed laminations are glued together with an epoxy resin – glass cloth adhesive to accurate finished dimensions. The pole pieces are produced in matched pairs to preserve magnetic symmetry.

Each magnet octant has its own 42 turn winding fabricated from 50 ft. lengths of extruded copper of section 1·375 x 2·625 in. The conductors are cooled by demineralised water pumped through a 0·2 sq in. hole in the centre. The windings of the octants are all connected in series and carry a peak current of 9,150 amps. The total power dissipation is 3 MW at the normal repetition rate of the machine. The weight of copper in the coils is about 350 tons.

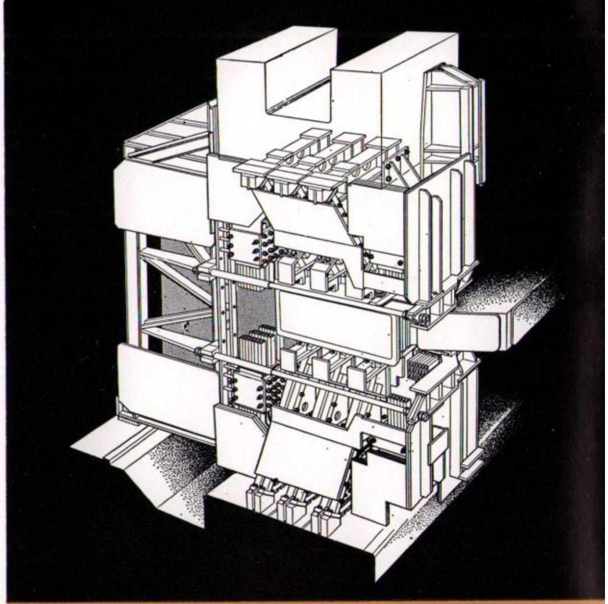


1 Magnet Sector
2 Magnet Coils
3 Pole Tips
4 Outer Vacuum Chamber
5 Inner Vacuum Chamber
6 Header Chamber
7 Pole Face Windings
8 Pressure Pads
9 Pole Tip Jacks
10 Main Pumping Port
11 Beam Exit Window

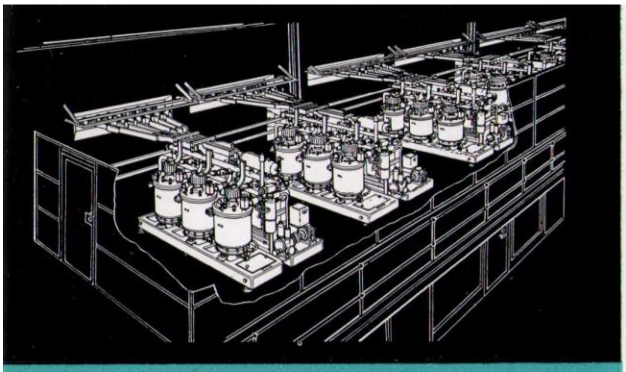
CROSS SECTION THROUGH 7 GEV MAGNET OCTANT



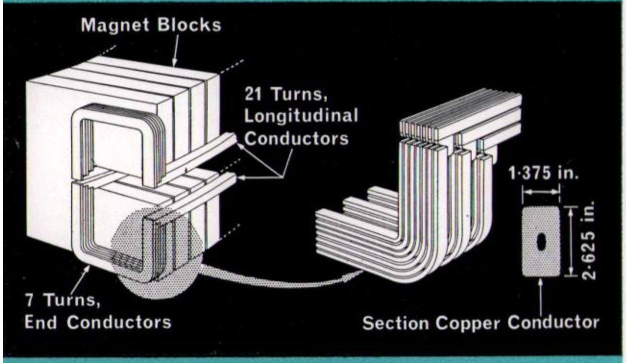
7 GEV MAGNET SECTOR ASSEMBLY



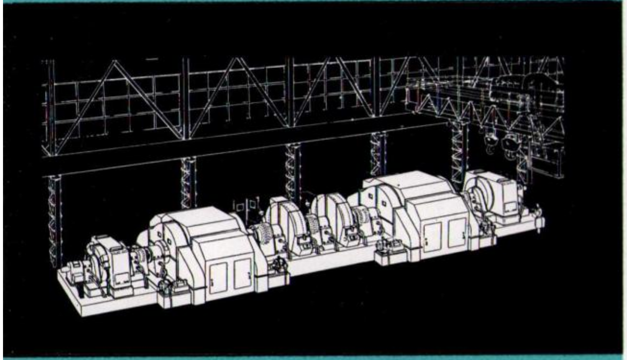
OCTANT END STRUCTURES



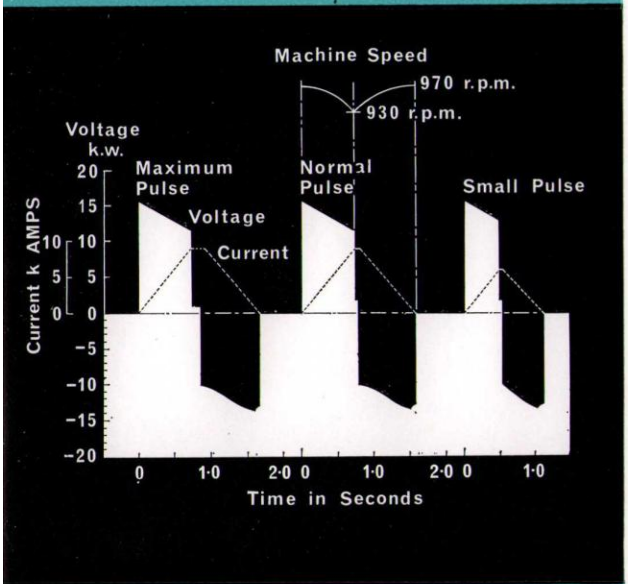
RECTIFIER INSTALLATION



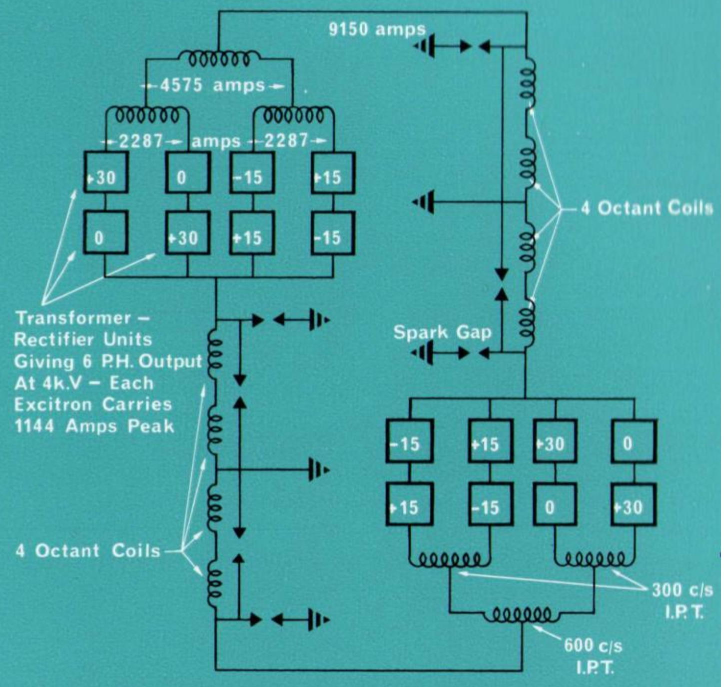
COIL LOCATION ON MAGNET BLOCKS



MOTOR ALTERNATOR SET



PULSE SHAPES, MAGNET POWER PLANT



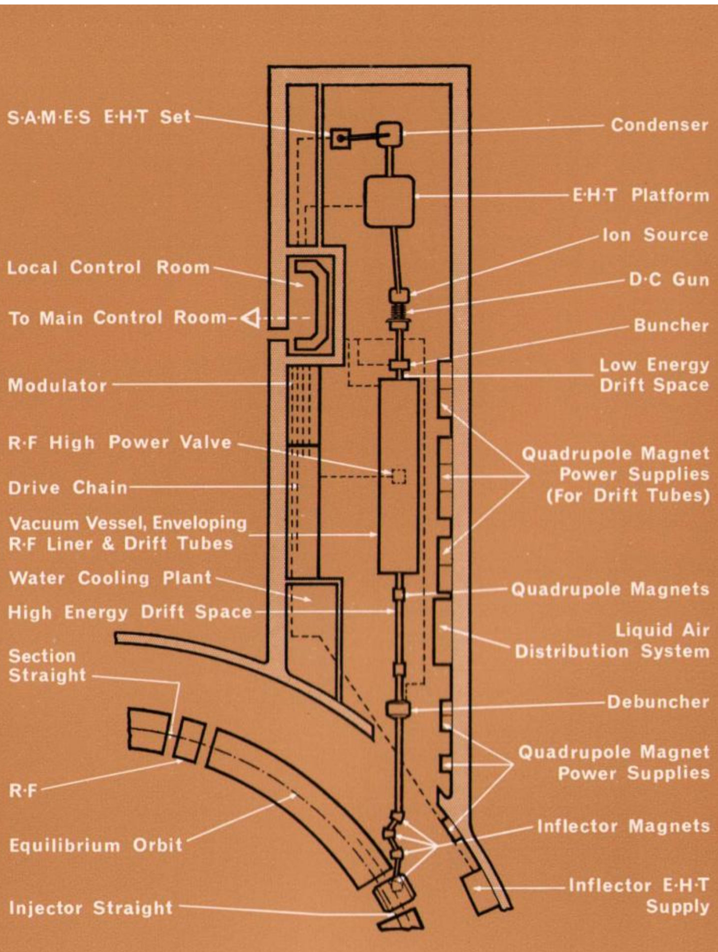
Magnet Power Supplies

The magnet coil demands large pulses of direct current which is generated by an A.C. induction motor driven flywheel-alternator set giving direct current through grid controlled rectifiers.

The plant comprises two 5,100 h.p. 50 c/s 1000 r.p.m. slipring induction motors with rotor resistance control for starting, driving two flywheels and two 60 MW salient pole alternators on a common shaft.

The alternators feed the large electromagnet via phase multiplying transformers and 96 single anode grid controlled mercury arc rectifiers to give pulses up to 10,525 amps at 15·5 kV D.C., the total peak output of the alternators being 180 MVA, the energy supplied mainly from the flywheels with rise time of 0·8 seconds. During the decay period the rectifier groups are inverted and the magnet energy is restored to the flywheels via the alternators which act as motors.

The foundation problem is relieved by supporting the massive reinforced concrete machine block on steel springs.



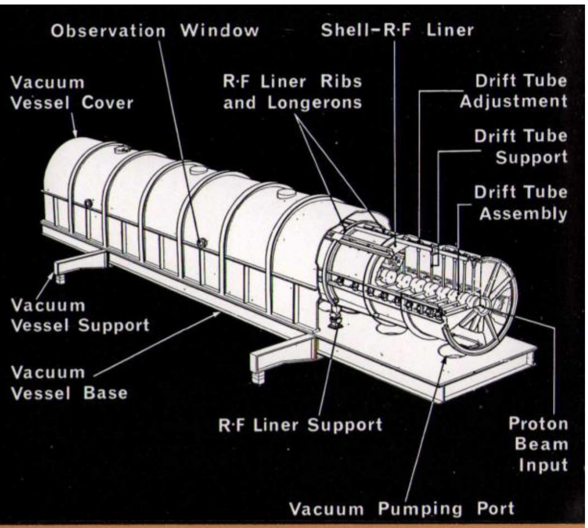
Injector

The injector is a 15 million electron volt (15 MeV) linear accelerator, designed to provide a high intensity beam of protons for injection into the 7 GeV (7,000 MeV) synchrotron.

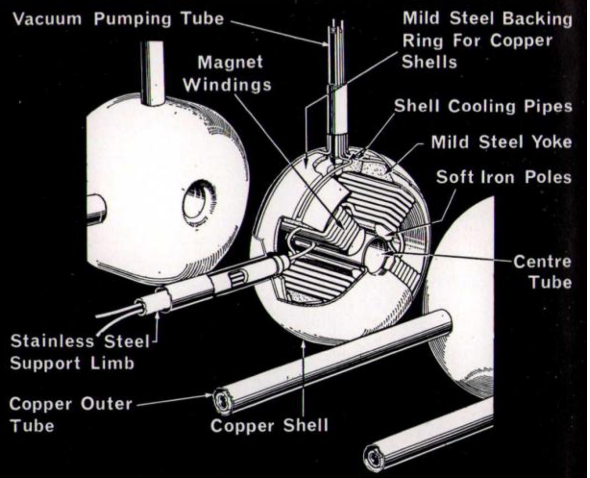
The origin of the proton beam is the ion source, where hydrogen gas at low pressure is ionised in a discharge induced by a Radio Frequency field. Pulses of protons are then extracted and accelerated to an energy of 0·6 MeV. This comprises the ION GUN or PRE-INJECTOR.

The beam next enters the LINEAR ACCELERATOR which is essentially a highly evacuated, cylindrical copper cavity, 44 ft. long by 5 ft. 6 in. dia. This cavity is resonated by a 115 Mc/s R.F. source, producing an alternating axial electrical field. The protons passing along the axis of the cylinder are shielded from the decelerating parts of this field by a series of DRIFT TUBES. Each drift tube contains a four-pole focussing magnet to prevent loss of proton beam by excessive expansion during acceleration. Since pulses of up to 0·002 seconds long at intervals of about two seconds are required by the synchrotron, the accelerating cavity is pulsed by about one Megawatt of R.F. power when required.

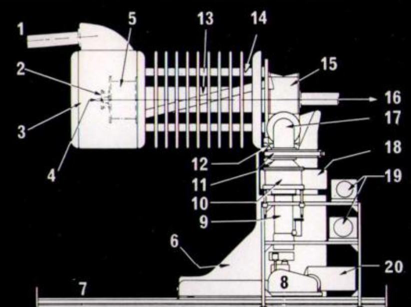
The 15 MeV proton beam is introduced into the main magnet ring by means of a 25° deflection system, consisting of four bending magnets followed by an electrostatic deflector.



LINEAR ACCELERATOR

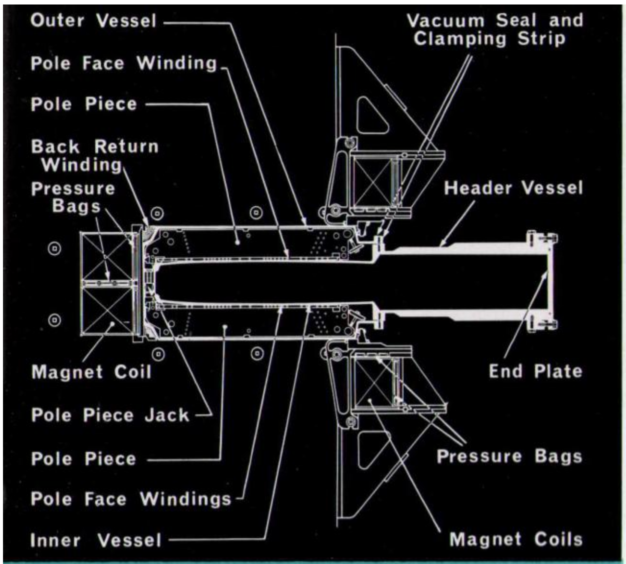


DRIFT TUBE

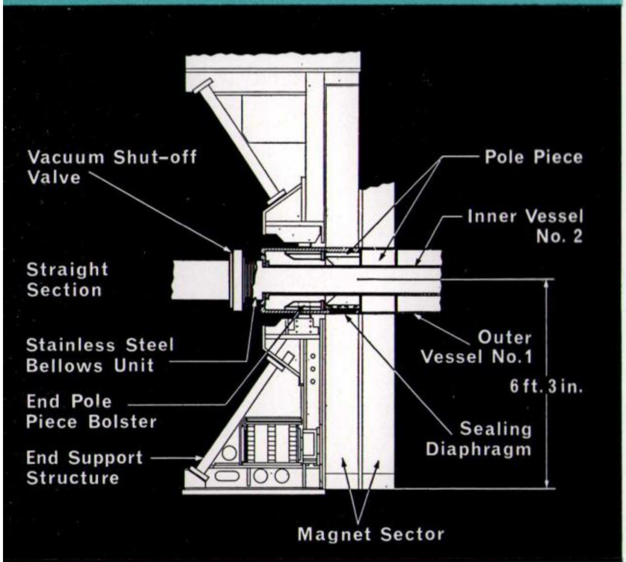


1 Tube From E·H·T Platform Carrying Electric Cable & Hydrogen Supply Pipe
2 Ion Source
3 Bun Casing
4 Hydrogen Inlet Into Ion Source
5 Focusing System
6 Light Alloy Fairings
7 Support Stand Rails
8 Backing Pump
9 Diffusion Pump
10 Cold Trap
11 Shut–Off Valve
12 Elevating Screw
13 Accelerating Column
14 Fibre Glass Tie Rods
15 Vacuum Manifold
16 Beam Path
17 Vacuum Elbow
18 Support Stand
19 Refrigerators
20 Compressed Air Cylinder

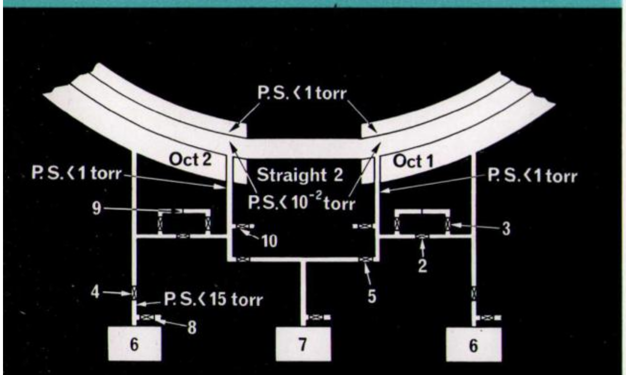
D. C. GUN SUPPORT STAND & VACUUM EQUIPMENT



VACUUM VESSEL & SUPPORT SYSTEM

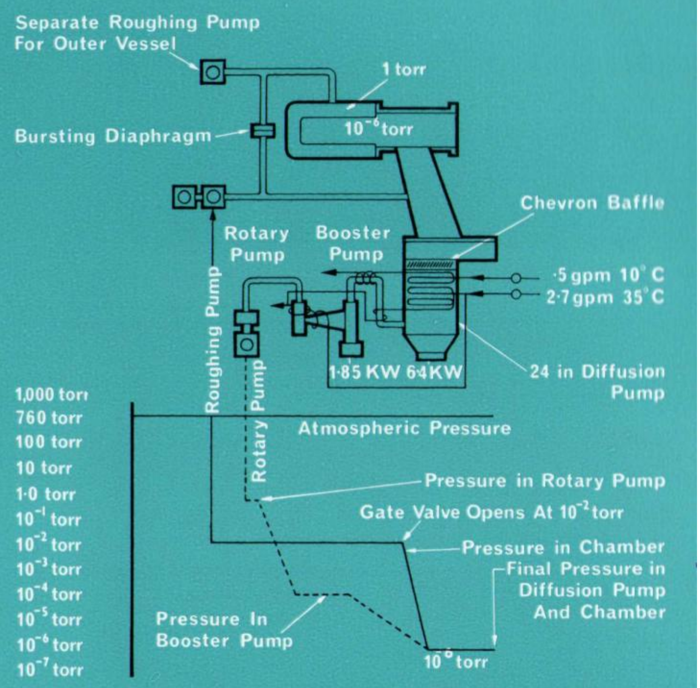


OCTANT END STRUCTURE



1 PS – Pressure Switch
2 Equalising Valve
3 Lockable Manual Valve
4 Outer Roughing Valve
5 Inner Roughing Valve
6 Outer Roughing Pump
7 Inner Roughing Pump
8 Vent Valve
9 Bursting Disc
10 Air Admittance Valve

LAYOUT OF ROUGHING SYSTEM

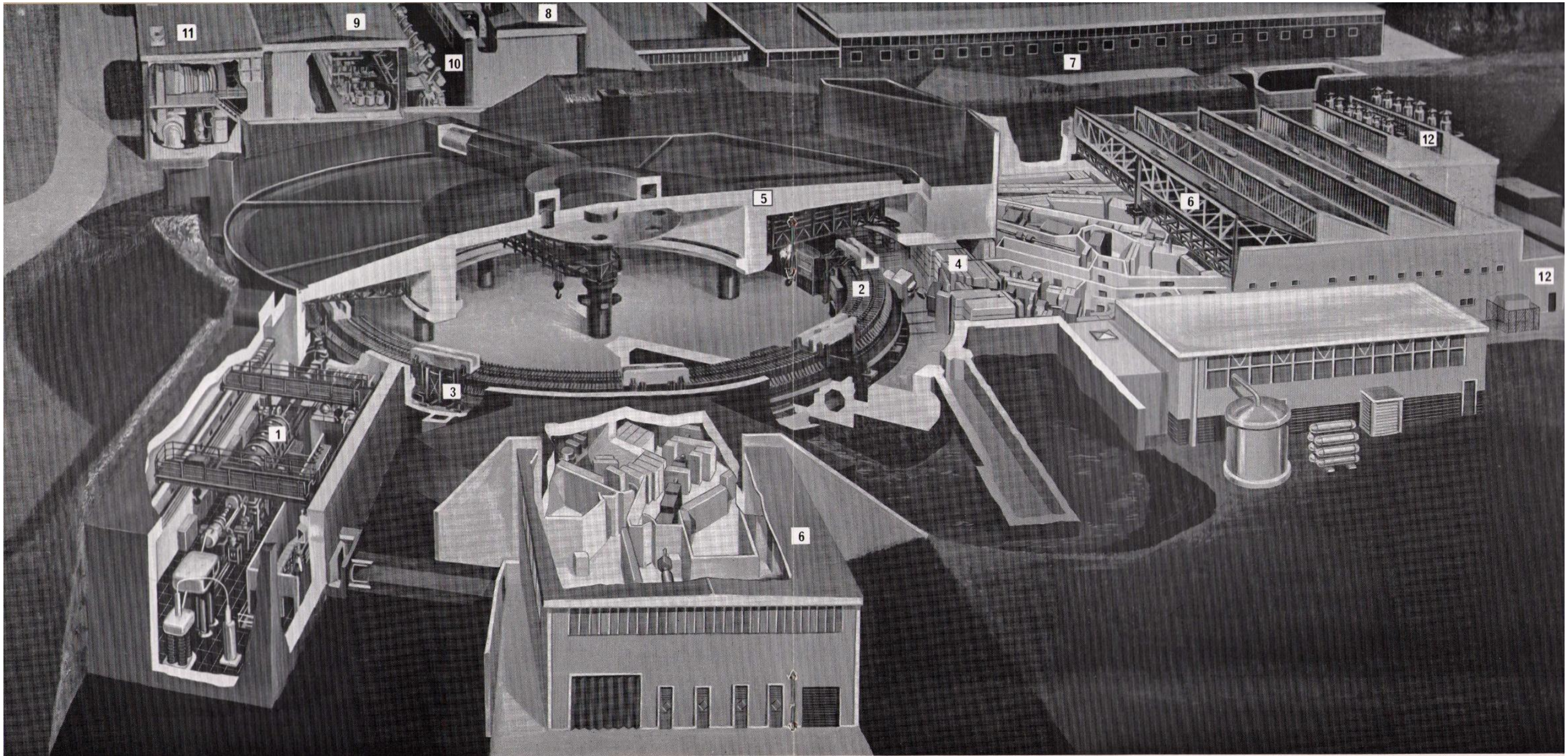


Vacuum System

The vacuum chamber comprises eight double walled vessels of glass reinforced epoxy resin each the whole length of an octant. An outer vessel with thin walls is sandwiched between the poles and yoke of each magnet octant. An inner vessel of similar length is placed within the octant gap and evacuated to 10^{-6} torr, while the space between the two vessels is evacuated to about 10^{-2} torr. Thus the magnet structure supports practically all the atmospheric load and the inner high vacuum vessel has only a small differential pressure to withstand.

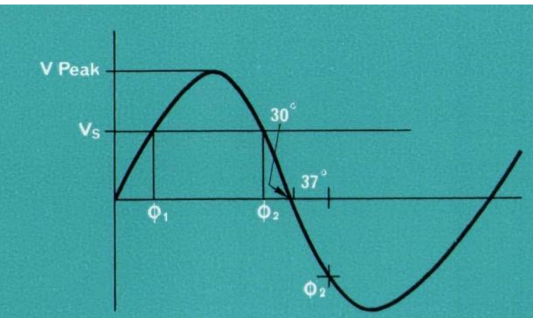
The inner vessels are evacuated by a total of forty 24 in. diameter oil diffusion pumps which exhaust the vessel via a substantial header chamber of similar construction to the main vessels.

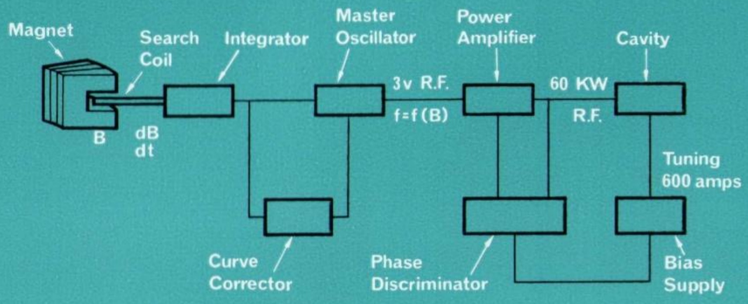
The gaps between octants are bridged by single walled vessels, incorporating expansion bellows and shut-off valves, allowing a clear high vacuum path measuring at least 9½ in. vertically and 36 in. radially, round the ring in which the protons can travel.

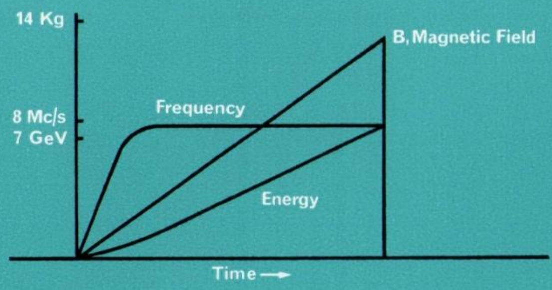


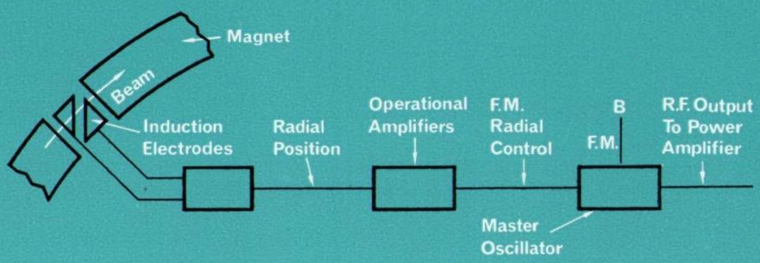
7 GeV PROTON SYNCHROTRON

1. **Injector.** This unit gives an initial acceleration to the protons up to an energy of 15 MeV.
2. **Electro-magnet.** The large magnet guides and focuses the protons in an orbit of constant radius.
3. **R.F. System.** The radio-frequency accelerating unit gives the protons a peak 7 KV kick on each orbit.
4. **Shielding Wall.** This is made of steel and concrete giving radiation protection to the Experimental Halls.
5. **Shielding.** The synchrotron is enclosed in a shield of concrete with additional earth shielding on the roof and around the sides.
6. **Experimental Halls.** Beams of protons are admitted to the Halls through 'beam lines'.
7. **Control Room.** Contains all the instruments controlling the operation of NIMROD.
8. **Alternator House.** The rotating plant comprises two 60 MVA, 1,000 rev/min alternators and two 24 ton flywheels driven by two 5,100 h.p. induction motors.
9. **Converter House.** Contains the 96 water cooled single anode, grid controlled mercury arc converters.
10. **Transformer Yard.** Eight 12 MVA phase splitting transformers.
11. **Plant Room.** Contains the air-conditioning plant for the Magnet Room.
12. **Bubble Chambers.** Chambers containing liquid hydrogen or heavy liquids used for the study of collisions between elementary particles.



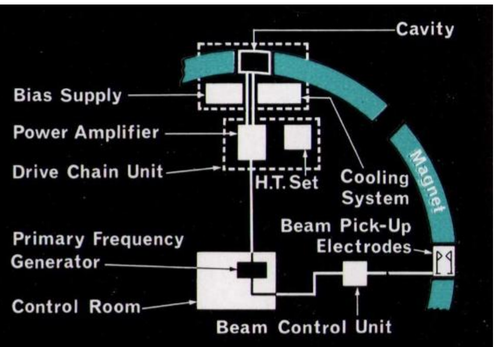




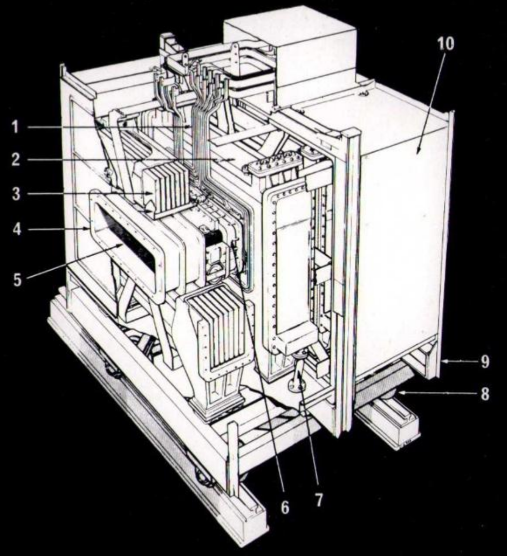


Accelerator System

THE ACCELERATING SYSTEM comprises a primary frequency generator, a bias supply, a beam control unit and an accelerator unit. The accelerator unit is designed as part of the main vacuum system the flanges of the vacuum vessel located within the R.F. unit actually acting as electrodes for beam accelerating purposes. The cavity is excited by a variable frequency oscillator whose frequency must vary from 1·4 to 8 Mc/s between beam injection and extraction. The peak voltage across each insulator rises to 7 kV. The frequency control of the cavity is obtained by magnetically biasing the ferrite cores by a direct current which changes the incremental inductance of the circuit. These cores are of a picture frame type and are produced by bonding sintered blocks with an epoxy resin cement. Some 12,000 lb of ferrite is used.

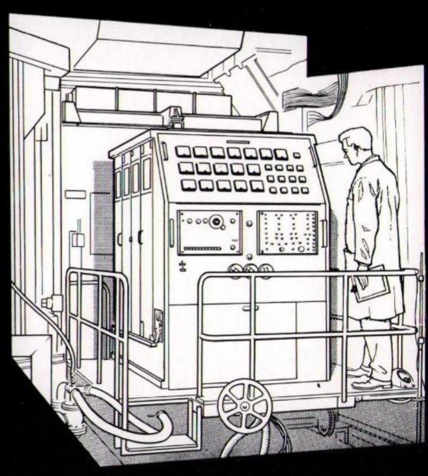


DIAGRAMMATIC LAYOUT OF ACCELERATING UNIT

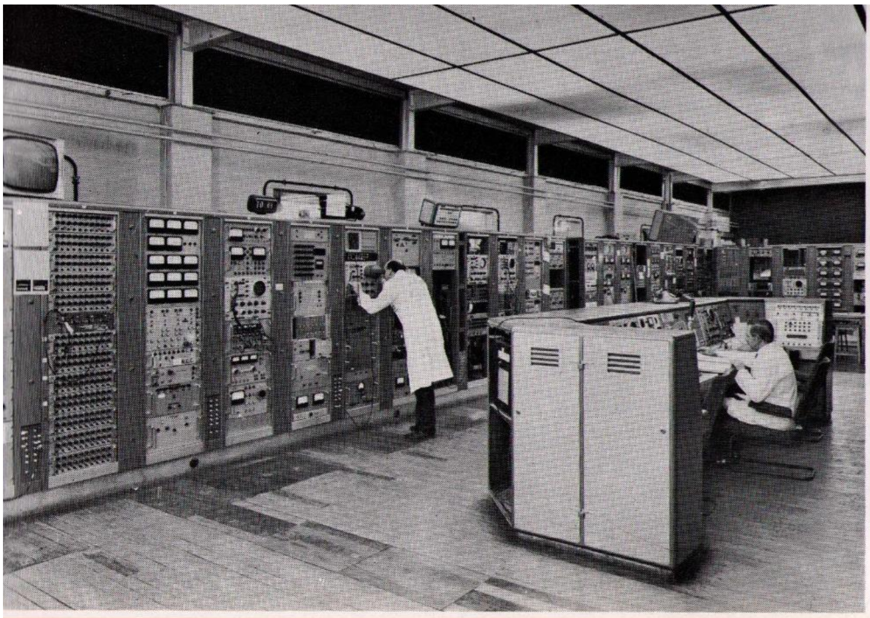


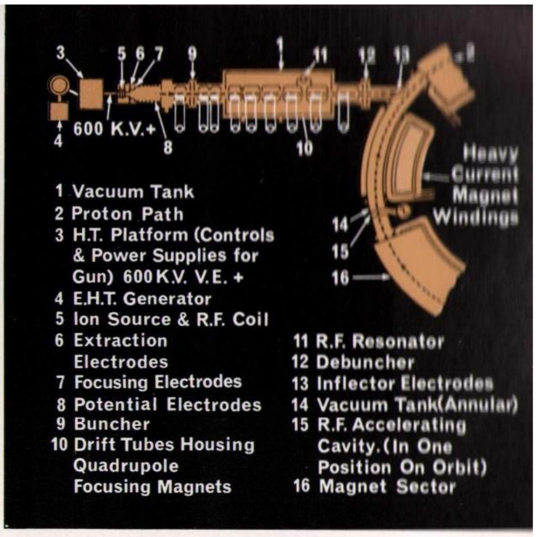
1 Windings
2 Cooling Jackets
3 Ferrite Frames
4 Vacuum Vessel
5 Proton Beam Path
6 Insulator (One of Two)
7 Coolant Oil Inlet
8 Trolley
9 Base Unit
10 Cavity Shell

R.F. CAVITY



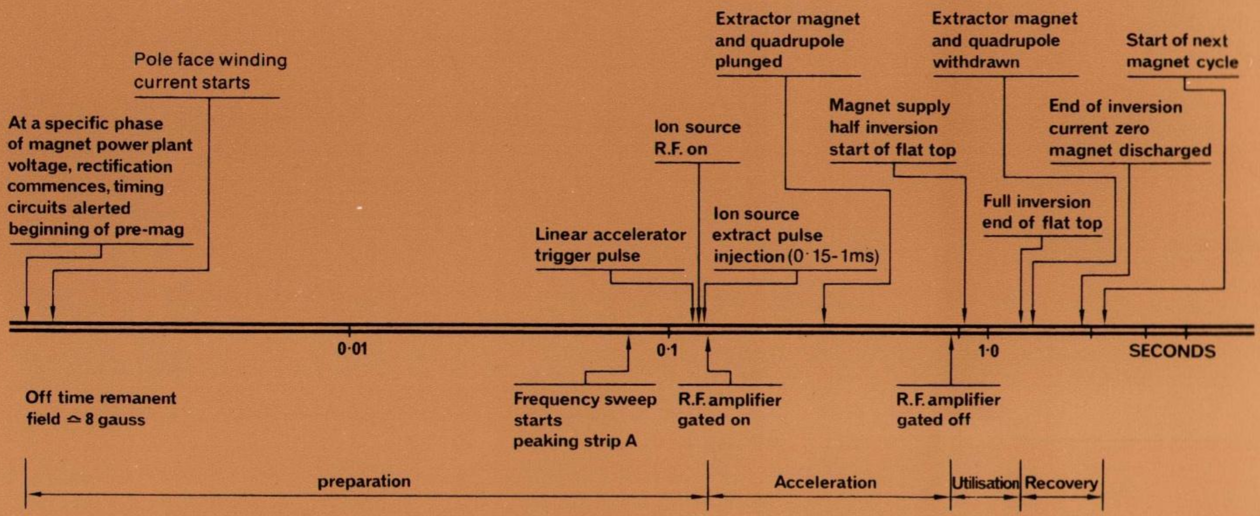
SYNCHROTRON R.F. TRANSMITTER





OUTLINE OF OPERATION

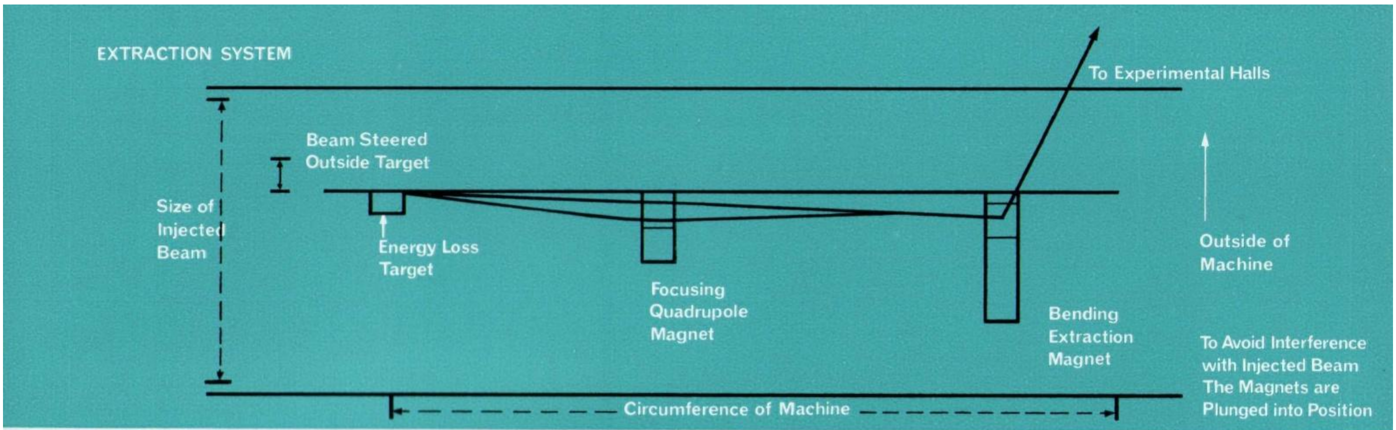
MAIN CONTROL ROOM

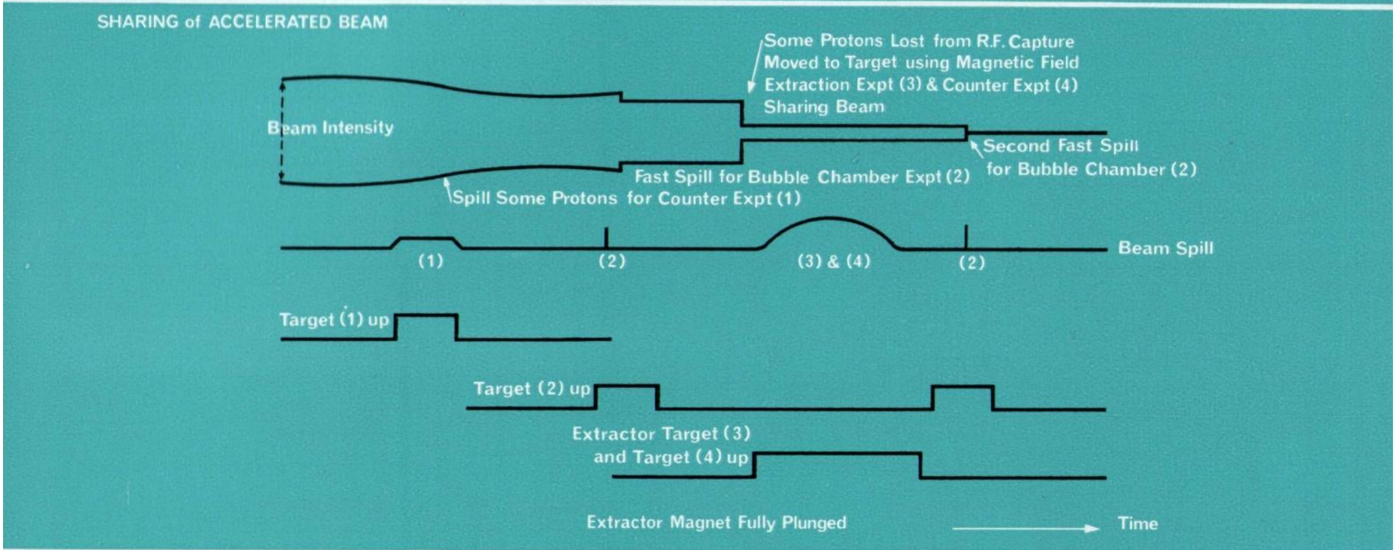


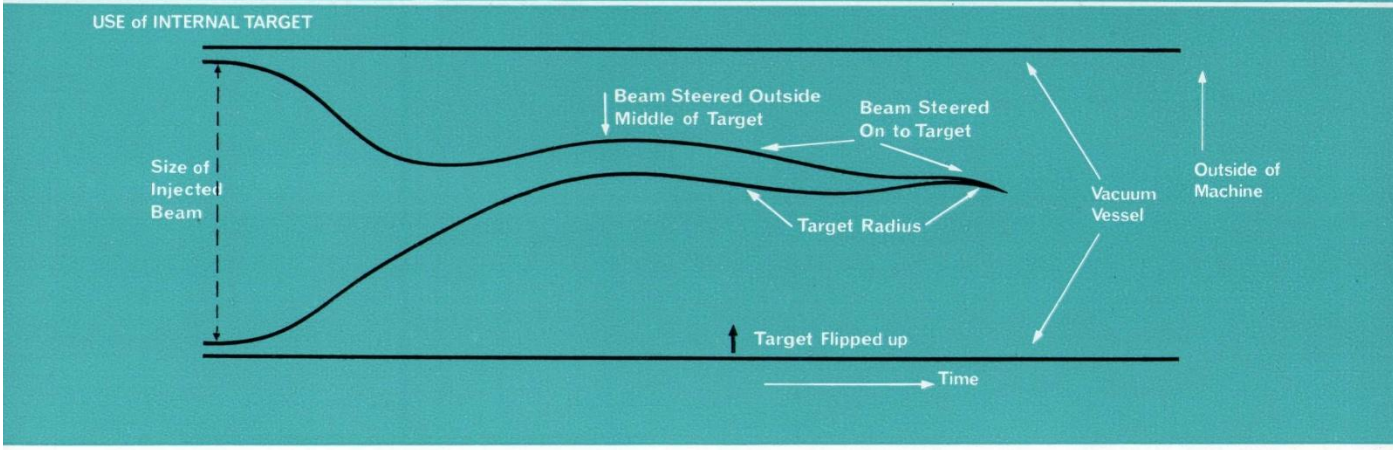
Control System

THE CONTROL SYSTEM of the proton synchrotron has the duty of maintaining at the preselected value during successive pulses, all critical variables associated with the equipment. It must also maintain the proper sequence of events and ensure the correct relative values of the variables during a pulse as acceleration takes place and be capable of extension to experimental apparatus.

The control room accommodates all the important instruments relative to the operation of the plant and the control and protection of personnel. The complete plant has been interlocked in the interests of general and radiological safety and strict control is maintained over traffic of personnel into areas of excessive radiation.

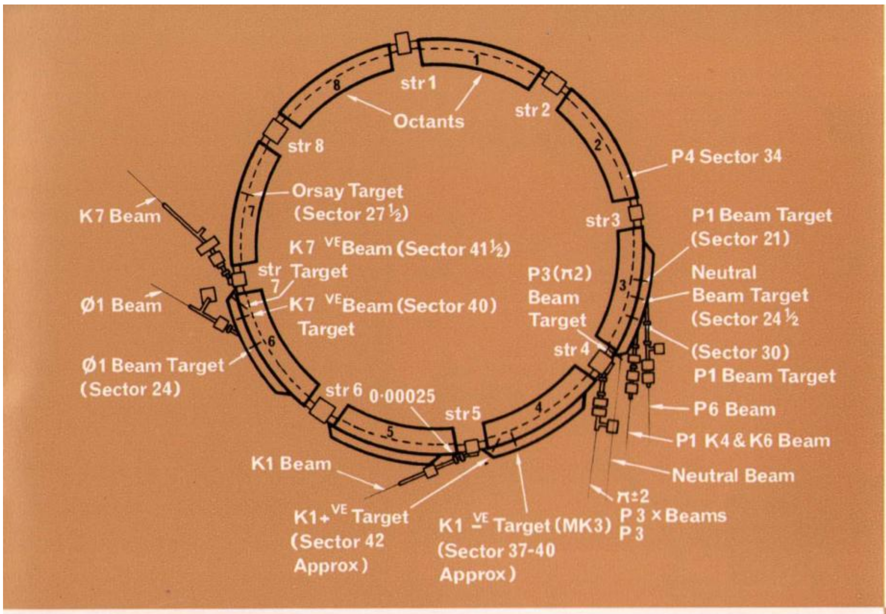






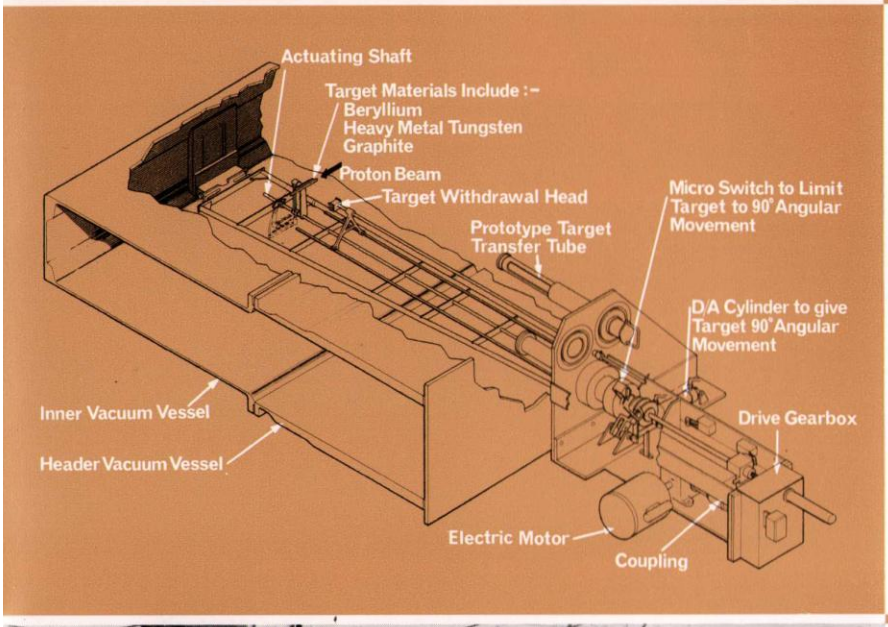
Utilisation of Accelerated Beam

After acceleration the protons are made to collide with a 'target' to produce the elementary particles required. One method is to steer the internal beam of protons on to a solid target inside the vacuum vessel using a magnetic field or the radio-frequency system. Alternatively some of the protons may be extracted from the machine and focused on to a target in the experimental area. The time taken to 'spill' on to the target is very important. For bubble chambers a spill lasting only 0·5 milliseconds is necessary; for experiments using counter techniques, uniform spills lasting several tenths of a second are required. To make full use of the capabilities of Nimrod, the accelerated protons are shared among several experiments during each Nimrod cycle.



Target and Beam outlets

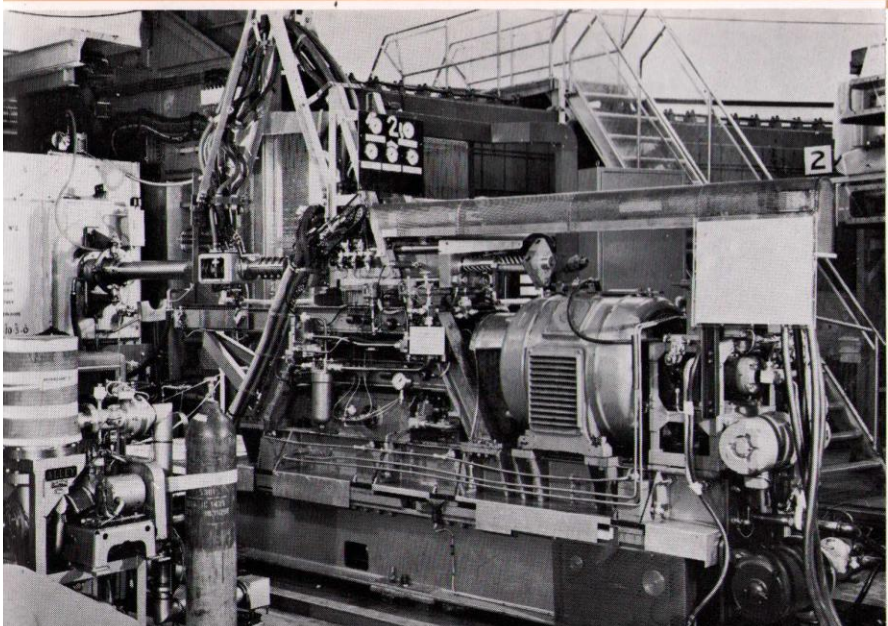
A small beryllium target is raised so that the beam strikes it. When the accelerated protons pass through matter they undergo interactions resulting in the production of 'secondary particles'. These may be of any of the elementary particles which the protons are energetic enough to produce. Those which are travelling at a favourable angle come out of the synchrotron down a beam pipe to be focused on experimental apparatus.



Target Mechanisms

The mechanisms are located in the main magnet field and are therefore made of non-magnetic materials. Their construction must not allow eddy currents to develop.

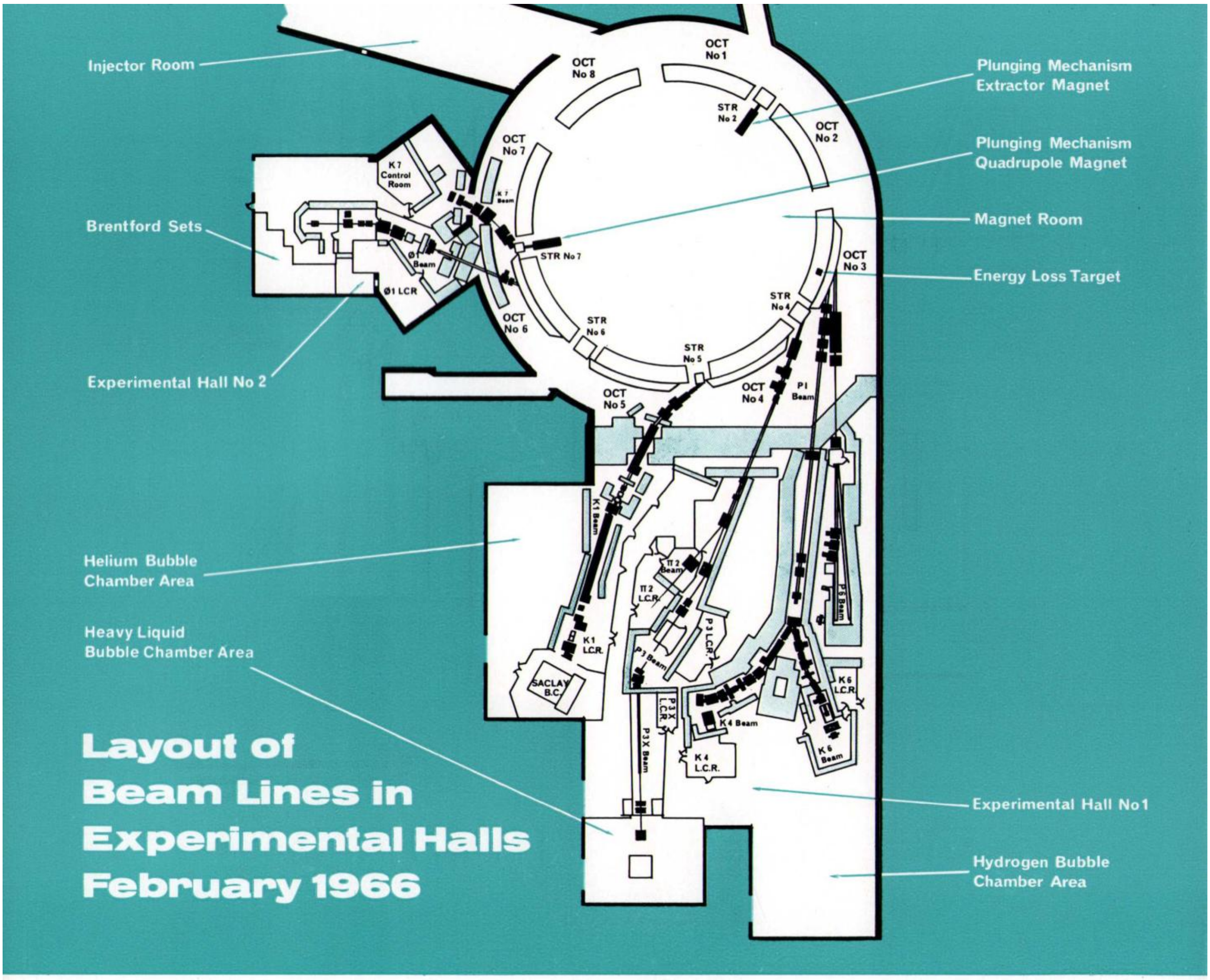
The target is mounted on the end of a small arm which can be rotated through a right angle. The actuating device is located outside the vacuum vessel.



Plunging Mechanism

The synchrotron proton beam is accelerated in a closed orbit and must be deflected magnetically out of its orbit. This is achieved by arranging for a target to spiral the beam into a quadrupole focusing magnet and thence into an extraction magnet, which deflects the beam outwards. To accomplish this without cutting off a major portion of the proton beam, these magnets must move in sympathy with the leading edge of the beam.

The quadrupole magnet weighs about 3 cwt. and the extraction magnet about 1 ton and they both move radially outwards into the beam orbit a distance of 20 inches.



Layout of Beam Lines in Experimental Halls February 1966

High Energy Physics using Nimrod

There are two types of interaction which are of prime concern in high energy physics, the so-called STRONG force which operates between nuclear particles and is responsible for the binding together of protons and neutrons to form atomic nuclei, and the so-called WEAK force which governs the decay processes.

Most of the nuclear particles have very short life-times (typically $\sim 10^{-8} - 10^{-10}$ seconds), and can only be created by bombarding atomic nuclei with protons which have been accelerated to very high energies. The secondary particles produced such as the π and κ mesons can be selected, formed into beams and transported to the Experimental Areas by complex systems of bending and quadrupole focusing magnets, known as 'beam lines'. These radiate out from Nimrod as shown and wherever possible are individually shielded with iron and concrete blocks to reduce the hazard from radiation.

Most of the experiments on the present programme are studying aspects of the STRONG INTERACTION. The protons used are in the form of liquid hydrogen targets on to which the beams of pions or kaons are focused. The momentum and direction of the incoming beam particles and the numbers, momenta and directions of the resultant particles must all be measured. Many techniques are used to detect the particles. These fall broadly into three categories although, in practice, they are often combined.

1. Scintillation Counters
2. Visual and Sonic Spark Chambers
3. Bubble Chambers

In each experiment the results of many hundreds of thousands of interactions are usually recorded on paper tape, magnetic tape or film, and later analysed.

Experiments on Nimrod are carried out by collaborations involving groups from eleven Universities and three Research Establishments. The tables on the right show the teams who were participating in the experimental programme in February, 1966; and the numbers of physicists, research students and support staff directly involved. These figures do not show the large numbers of support staff who, although not members of experimental teams, contribute in many ways to the success of these experiments.

Table 1

Teams participating in Experimental Programme, February, 1966

a. A.E.R.E. (Harwell)/R.H.E.L./Oxford University
b. A.E.R.E./Southampton University/University College, London/R.H.E.L.
c. Birmingham University/Cambridge University/R.H.E.L.
d. Birmingham University/École Polytechnique/Glasgow University/Imperial College/R.H.E.L./Saclay (France) (Hydrogen Bubble Chambers)
e. Bristol University
f. Imperial College
g. Oxford University (Counters)
h. Oxford University (Helium Bubble Chamber)
i. Queen Mary College/A.E.R.E./R.H.E.L.
j. R.H.E.L./Oxford University
k. University College, London (Heavy Liquid Bubble Chamber)
l. University College, London/Westfield College

Table 2

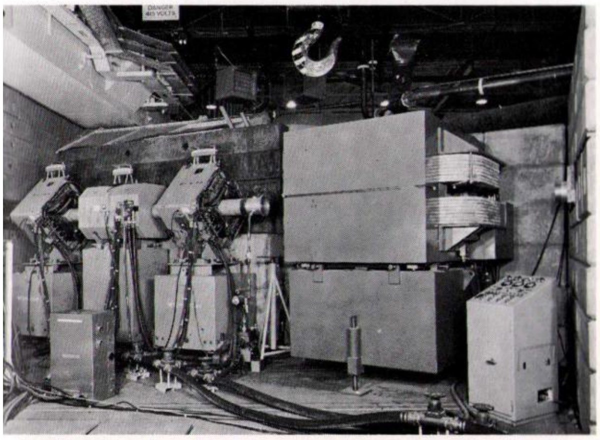
Composition of Teams

	Physicists	Research Students	Support Staff
Visitors	89	60	42
Residents	23	0	28
	112	60	70

Table 3

Experiments completed or in progress – February, 1966

1. Proton – proton diffraction scattering in the coulomb interference region
2. Pion – proton differential cross-section and polarization measurements in the momentum region from 875 to 1579 Mev/c
3. Elastic charge exchange scattering of neutrons
4. Pion – proton differential elastic cross-section measurements near 2 Gev/c
5. Charge exchange scattering experiments with negative pions
6. Two body decays of the ω° meson
7. A study of multipion resonances in $\pi^{\mp} + p \rightarrow \begin{cases} n + x \\ p + x \end{cases}$
8. Proton – proton and proton-neutron total cross-section measurements
9. A study of the leptonic decay modes of positive kaons
10. A study of the decay modes of the η° meson in deuterium
11. K^{-} – p and K^{-} – n studies using the Saclay 80 cm Hydrogen Bubble Chamber
12. $K^{\pm}$ – nucleon total cross-section measurements in the range 0·6–2·5 Gev/c
13. A check on CP violation in K°_{2} decay
14. K^{-} proton polarization measurements in the momentum range 700–1300 Mev/c
15. A measurement of the partial width of $\phi \rightarrow e^{+} + e^{-}$
16. Proton – proton inelastic scattering measurements at various energies

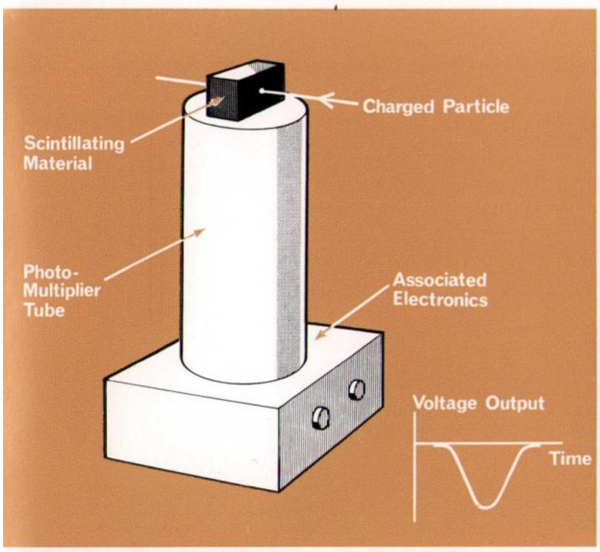


Two type 2 and one type 4 quadrupole magnets with a type 2 bending magnet in a beam line. Some of the concrete and iron shielding can be seen in the background and at the sides.

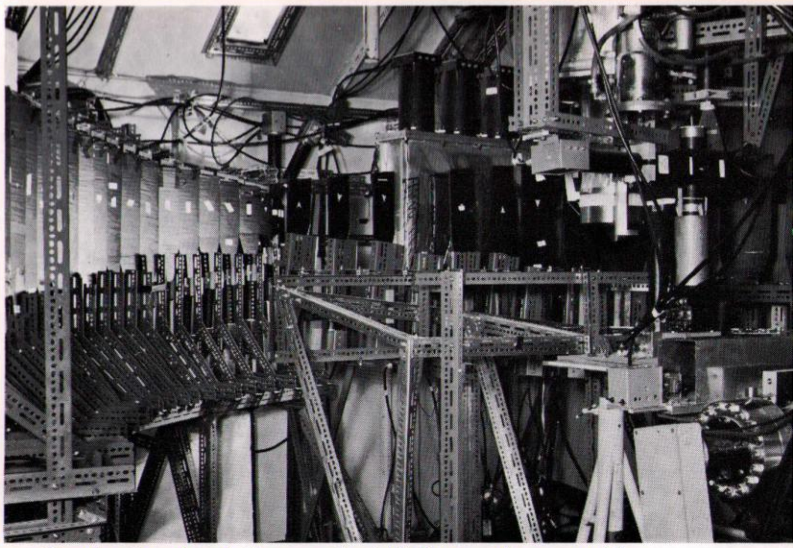
Bending & Quadrupole Focusing Magnet Parameters

Bending Magnets	**Type I**	**Type II**	**Type III**	**Type IV**	
AIR GAP (NOMINAL)	6	6	8	6	Inches
FIELD AT NOMINAL GAP	15·7	16	3·4	15·9	Kilogauss
TOTAL WEIGHT	15·4	28	0·52	24·8	Tons
MAXIMUM CURRENT	500	500	500	500	Amperes
POWER	95	95	48	95	Kilowatts

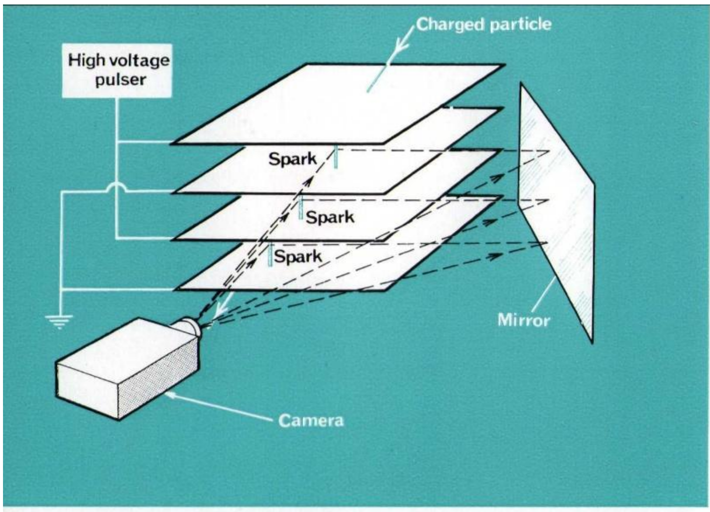
Quadrupole Magnets	**Type I**	**Type II**	**Type III**	**Type IV**	
APERTURE DIAMETER	8	8	8	8	Inches
POLE LENGTH	30	15	15	30	Inches
MAX. FIELD GRADIENT	1100	1100	1000	950	Gauss/cm
TOTAL WEIGHT	6·5	2	1·33	2	Tons
MAX. CURRENT REQUIRED	500	500	1000	1000	Amperes
MAX. POWER	48	48	95	95	Kilowatts



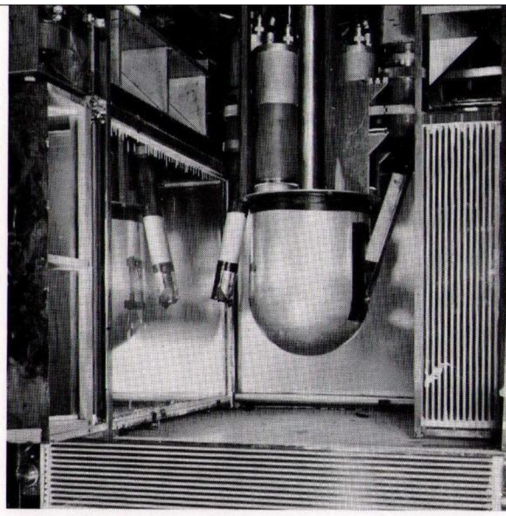
Scintillation Counter. The minute flash of light caused by the passage of a charged particle through the scintillating material is converted to an electrical signal by the photo-multiplier tube.



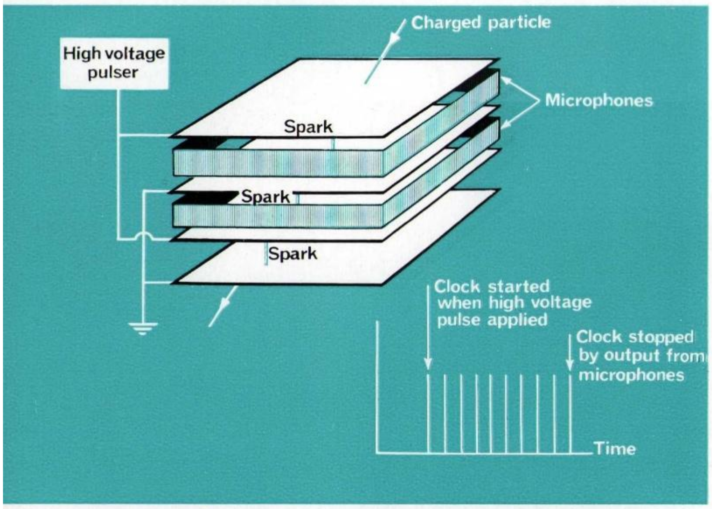
Counter Experiment. The arcs of scintillation counters around the liquid hydrogen target are used to detect the scattered particles.



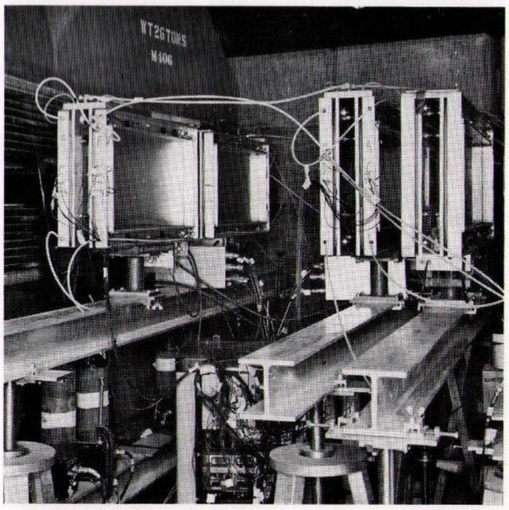
Visual Spark Chamber. Sparks are formed along the path of the charged particle if the high voltage pulse is applied very quickly after the passage of the particle.



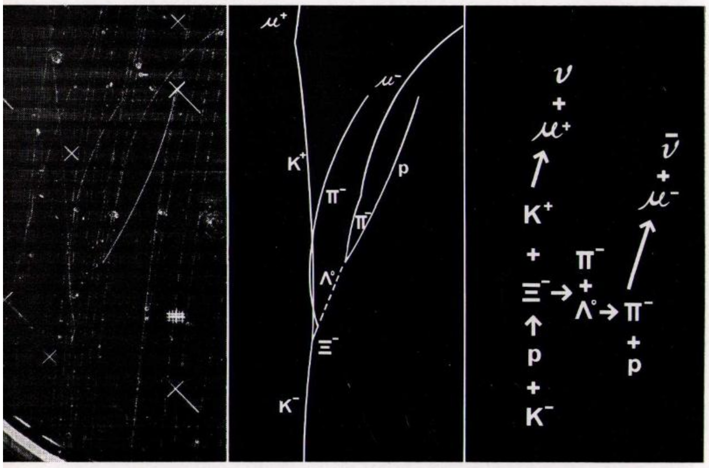
Visual Spark Chambers. These chambers are mounted around a liquid hydrogen target to define the paths of scattered particles. A chamber on the side nearest the camera has been removed for the photograph.



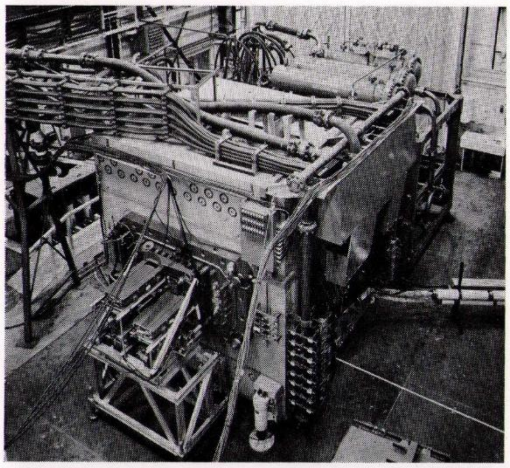
Sonic Spark Chamber. The sparks are produced in the same way as in the VISUAL SPARK CHAMBER. Instead of photographing the sparks the position of the spark in each gap is measured by timing the interval between applying the high voltage and the sound waves from the spark falling on microphones along the sides of each gap.



Sonic Spark Chambers. The chambers are mounted in front of a bending magnet to determine accurately the direction of each charged particle passing through the magnetic field.



Typical bubble chamber tracks. The bubble chamber has a superimposed magnetic field which produces curvature of the tracks enabling the momenta of the particles to be deduced.



In the bubble chamber the chamber filling acts both as target and detector. Photographs are taken of the minute bubbles which form along the paths of charged particles.

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