DNPL 02

4 GeV ELECTRON SYNCHROTRON

Progress Report to 31st October, 1965

Daresbury Nuclear Physics Laboratory
Daresbury, Nr. Warrington, Lancashire

4 GeV ELECTRON SYNCHROTRON

Progress Report to 31st October, 1965

CONTENTS

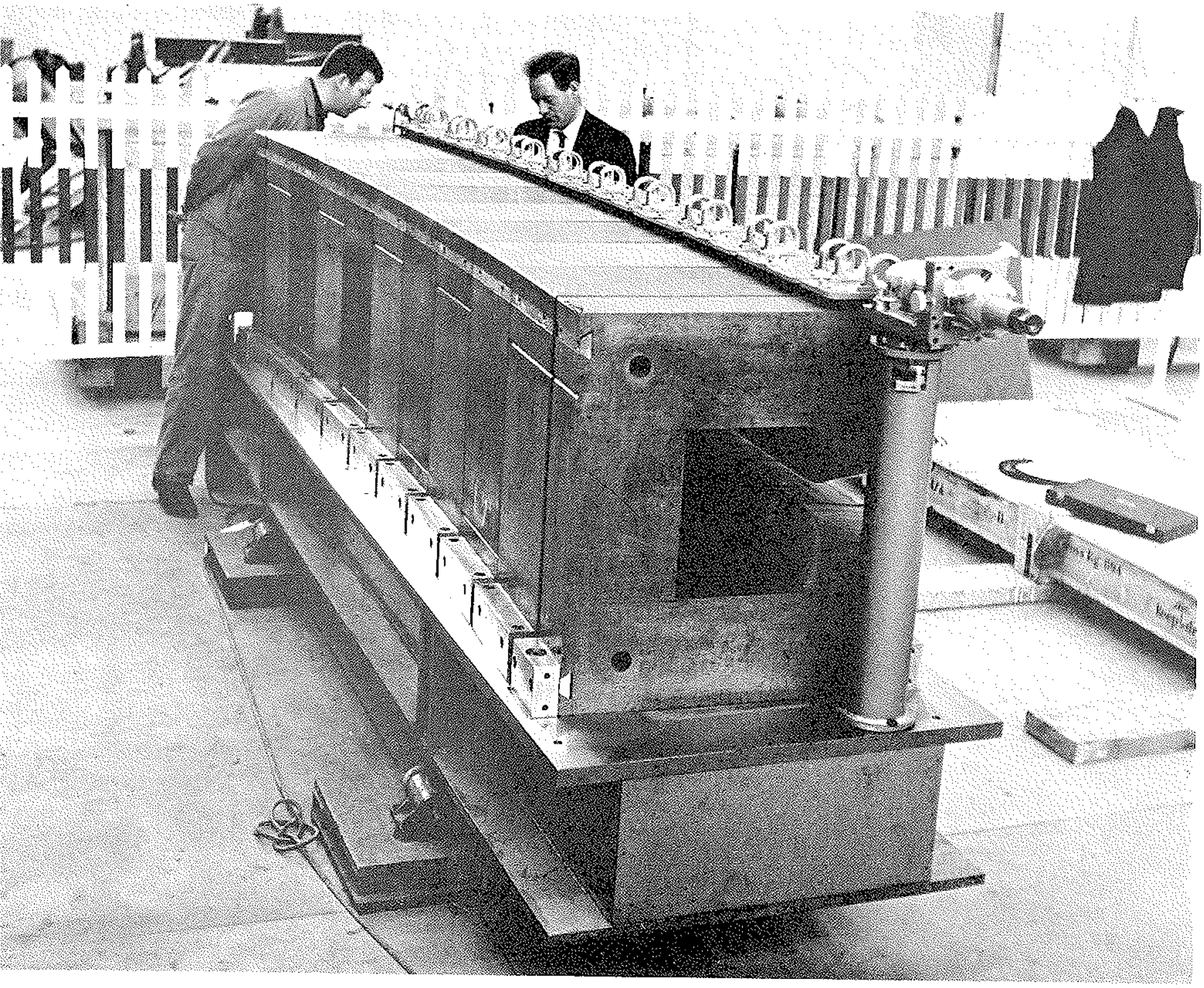


Fig. 1. Positioning the Magnet Blocks on the Base Plate

4 GeV Electron Synchrotron
Progress Report to 31st October, 1965

1. INTRODUCTION.

The Daresbury Nuclear Physics Laboratory (DNPL) was set up under the auspices of the National Institute for Research in Nuclear Science in July 1962. Following the re-organisation of civil science in the United Kingdom the National Institute was merged into a wider organisation, the Science Research Council, on 1st April, 1965.

The initial task of the Laboratory is to build a 4 GeV electron synchrotron (NINA) and its associated buildings. An account of the layout of the site and of the design of the accelerator has been given in DNPL.1. The present report is a study of progress made towards the completion of the project by the end of October 1965, at which date the buildings initially planned were complete apart from minor finishing operations and good progress had been made on the installation of equipment. It is hoped to issue further progress reports at half-yearly intervals, and these will eventually include some details of the nuclear physics experiments to be carried out using the accelerator.

Space does not permit detailed consideration of the wide range of design problems encountered in such a project, but a brief outline of some of the more interesting problems is attempted, which, it is hoped, will lead to fruitful discussions with members of other laboratories and organisations working in the same field.

2. MAGNETS.

2.1. Magnet Blocks.

A brief description of the synchrotron magnet system and of the reasons for the choice of magnet arrangement in NINA has been given in DNPL.1. There are 40 magnets in the ring, 20 radially focusing and 20 defocusing. Each magnet consists of 9 normal blocks of laminations, 12.4 inches in thickness, and 2 end blocks which are specially shaped to give the correct B-length across the useful aperture. The contract for making the magnet blocks was placed with Siemens-Schuckertwerke A.G., Germany, suitable steel laminations having previously been purchased by the Laboratory from Armco Steel Corporation, U.S.A., and all the blocks have now been delivered to Daresbury.

During the manufacture it became obvious that Siemens would not be able to produce the required total number of blocks from the steel available although this included 7% for wastage. Due to manufacturing difficulties several blocks had failed under the shear test, and a number exceeded the tolerances laid down. Consequently, Siemens developed a chemical and thermal process for recovering the laminations from the unacceptable blocks. A trial block made from recovered laminations was delivered and incorporated in an assembled magnet. The magnetic properties were found to be entirely satisfactory, and consequently the manufacturer was given permission to use this process.

Two prototype end blocks of each type were assembled in magnets and measurements made of the effective magnetic length (the B-length) at injection and high field. There was a certain amount of fanning out of the milled laminations in these end blocks leading to incorrect profiles and consequent errors in the B-length. Siemens were able to correct this, and acceptable end blocks have now all been delivered.

2.2. Magnet Coils.

The magnet excitation current for a peak gap field of 9 kGs is 681 A d.c. and 481 A (rms) a.c. The excitation is provided by four water-cooled coils, connected in a series-parallel arrangement. The insulation is glass tape and mica, impregnated with an epoxy resin, all materials with a high radiation resistance.

The contract for the coils was placed with Oerlikon Engineering Co., Zurich, in April 1964. Oerlikon ran into unexpectedly difficult problems in the manufacture of the magnet coils. The insulation of these is formed in two stages, first the interturn insulation and then the insulation to earth. The first process presented no difficulty, but in adding the additional insulation large voids were produced within the coils. These coils absorbed large quantities of water during the water immersion tests, and of course did not then pass the high voltage tests. Production was stopped at the end of March to enable development work to be carried out to solve this and several other difficulties. The moulds have been considerably modified, changes have been made in the method of applying the outer insulation, and tests are being carried out varying the parameters of the vacuum impregnation cycle. Encouraging results have been obtained and production was re-started in July. By the end of October 23 coils had been delivered. It is clear, however, that even if no further difficulties are encountered the magnet assembly programme will be entirely determined by coil deliveries, and will be considerably behind schedule.

To enable magnet testing to commence, Oerlikon delivered 8 prototype coils early in February. These were moved from magnet to magnet as assembly proceeded.

2.3. Magnet Bases.

Magnet blocks are assembled on a strong base frame, the mounting surface of which is machined smooth and flat to within 0.002 in.

The base frame is so designed that when fully loaded and supported by four screw-jacks located on its nodal lines the maximum deflection from the unloaded position is less than 0.001 in. The magnet is excited at 50 c/s so that the natural frequency of the loaded base plate must be well separated from this frequency. The design frequency was 85 c/s. Using a prototype base plate loaded with concrete blocks in such a way as to simulate the magnet loading as closely as possible, the natural frequency of the system has been measured to be 80 c/s.

The contract for these frames was placed with Fairey Engineering Limited, Stockport, in October 1964. After some initial difficulties the fabrication of the base plates has proceeded satisfactorily. The full order of 40 bases plus 2 spares is now on site and final tests are being made on them.

2.4. Pole Face Windings.

It is necessary to correct the magnetic field of the 40 synchrotron magnets at injection. Independent dipole, quadrupole and sextupole field corrections are provided by pole face windings. These consist of sets of 1 mm diameter copper conductors located close to the magnet pole faces and passing continuously along the full length of each of the 40 magnet units. The conductors are embedded in a 2 mm thick layer of epoxy resin and glass cloth designed to fit accurately over the magnet pole face and to locate and insulate the conductors.

Terminals and inter-connections between conductors are located at the ends of the pole face winding units. The pole face windings are supported at the ends by resin-glass-cloth plates which attach the units to the ends of the magnets and by springs, located between the pole faces, which press the upper and lower pole face winding units onto their respective pole faces.

The dipole, quadrupole and sextupole windings are completely separate circuits energised by current stabilised d.c. power supplies.

Great care was taken in the selection of materials to be used in the construction of the windings to ensure good electrical and mechanical stability under irradiation.

The contract for manufacture of 46 F-type and 46 D-type pole face windings was placed in August 1964 with A.E.G. in West Germany. The units are being manufactured at the A.E.G. (IF) works at Kassel. Following delivery of some sample units for approval, full scale production was started, and to date 3 F-type and 1 D-type windings have arrived at Daresbury.

2.5. **Magnet Assembly.**

Positioning of Magnet Blocks on Base Plate.

The spread in position of the circulating beam in a synchrotron is very sensitive to random errors in the position of the magnets. For the Daresbury machine the amplification factor for these errors is approximately 35 and in order to minimise this effect each magnet block is placed upon the base plate to ±0.002 in of its ideal position in the circular arc.

This is achieved using an optical method of alignment. Briefly, a column of greater height than the magnet blocks is located at each end of the base plate so that it is accurately perpendicular to a fiducial mark. A line of sight is set up by mounting a telescope upon one column and an illuminated target upon the other. Each magnet block is then located by means of two glass targets offset from a groove in the top surface of the magnet block which is accurately parallel to and above the equilibrium orbit position. The offsets for each target are calculated so that the centre of the groove in each magnet block is a tangent to the circular arc which is an approximation to the equilibrium orbit. Thus the magnet is positioned radially by adjusting it so that the line of sight passes through the centre of each target. The system is made reproducible by mounting the glass targets for each magnet block position onto a table which is positioned by means of a rod which sits in the groove and which is fixed to the table. Thus for a complete magnet assembly, there are 11 tables for each of the two types of magnet. Each table is also centrally located on each magnet block so that the magnets may be positioned azimuthally by adjusting the distances between the centres of tables on adjacent magnet blocks. A photograph of the arrangement is given in Fig. 1.

Positioning of Magnet in the Ring Tunnel

Each of the 4 screw jacks is mounted on a piston operated adjusting box which enables the magnet to be moved in the horizontal plane when the piston is raised with hydraulic pressure. Using these adjusting boxes the end of the magnet nearest to one of 8 survey monuments is adjusted to the correct distance and angle from the monument using Invar tapes and standard survey equipment. The entire magnet is then rotated about this point until the line of sight on the base plate makes the correct angle with the line of the survey monument. The rotation is accomplished by means of a fifth jacking point which is located directly underneath the surveyed end of the magnet and which just removes the load from the two normal jacks nearest to it when in use. This extra jack is removed when the survey is complete. The positioning tolerances are ±0.005 in in the radial and azimuthal directions and ±0.002 in in height.

Magnet assembly is now proceeding satisfactorily; to date five complete magnets of each type have been assembled. Two of these magnets have been installed and powered in the Ring Tunnel. This experiment has proved the survey procedure and also provided some information in vibration levels to be expected in the concrete ring beam. Although it is not possible to extrapolate from these results and estimate the vibration levels when all 40 magnets are under power it does seem that these levels will not be excessive.

2.6. **Magnetic Measurements.**

Until recently no production magnets have been available for testing. Measurements have been made on prototype F and D magnets both to find out more about the magnets and to perfect the measurement techniques and data processing.

The important parameters which must be measured for each of the 40 NINA magnets are the B-length:

$$l_B(r) = \frac{1}{B(r)} \int_{-\infty}^{+\infty} B(r)dy$$

and the G length:

$$l_G(r) = \frac{1}{G(r)} \int_{-\infty}^{+\infty} G(r)dy$$

where B is the magnetic field, y distance along the azimuth, G the field gradient in the radial direction of the magnet. The denominators, $\bar{B}$ and $\bar{G}$, are the average field and gradient in the centre of the magnet away from the stray fields.

These measurements are made with the field at the injection level of 64.3 Gs using peaking strips, and at maximum field, using long search coils and an electronic integrator. The outputs of both these systems are recorded on paper tape using a data logging system, in a form which enables them to be fed directly into the Mercury computer at Risley for analysis. This system, after some initial teething troubles, works very satisfactorily and has proved extremely useful.

At injection field a reproducibility of field measurement of about one part in 10^4 has been achieved, with hopes of improving this a little by better temperature controls and some improved amplifiers which are on order. The peak field measurements are consistent to a few parts in 10^5. These figures lead to errors in B-length of 0.017 cm and 0.005 cm respectively. The B-length of a magnet is 326.250 cm ideally. Some experiments have been done using the coils and integrator to measure the B-lengths at injection because measurements with coils and integrator are much easier and quicker to do than peaking strip measurements. However, their sensitivity is proportional to the field level and so one must expect a lower accuracy at injection field than at peak field. Repeated measurements on the same magnet show a scatter of about 0.030 cm in the measured B-length.

Results on the prototypes have shown that the end blocks have to be positioned differently from their intended positions in order to get the correct B-length on both the F and D magnets. It has also been shown that the energising coils must be carefully placed in position on the magnet since the B-length is sensitive to this positioning. Some measurements were also made to ascertain how closely one may position steel radiation shields to the magnets without affecting the field distribution.

3. MAGNET POWER SUPPLIES.

3.1. Introduction.

The magnet power supplies are required to produce in the ring magnets a field with a 50 c/s sinusoidal waveform superimposed on a d.c. biasing component. Under maximum operating conditions the reactive power loading of the magnets is approximately 70 MVAr, and therefore a circuit which is resonant at 50 c/s is used. The requirements of high accuracy and uniformity in the magnetic guide field pose special problems in the magnet-network arrangement, excitation methods and control. A paper* giving details of the design was published in June 1965 and so not much need be said in this report about design aspects.

The windings on the 40 magnets are connected in 10 series groups, each group having its associated resonant capacitors. A special arrangement of interconnection between the various coils on the 4 magnets in each group has been devised in order to make the excitation as uniform as possible. Each group of magnet capacitors is connected in parallel with a winding on the energy storage choke. One of the choke windings is split into two equal halves for connection of the d.c. bias and the network is earthed at this point.

Each choke secondary winding has an associated primary winding. These 10 windings are connected in parallel and power to make up the a.c. losses is fed into the primaries from a pulse power supply. A schematic diagram of the system is given in Fig. 2.

3.2. Model Network.

A one-tenth scale model of the complete resonant network of power supplies was constructed at the Rutherford Laboratory in order to confirm theoretical calculations and to investigate both the steady state and transient behaviour of the network. The model was originally commissioned in the summer of 1963, but was dismantled and subsequently re-erected at Daresbury in July 1964.

An iron-cored, multi-air-gap choke was used in order to enable the winding inductance to be set easily. This type of construction is not considered mechanically suitable for the full scale choke.

Initially, studies were made under biased conditions, with the a.c. excitation obtained directly from the mains supply. The general network sensitivity was studied and in particular the balancing effect of the circulating currents in the choke primary windings during mis-match of the resonant capacitors.

*J. A. Fox, "Resonant Magnet Network and Power Supply for the 4 GeV Electron Synchrotron NINA". Proc. I.E.E. 1965, 112, p.1107.

Further studies were made using an a.c. pulse power supply to investigate the network and pulse power transients during conditions of resonant capacitor short circuit and faults on the pulse power supply; the effects of ripple in the d.c. bias supply; the delay line modes of resonance due to the excitation of distributed leakage capacitance; and the frequency variation caused by changing the phase of the pulse valve firing point.

Later, the model was used for tests on a scaled model of the energy storage choke and more recently, the transient conditions in the magnet current has been examined when "beam bumps" were applied to the magnets.

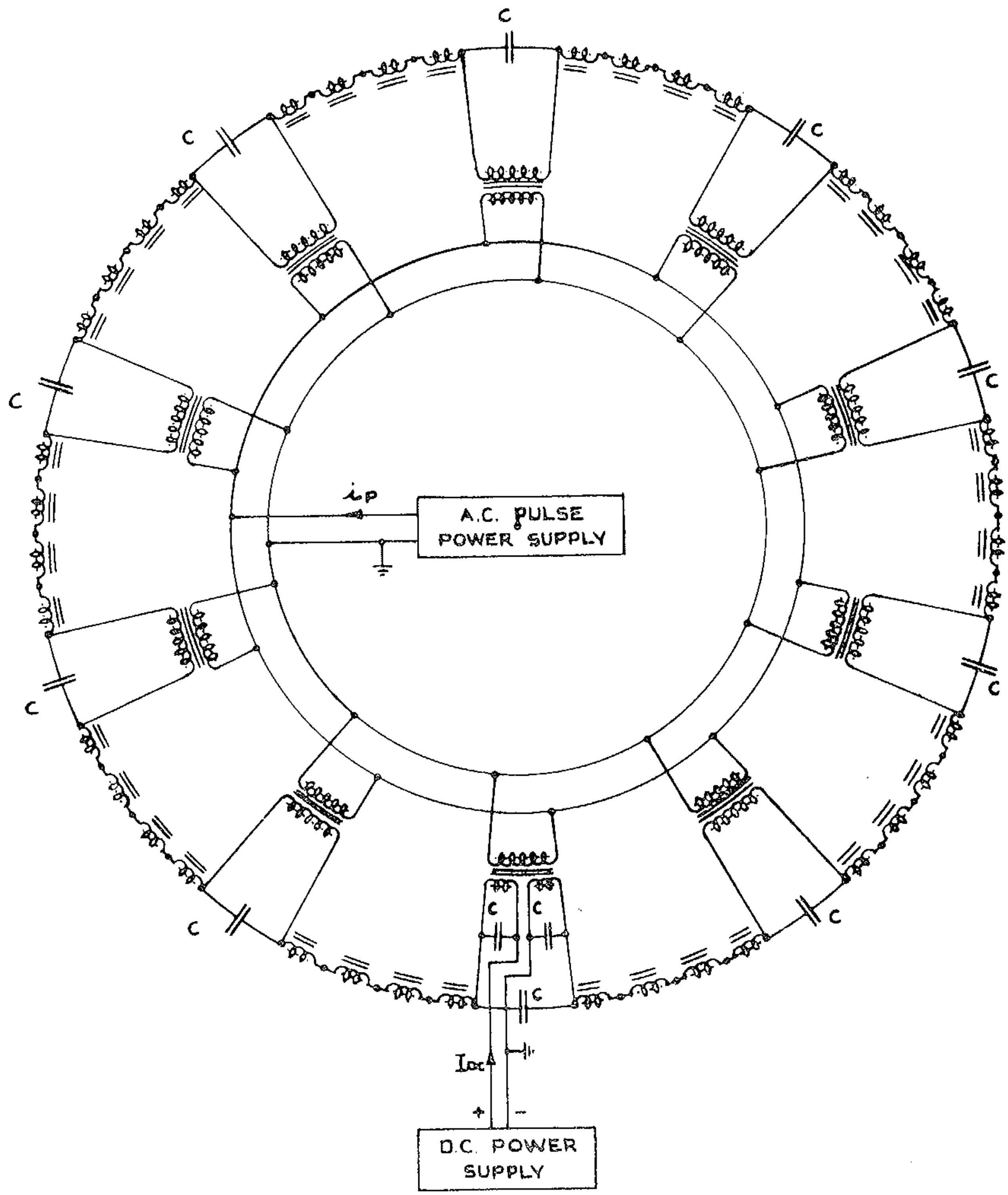


FIG. 2. SCHEMATIC DIAGRAM OF MAGNET POWER SUPPLY NETWORK

3.3. Energy Storage Choke.

The principal requirements of the energy storage choke are uniformity of flux linkage between the windings to obtain equal winding voltage, and strong magnetic coupling to eliminate spurious modes and ensure single frequency operation. It is also desirable that no interchange of capacitive currents should take place to disturb the magnet current uniformity.

The contract for the supply and commissioning of the choke was awarded to the English Electric Co. Limited, Stafford, in March 1964. The contract also included the supply of a scale model choke, designed similarly to the main choke, so that the design could be checked before construction of the main choke commenced. A sectional concrete enclosure which can be readily dismantled is to be provided for the main choke to reduce the noise level, estimated at 85 to 90 dB at maximum working, by about 25 dB.

The choke design consists of a number of vertically mounted circular coils surrounded by an iron mantle, constructed of hot-rolled, transformer steel laminations. The front and rear of the mantle are left open, to allow the emergence of the secondary and primary connections and the whole assembly is fitted into an oil tank.

Each secondary winding consists of four double-disc coils interleaved with the two single-disc coils that form the primary winding. The two halves of the split secondary winding and associated primary winding are placed near the centre of the assembly. The coils are connected to give a winding arrangement that minimises capacitive effects. Dummy end coils, connected to earth, are placed at each end of the coil stack to minimise capacitive leakage currents from the end windings. The primary windings are each fitted with a current transformer to enable measurement and monitoring of the primary circulating currents and the windings are connected in parallel within the enclosure.

With this arrangement, the flux distribution is not uniform because the coils are at different distances from the ends of the mantle. Thus, the inductance per turn is not uniform throughout the coil stack and the turns of both primary and secondary windings must be graded in order to achieve equality of voltage between secondary windings. There is no provision for external tap selection, but each coil disc is wound with one additional turn above the nominal number of turns. Final selection of the actual turns per coil used will be made during tests at the manufacturer's works.

The model choke was delivered to site for testing in conjunction with the one-tenth scale model network in September 1964. Tappings were available on all windings and tests were conducted under symmetrical and asymmetrical conditions to verify the grading of winding turns required to obtain voltage equality between secondary windings and acceptable values of primary winding circulating current. The model was returned to the English Electric Co. after completion of the tests in order to be available for further study by the manufacturer.

It was impracticable to use the model choke to investigate the vibration and mechanical aspects of the full scale choke, but a theoretical study of these characteristics was carried out by the transformer design department of English Electric Co. and a report was recently issued.

Delivery of the choke was scheduled for the end of October, but this was not achieved. Manufacture is, however, almost complete. On site, the foundations, which are separated from the building foundations to minimise transfer of vibrations, have been prepared. Steel inserts, finished flush with the floor, are provided to enable the choke to be removed from its normal position to a position beneath the Inner Hall crane, to facilitate dismantling and coil replacement on site, should this prove necessary.

The choke will be nitrogen filled, under pressure, during transportation to site. Two magnets will be omitted from the magnet ring to allow the choke into the Inner Hall. Because of the dimensions and weight of the choke and the absence of an adequately rated crane, it is necessary to build a temporary bridge over the magnet ring tunnel. The choke will be lifted onto, and lowered from this bridge by hydraulic jacks and moved to its prepared foundation on roller skates.

3.4. Resonant Capacitors.

Oil impregnated capacitors have a positive capacitance temperature coefficient, which would cause a frequency drift during the capacitor warm-up period and during changes in ambient temperature. Small network asymmetries would also be introduced if the temperature of the capacitor banks was not uniform. However, chlorinated diphenol impregnated capacitors show a negative capacitance temperature coefficient and each capacitor bank section is fitted with a number of each type so that the overall capacitance temperature coefficient is less than 0.01 % per °C.

Each capacitor bank is fitted with 72 chlorinated diphenol units of 14.8 μF and 140 oil impregnated units of 10.8 μF arranged in three tiers on an open steel framework. The manufacturing tolerance on the condensers is $\pm 7\frac{1}{2}\%$ and selection is used to bring the total capacity in a bank to within $\pm 0.5\%$ of the desired value. A series-parallel arrangement of connections is employed in order to limit the effect of failure of a single condenser. Units are fitted with an internal discharge resistor and protected by means of an expulsion fuse.

The contract for the supply, erection and commissioning of the 10 resonant capacitor banks was awarded to B.I.C.C., Helsby, in April 1964. All frames are now erected in their final position in the Inner Hall. Erection and connection of the condensers, busbars and fuses on the frames is proceeding and only one section now remains to be completed.

3.5. Pulse Power Supply.

Under resonant network conditions the network presents a resistive load to the a.c. power supply, with a power requirement of approximately 920 kW at maximum magnet excitation level. Direct connection to the a.c. mains is, however, impracticable because of random variations in voltage and frequency. The pulsed method was chosen chiefly because of its general operational flexibility and because of the reliability experienced with this system on the one-tenth scale model experiments.

A pulse of energy of short duration, equal to the cyclic a.c. power loss, is introduced during the descending portion of the magnet current waveform. Any disturbances introduced are completely attenuated before the next particle acceleration occurs during the rising portion of magnet current waveform.

The circuit is shown in Fig. 3. The grid controlled, 6-phase rectifiers charge the energy storage capacitor, C_F, via the filter choke L_F, to twice the peak choke primary voltage. The pulse valve V is then triggered from the magnet network and discharges C_F via the pulse choke L_P and the energy storage choke primary windings. Polarity reversal links are provided in the event of the synchrotron being used for the acceleration of positrons. The a.c. component of magnet current is controlled to an accuracy of 0.01 % by the pulse power supply servo control system.

The contract for the supply, installation, interconnections and commissioning of the pulse power supply was placed with the English Electric Co., Nelson Research Laboratories, in September 1964.

The pulse valve to be used is an oil-cooled, mercury arc excitron type valve, similar to those used in present-day development for high voltage d.c. transmission. The valve has a substantial margin in current capacity and voltage holding off properties in order to meet the normal operation and transient fault conditions. The supply of a spare pulse valve is included in the contract and both valves have now been delivered.

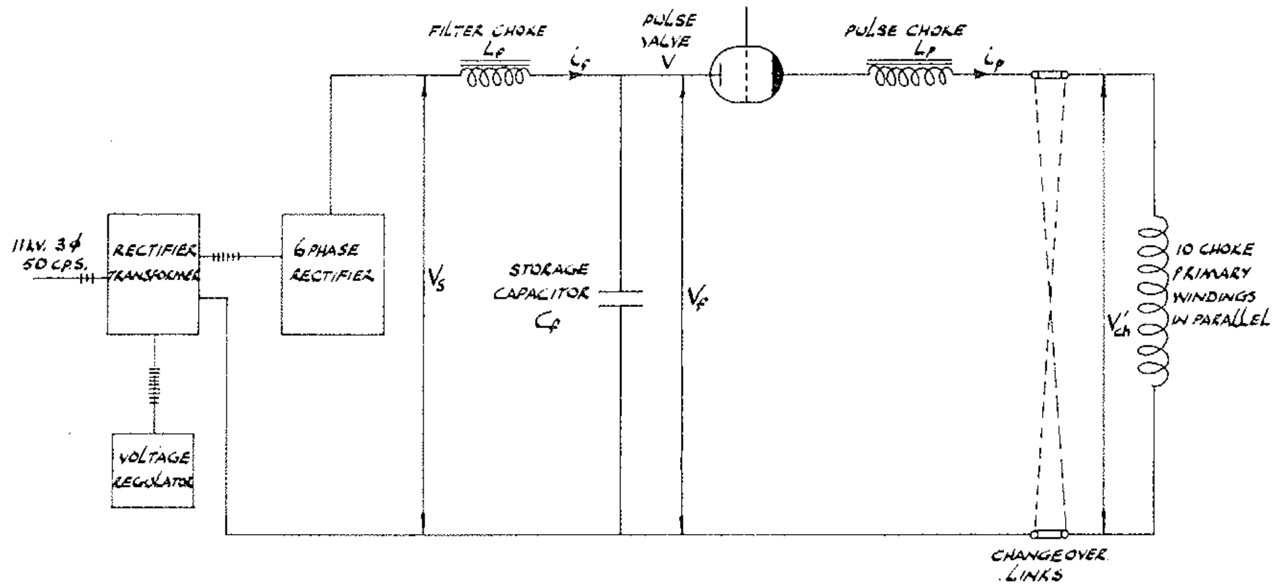


FIG. 3. SCHEMATIC DIAGRAM OF PULSE POWER SUPPLY CIRCUIT

Design of the major components is complete and manufacture is well advanced. The finished floor around the pulse power equipment is of chequer plate construction, suspended two feet above the building foundations, with the concrete foundations for heavy equipment finished level with the chequer plate. This arrangement provides ready facilities for oil retention beneath the oil-filled electrical equipment in the event of leakage, and also affords easy access to cabling.

3.6. DC Bias.

The d.c. component of the magnet current is provided by a grid controlled, 6-phase, mercury arc rectifier set, supplied from a 3/6-phase transformer and voltage regulator and is capable of 10-100% control of output voltage. An LC filter network is provided to attenuate the inherent rectifier harmonics, and the filter capacitor is also used to divert from the rectifier the a.c. current which may flow due to small network asymmetries. The d.c. bias is connected into the network as shown in Fig. 2. The current is controlled to accuracies of 0.03% at 10% rated current to 0.01% at rated current by a servo control system.

A contract for the supply, installation, interconnections and commissioning of the d.c. bias equipment was placed with English Electric Co., Nelson Research Laboratories, in November 1964. Detailed design of the equipment components is complete and manufacture is proceeding satisfactorily. The equipment foundations on site have been prepared, the finished floor being of chequer plate construction similar to that for the pulse power supply.

3.7. Busbars.

The electrical connections between the energy storage choke, resonant capacitors and magnet system are carried out in tubular copper busbars on porcelain insulators. This system was chosen in preference to power cabling mainly because of the reduced leakage capacitance and hence better equality of magnet current.

The busbars are run from above the energy storage choke horizontally at roof level across the Inner Hall and vertically down the wall of the D areas to the magnet basement. End connections at the magnets and choke are carried out in short lengths of polythene insulated, aluminium wire armoured cables and flexible tails.

The contract for the installation and commissioning of the complete system, including screening, was placed in February 1965, with B.I.C.C. The installation of the system is now well advanced and is expected to be completed early in 1966.

4. VACUUM SYSTEM.

4.1. Vacuum Pumps.

The vacuum requirement for the ring is that the pressure should be better than about 10^{-6} torr to minimise gas scattering of the orbiting electrons. At this pressure the estimated loss is 1-2%. Low pressure is also necessary to prevent r.f. breakdown in the accelerating cavities, though model tests have shown that a pressure of 7×10^{-6} torr may be tolerated.

Ion pumps have been chosen for the accelerator because of their complete cleanliness, their simplicity of control and operation, and the fact that their operating current gives direct indication of pressure. The pump to be used is the Ferranti 140 l/sec. getter-ion pump and the total number of these in the system is 54 for a total volume of about 5-6000 litres. The distribution of the pumps round the system is not uniform, since extra pumps are positioned where requirements are greater, that is, at the r.f. cavities and the inflector. There is always, however, at least one pump between each of the magnets.

At the end of October all ion pumps had been delivered. The ion pump power supplies are on the same contract, and all but six units have been delivered.

For initial evacuation of the system from atmospheric pressure to 10^{-4} torr, at which pressure the ion pumps are switched on, Pfeiffer turbo-molecular pumping sets are to be employed. These consist of a combination of rotating vane type pump and a very high speed turbo pump. Turbo-molecular pumps were chosen on several grounds. They have a pumping speed from 10^{-2} torr to 10^{-8} torr of 140 l/sec. This means that ion pumps can be started at a lower pressure than is possible with a rotating vane type pump alone, making for longer life and less heating of the ion pumps during starting. They can also cope with the initial gas bursts which occur when a well used ion pump is restarted. All units have now been received on site and are being tested.

4.2. **Control Circuits.**

For convenience in installation, testing and maintenance, the ring is divided into 10 sections by isolating valves. Each sector has its own roughing system. The number of ion pumps varies, according to whether the sector contains an r.f. cavity or not, from four to six. Local control consoles are used for the starting of any sector. The control is basically manual but a number of protective devices are incorporated including Penning gauge operated relays. A schematic arrangement of the vacuum equipment in a sector is given in Fig. 4.

The main control console is to be located in the Inner Hall and the racks for this are in position. These racks are to house the ion pump control units and controls for the mechanical pump sets and the main pneumatically-operated sector valves. A mimic diagram will be used to give an overall picture of the state of the valves, ion pumps and mechanical pumps.

The main synchrotron Control Room is to house a data logger into which will be fed voltages proportional to ion pump currents, thus enabling pressures around the system to be printed out as required. These voltages, applied to a long persistence oscilloscope, will also give a graphical display of pressure conditions round the ring.

Control consoles started arriving on site in July and delivery is now complete.

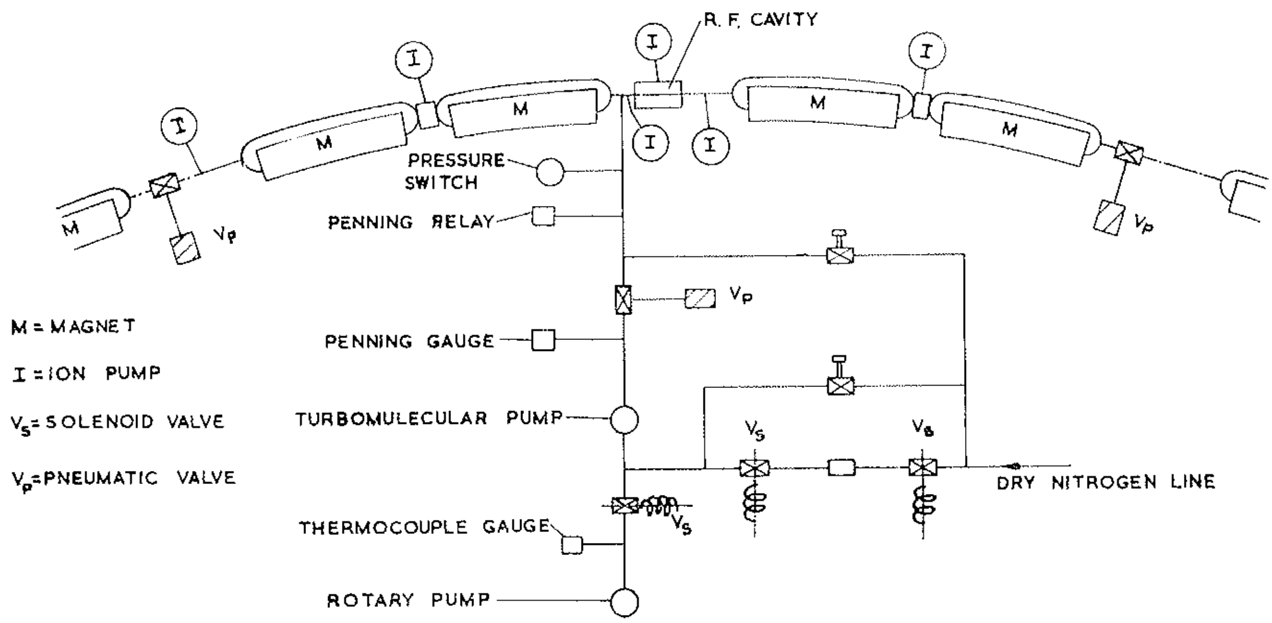


FIG. 4. SCHEMATIC LAYOUT OF VACUUM SECTOR

4.3. **Vacuum Chambers.**

These chambers which fit between the poles of the F and D magnets have to comply with a number of difficult parameters.

(*a*) The chamber must be evacuated to a pressure better than 10^{-6} torr and be able to withstand atmospheric pressure.

(*b*) The chamber must be of such a material that virtually no distortion of the magnetic field is produced due to eddy currents in the chamber walls.

(*c*) The inner walls must be conducting to prevent build-up of charges which would again affect the beam path.

(*d*) The chambers must have maximum resistance to the synchrotron and high energy radiations including showers produced from the wall materials.

(*e*) The chambers must be able to be heated to 90°C to enable speedy desorption of water vapour from new chambers and short pump-down times for the system after it has been opened for any period. Heating may be effected by passing a current through the metal structure of the chambers.

The final design of the chambers now under construction is similar to that at present in use at C.E.A. (see Fig. 5) except that a high resistance titanium alloy is being used for the horizontal sectionalised portions, as it was found to be the only material giving a sufficiently high resistance to the induced eddy currents.

The chamber consists of two vertical side pieces made from extruded stainless steel of low permeability. The upper and lower portions are made from ½ in wide strips 0.104 in thick of titanium alloy 318A. These strips are separated by an 0.004-0.008 in gap, apart from the spot welds, and these gaps are filled with an epoxy resin mix. The top and bottom elements are joined to the side member ledges by an insulating joint of glass cloth and epoxy resin.

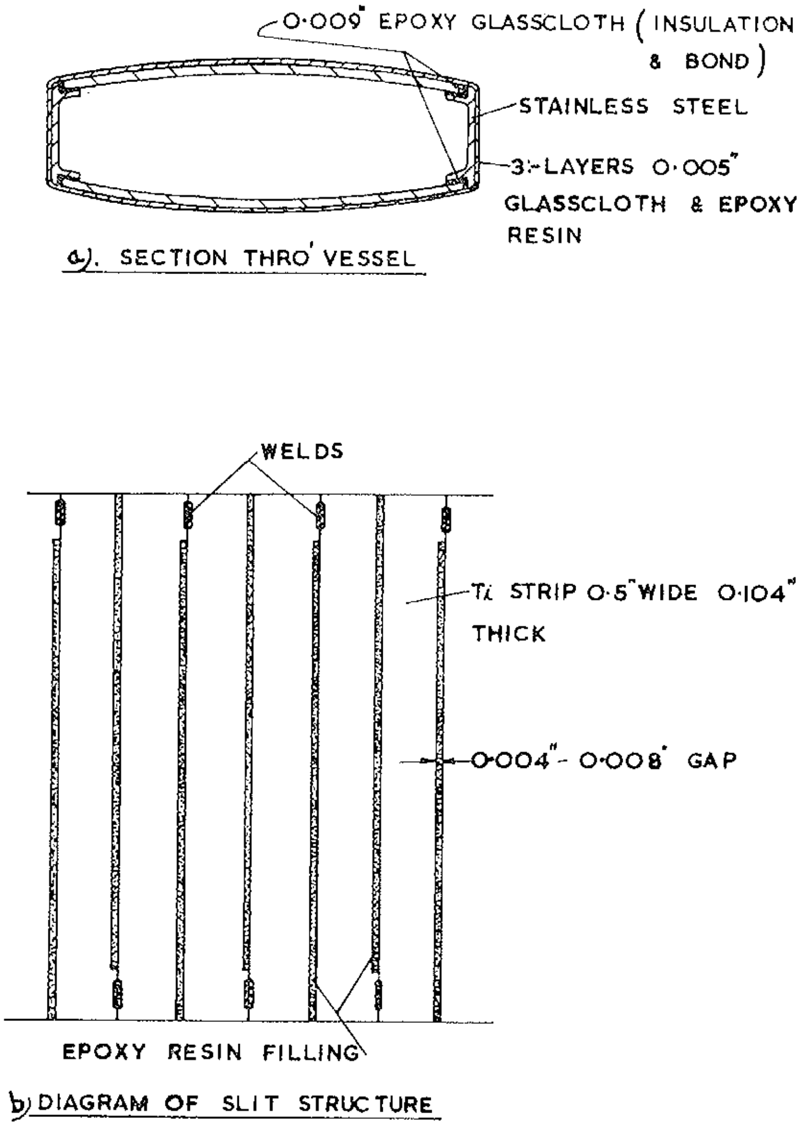


Fig. 5. Construction of Vacuum Chamber

The whole metal skeleton is then wrapped with a number of layers of glass cloth and epoxy resin. The ends are terminated by (but electrically insulated from) elliptical bellows units with flanges to permit connection to the rest of the pipework and pumps.

All gaskets in the beam line are made from 0.036 in diameter pure aluminium wire, butt-welded and clamped between stiff flanges which are machined to a good finished free from radial scratches.

The connecting pipework in the straight sections is made from 6 in diameter stainless steel pipe, electro-polished internally, with tee pieces for pump connection. In every short straight section a vacuum box is placed to house pick-up coils for beam position indication and to connect an ion pump to the system. Similar boxes are provided in 15 long straights for the same purpose. Each straight section has provision for sampling with a Mass Analyser to assist in assessment of gas condition in the system. The pipework and vacuum boxes are on order and delivery commences in early November.

The vacuum chamber manufacturing details are finalised and English Electric Co., Limited, Luton have supplied a sample 24 in length of chamber, manufactured using production jigs and tools. This seems satisfactory and the first two full size chambers, one of each type, are expected shortly. DESY have agreed to carry out a test on the sample length by subjecting it to a period of bombardment by their high energy extracted beam.

4.4. Laboratory Tests.

A considerable amount of laboratory work is going on as follows:

- Work on resin systems and improving adhesion to metals.
- Development of a materials outgassing measurement rig.
- Completion of a gauge calibration unit.
- Testing of Penning switches after development.
- Investigations into leak testing sensitivity improvement.
- General investigations into ion and turbo pump performance.

5. R.F. ACCELERATING SYSTEM.

5.1. Introduction.

A description of the r.f. accelerating system has been given in DNPL.1 and no significant changes have been made. A simple block diagram is shown in Fig. 6. To re-capitulate briefly, the accelerating structure consists of 5 cavities distributed uniformly round the ring in long straight sections, fed by short lengths of waveguide from a waveguide ring which is resonant and serves to couple the cavities strongly together. Power is fed into the waveguide ring at one point from the power amplifier, through a ferrite isolator.

The final amplifier is a super-power triode driven by a tetrode. The rated output of the amplifier is 480 kW peak and 150 kW mean. This is the power required to accelerate 1.2×10^{12} electrons per pulse to 4 GeV. The peak output can probably be increased and it should be possible to reach 5 GeV with one-tenth the above current (i.e. 1 μA mean) or 5.4 GeV at very small currents.

The low-power amplifier chain comprises the master oscillator, first amplifier, and pre-driver, with an output of 500 W peak. It will include facilities for amplitude, frequency and phase modulation. It also includes the injector drive amplifier.

Ancillary equipment includes the following: automatic cavity tuning, comprehensive monitoring and protective circuits, and large scale cooling systems principally for the triode and tetrode.

5.2. Power Amplifier.

The output triode is an RCA type 2054. The triode with its circuit and also the drive amplifier, an RCA 2041 tetrode and its circuit, were bought complete from RCA. The cubicles, power supplies, crowbars, cooling equipment, and all monitoring and control equipment, have been designed or specified at DNPL and manufactured by various sub-contractors.

At the date of this report, all the cubicles and equipment are complete, and installation in the Inner Hall of the accelerator building is complete. Pressure testing of the cooling circuits has been carried out.

The driver tetrode had previously been fully working in the laboratory and had been used for testing the prototype accelerating cavity, so re-commissioning in its final location did not take long. It was run up to full power in early October.

The triode and tetrode are in separate cubicles, with separate power supplies. Both use excitron (grid-controlled mercury arc) rectifiers for their anode supplies, with maximum voltages of 14 kV. The only modulation is the r.f. grid drive. The tetrode circuit is grounded cathode, giving a power gain of over 100, the triode is grounded grid giving a gain of about 10. The d.c. supplies to all electrodes are protected by "crowbar" circuits, using CX.1140 thyratrons as the "crowbars", except for the triode anode supply, a 600 kVA supply with 350 μF smoothing capacity, which uses a BK.178 ignitron triggered by a CX.1140. The crowbars on the anode supplies are backed up by arc suppression on the rectifiers, saving wear and tear on the circuit breakers, which are not used in conjunction with the crowbars.

Commissioning of the power supplies and crowbar circuits for the super triode has been carried out and the valve itself is being powered. Some difficulty is being experienced, owing to the occurrence of parasitic oscillations, and investigations are in progress to find ways of avoiding them.

There are several high pressure cooling circuits. Circuit 1 provides very high purity (0.2 micro-mho/cm conductivity) water for the grid cathode cooling on the 2054. Circuit 2 provides 1 micro-mho/cm water for all the other electrodes on the triode and tetrode, and also for the 2054 circuit, the isolator, and the 2054 filament supply rectifiers. Dry air at 50 lb/in^2 is also required to cool both amplifier circuits. There is a third circuit, providing water of controlled conductivity to the waveguide dummy load; and raw water is used to cool the coaxial filament connectors to the 2054 (7000 A d.c. at 6 V) and the smaller coaxial dummy load used for testing the 2041.

Water treatment is by a Permutit de-ionisation plant, and the air cooling is by a Dry Air Plant, both used for the r.f. equipment only. The heat is transferred from the demineralised water to canal water by heat exchangers.

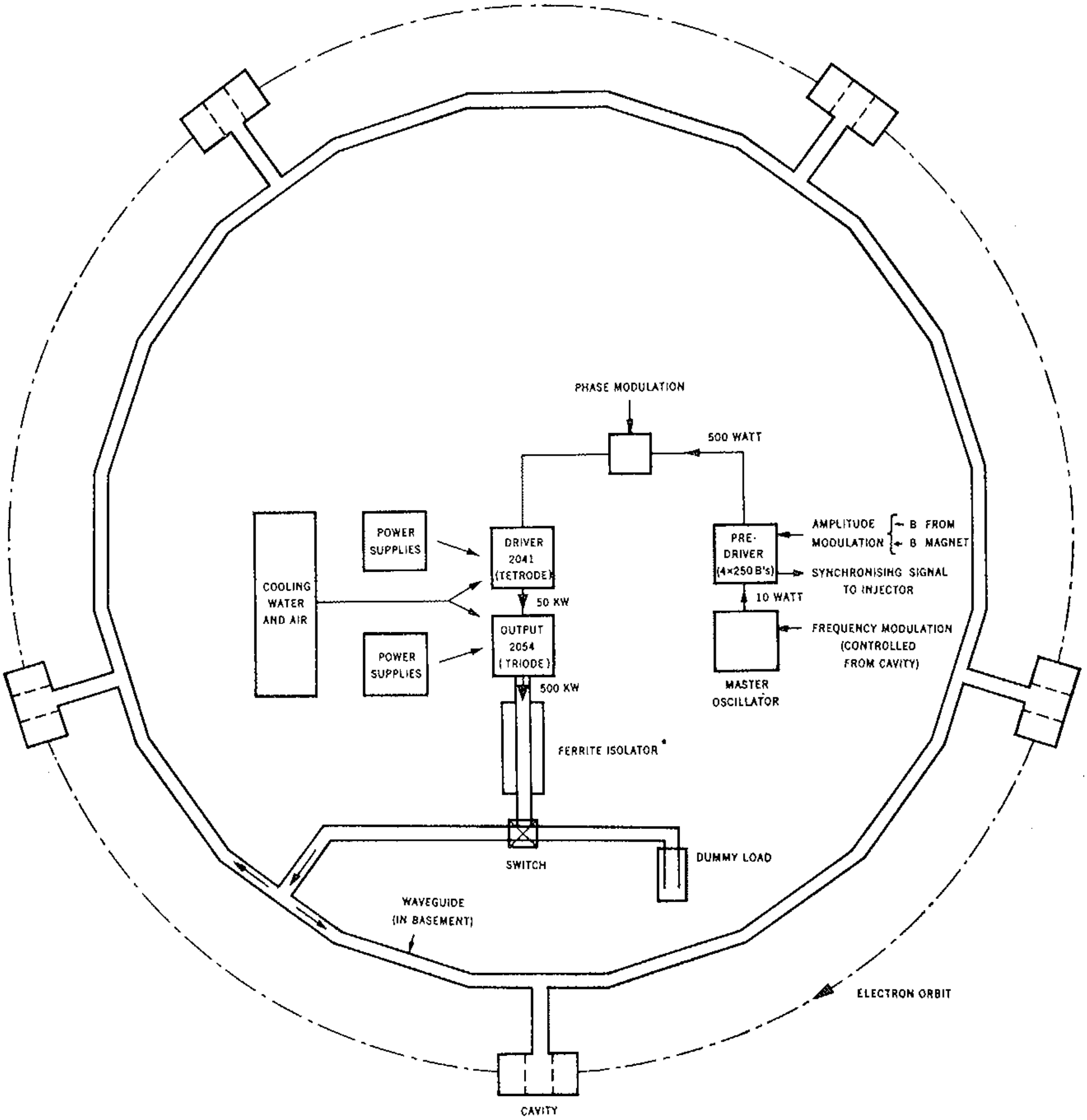


FIG. 6. RADIO FREQUENCY SYSTEM SCHEMATIC DIAGRAM

5.3. **Pre-Driver and Modulation Equipment.**

The master oscillator is being developed and will be described in a future report. It must provide a frequency which at the beginning of an acceleration cycle is sufficiently precise to operate the injector as well as the synchrotron cavities, i.e. 1 in 10^6 accuracy, but which can be frequency modulated during the cycle with a fractional deviation of 2×10^{-4}, at a rate corresponding to a time constant of about 10 microsec. It is being designed to have a power output of 10 W, and in the meantime a crystal oscillator and multiplier are being used for test purposes.

The remainder of the pre-driver chain is installed and commissioned. It consists of a first amplifier, a 4X250B tetrode, giving 50 W, followed by the pre-driver, two 4X250B's in parallel, giving 300 W average or 500 W peak pulse output. This stage is screen-grid modulated, with a time constant of under 1 microsec.

The injector drive amplifier will be a copy of the pre-driver stage, driven by half of the 50 W output of the first amplifier. It will supply a synchronising signal to the injector.

The frequency modulation will be controlled by feedback from a phase detector to keep the cavities on tune during the acceleration cycle in the presence of beam loading. This will be a relatively slow loop.

The amplitude programme, V, will be derived from B, $\dot{B}$ and a sin ϕ_s function generator, according to the equation:—

$$V \sin \phi_s = K_1 \dot{B} + K_2 B^4$$

where B is the magnetic flux density and ϕ_s the synchronous phase angle.

An electronic circuit for this is under development. A feedback loop will ensure that this voltage programme is reproduced at the cavities, compensating for the effect of non-linearities and varying beam loading. This loop too will probably have to be relatively slow, but theoretical investigation is in progress to see if the pass-band could be extended to cover phase oscillation frequencies without instability.

To assist in capturing an intense beam, it is proposed to apply a phase jump at injection. This would be done using semiconductor diode switches and two coaxial lines of adjustable lengths on the output of the pre-driver stage. For the future, it would be very desirable to have fast continuous phase modulation at this level, as this is probably the best way of damping the phase oscillations. This will be investigated at a later date.

5.4. **Waveguide and Cavities.**

The waveguide system consists of a 20-sided polygon to be situated in the ring tunnel basement, with the tee junctions for risers to cavities at 5 points and a sixth tee for the input. The ring is resonant, with 41 guide wavelengths between each cavity tee. Each cavity tee has iris coupling to the cavity riser, and is matched by a post.

This arrangement ensures tight coupling between cavities, tending to equalise the fields in the 5 cavities despite detuning of individual cavities. Each section of waveguide between cavities includes a fixed 3-iris phase shifter and a variable phase shifter, to adjust the electrical length to resonance, and a double directional coupler for diagnostic purposes.

The riser to a cavity is adjusted in electrical length by fixed and variable phase shifters to ensure that if a cavity goes short-circuit, for instance due to poor vacuum causing ionisation, this reflects as an open-circuit rather than a short-circuit at the tee junction. The cavity is coupled to the guide by a window in the narrow side of the guide, and the guide is terminated by a short-circuit a quarter wavelength beyond an adjustable post. This post enables the cavity to be matched to the guide for a range of beam loading conditions without changing the window iris. A double directional coupler before the cavity provides signals for monitoring, cavity tuning and frequency control. The waveguide is on order, and approximately three quarters of the ring components are delivered. Installation of the ring started in August and is expected to take about three months, following the installation of magnet busbars which must go in first. The risers and cavities will be installed by April 1966. The waveguide is made by C. H. Jucho (Dortmund).

The cavity design is shown in Fig. 7 and Fig. 8 is a photograph of the prototype. It is similar in design and construction to those at DESY. It consists of three sections or cells, supporting an E_{01} type of field, coupled together by irises and operated in π mode. The waveguide input is in the centre cell, which is 0.3% smaller in diameter than the outer two. The waveguide window is alumina of 99.5% purity. The cavity is water cooled, and rated at 20 kW dissipation, which corresponds to about $5\frac{1}{2}$ GeV operation.

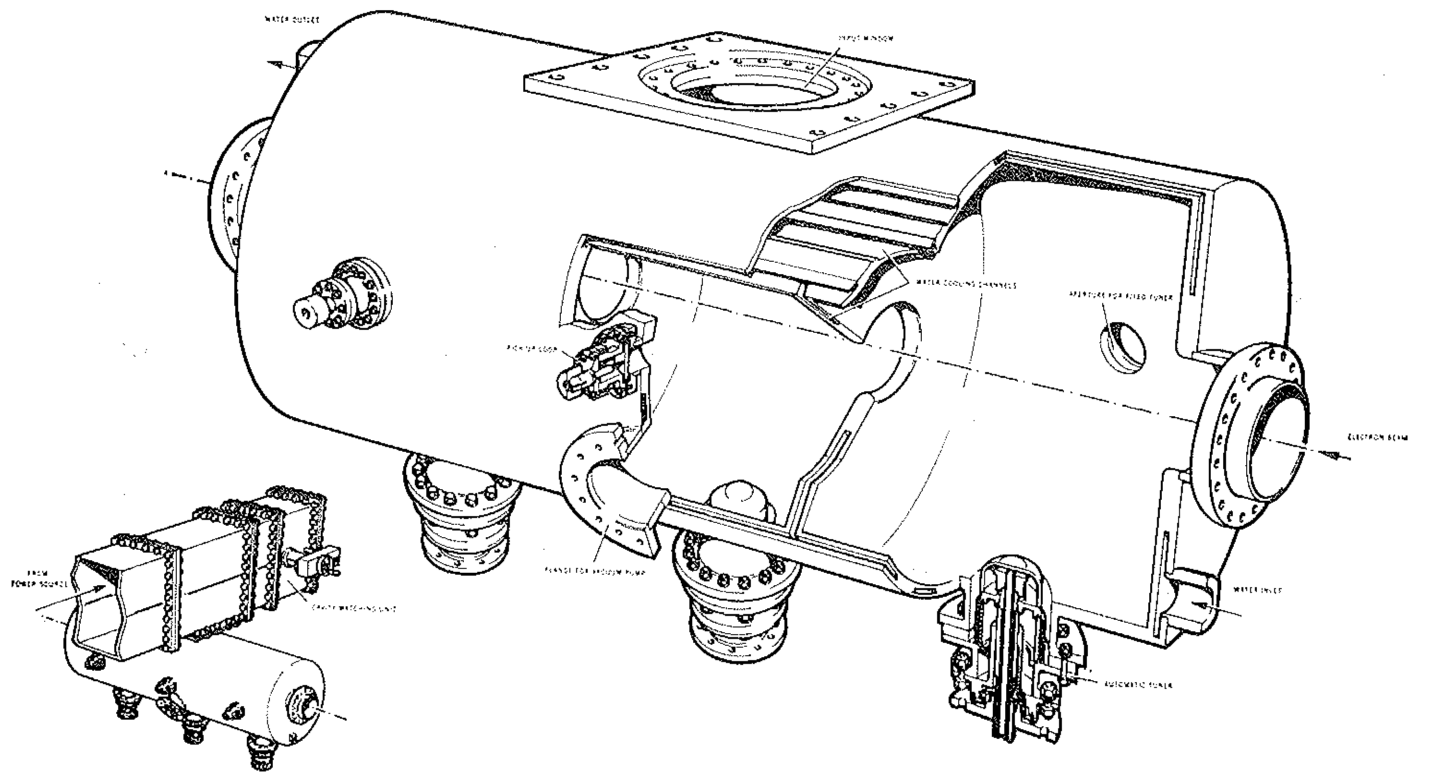


FIG. 7. RADIO FREQUENCY CAVITY—PART SECTION

The cavity is made by a combination of electroforming and brazing, by C. H. Jucho (Dortmund), the electroforming being sub-contracted. Apart from the flanges, the cavity is entirely made of electro-formed copper. The input flange is bronze, and all other flanges are stainless steel. The flanges are brazed onto copper branches, and these are silver brazed to the cavity after electroforming the cylindrical wall. Water cooling channels are cut in the irises and end walls as shown in Fig. 7, and during electroforming, channels are formed in the cylindrical wall and joined to those in the discs.

A prototype cavity has been fully tested and found satisfactory and the first production cavity has recently been delivered.

The cavities have a fixed tuner in each cell to compensate for manufacturing tolerances, and also an adjustable one. The latter will be controlled by a servo motor driven by a phase detector. They can be operated singly or ganged together. This automatic tuning system has been tried on the prototype cavity and keeps the cavities on tune to $\pm 1°$. The variable tuners are bellows-operated and water-cooled.

A pick-up loop is provided in each cell, situated behind an alumina window. As it is on the same horizontal level as the beam, and relatively close, mineral insulated cable will be used from the probe directly down to a junction box, to avoid the possible radiation damage which might occur if polythene cable or, more particularly, PTFE insulated connectors were used.

Low power tests on the prototype cavity were used to check the dimensions required to achieve the correct resonant frequency. The internal cavity dimensions have all been toleranced +0.004 in, −0.000 in, but it is apparent that this cannot be maintained after the brazing operations.

The unloaded Q has been measured as 49,000, and the ratio of shunt impedance to Q is 450 Ω. With a transit time factor of 0.75, the effective shunt impedance, including transit time effects, is 16.5 MΩ.

With no iris in the cavity input window, and no beam loading, the cavity is overcoupled to the guide with $\beta = 5.2$ giving a loaded Q of 8,500. The equivalent circuit and reference planes of the cavity with its transition have been explored.

On high power test no problems were encountered in running the cavity at 20 kW continuously, or 50 kW peak with 20 kW average. These powers were limited by the output of the amplifier, not by the cavity.

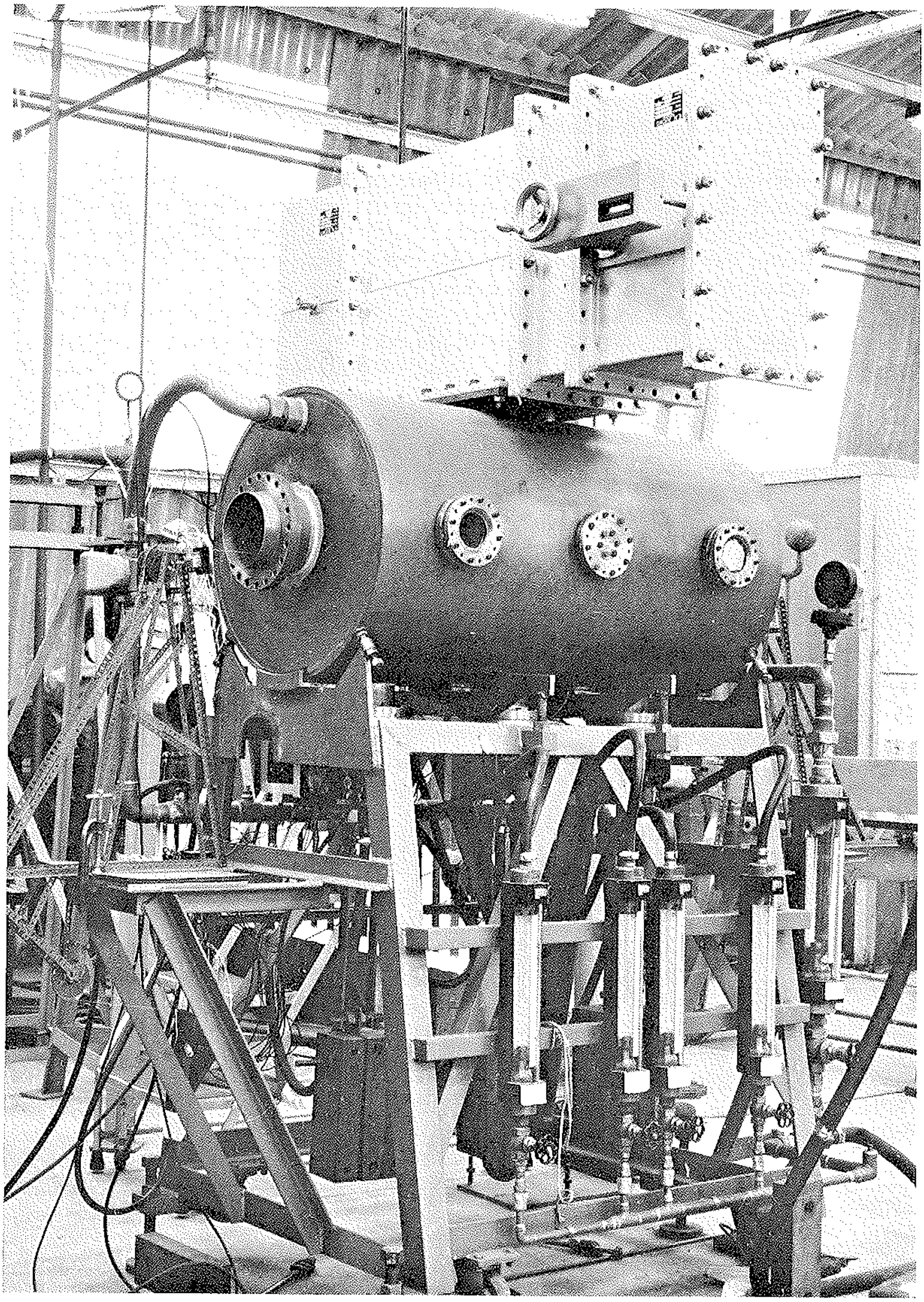


Fig. 8. Prototype Cavity on Test

This is a fairly realistic approximation to the actual machine. It assumes momentum matching from the injector, it assumes no coupling with the betatron oscillations, and the only important omission is the gap in the circulating beam due to the inflector turn-off. That is, apart from the effects due to there being 5 cavities rather than one.

The way the parameters are chosen for computation is to consider the steady-state vector diagram (Fig. 10) and to guess at optimum conditions. The results of the computations are interpreted in terms of the vector diagram, and the parameters modified accordingly. The aim is to move from an initial vector diagram when $I_b = 0$ before injection, to a final arrangement suitable for steady-state acceleration, without losing too many particles in the transition, and remembering that the number of particles lost governs I_b and hence the final conditions.

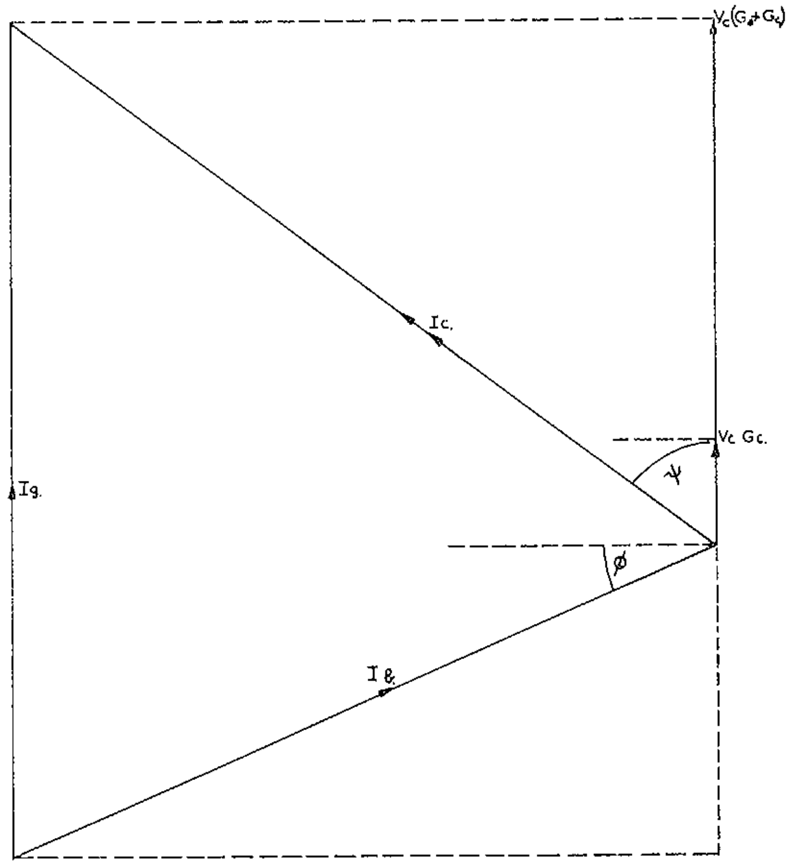


FIG. 10. STEADY-STATE VECTOR DIAGRAM

We now summarise briefly the results to date and our ideas for counteracting the effects of beam loading.

If a large beam is injected into the synchrotron with the cavities on tune and constant generator current, then usually all the beam is lost. If the generator current is too low, the cavity voltage varies rapidly, the particles are lost from the phase-stable region, and instability can result. If the generator current is high, then the particles perform large amplitude oscillations and hit the walls. The first and apparently vital step to take is to detune the cavities. This means that before the beam is injected, there is a large "reserve" of reactive current of such a phase as to tend to compensate for the beam loading. When the beam is injected, under these conditions the cavity voltage rises rather than falls, and though the phase varies fairly rapidly, this stabilisation of the voltage enables a considerable proportion of the beam to be kept.

Without detuning, though for small injected currents (50 mA) 4 out of 7 injected bunches may be trapped, for larger currents (350 mA) not more than 2 out of 7 may be kept. With a cavity detuning of 80°, 4 out of 7 bunches can be retained with an injected current of 500 mA.

The injector frequency is seven times the synchrotron radio frequency, and so during each cavity cycle, seven bunches are injected. These cannot all be captured, and the bunches being lost, and executing large amplitude oscillations have a considerable effect on the cavity voltage.

If each group of seven injected bunches could be compressed into one, it should be possible to trap the whole bunch, more easily than to trap even a large proportion of an unbunched beam. Computations have been carried out and this has been shown to be true. With a detuned cavity and high generator current, the whole of a pre-bunched beam (with $\pm 1\%$ energy spread) has been trapped. The injector is being provided, in Phase II, with a chopper to achieve this condition.

Considering again the non-prebunched beam, if I_g could be changed at injection, in phase and amplitude, then this could compensate for I_b, and I_c and hence V_c could be kept constant and the effect of beam loading would be almost eliminated. This is feasible in practice, and provision is being made for it. Computer runs have shown it to have the expected effect. A recent run with 500 mA injected current, a cavity detuning of 82° (inconveniently large in practise admittedly) and a phase and amplitude jump at injection showed nearly 5 out of 7 bunches (13 μA mean) captured after 300 orbits.

A programme for the Atlas computer has been written taking all these effects into consideration, and a considerable number of runs are planned. Some results were given in a paper* read at the High Energy Accelerator Conference at Frascati in September of this year.

6. INJECTION EQUIPMENT.

6.1. Linear Accelerator.

A 40 MeV electron linear accelerator is being made by M.E.L. Limited, Crawley. The design is their own, but it is aimed at meeting a functional specification giving DNPL requirements. The contract was placed in March 1964, and called for the equipment to be operating to the required specification by the end of March 1966. The operating frequency is 2855.16 Mc/s which is seven times the frequency of the accelerating system in the ring.

The specification calls for a one microsec current pulse of 500 mA to be within an energy range of 40 $\pm$ 0.2 MeV and within a maximum emittance of 3.2×10^{-6} m.rad. This should give sufficient beam current to obtain a circulating current in the ring of 272 mA corresponding to 10 μA mean. However, owing to high beam loading effects on the accelerating cavities in the ring coupled with the large phase oscillations, the actual current which will be captured is uncertain. A later stage therefore calls for a beam chopper to be installed in the injection path to the linear accelerator so that only one bunch is accelerated for every seven cycles of the RF wave. In this way the whole current can be injected into the synchrotron at the best phase angle, so that phase oscillations should be small. The calculations discussed in Section 5.5 show that in these circumstances, and with the assumptions made, there should be little difficulty in capturing all the current. The current requirements from the linear accelerator can be smaller in this case therefore, and 350 mA has been specified. However, since all this current is concentrated in one bunch per seven cycles, space charge effects become severe and it may prove much more difficult to keep the beam within the required emittance and energy limits.

The electron accelerator consists of four 2 m. lengths of corrugated waveguide, using three corrugations per wavelength since this has been shown to give the highest shunt impedance. The guide is electroplated in 1 m. lengths on a special former which is then dissolved away. The required dimensional tolerances are ± 0.1 thou. The field and phase law in the buncher section has been designed to give a balance of bunching forces and space charge debunching forces under the conditions which will prevail when a chopped beam is injected. A prebuncher at 2855.16 Mc/s must also be used since it is likely that only current injected within a phase angle range of about 40° will lie within the specified limits of energy and emittance.

The electron gun will be of the bombardment type, the cathode initially being a tungsten button. Experiments were also carried out with dispenser cathodes but no conclusive results were available on this type by the time a decision had to be made for production planning.

The maximum power input into each guide is 15 MW, the design level being 11 MW. A mode transformer for matching power from the rectangular waveguide to the circular corrugated waveguide and which, it was hoped, would handle these high peak powers, has been specially developed.

*"Computer Studies of Capture of Large Injected Beams into an Electron Synchrotron". M. H. R. Donald and D. J. Thompson.

The RF amplifiers used to supply the accelerating waveguides are the C.S.F. F.2049 valves which are rated to give 30 MW peak power at 8 kW mean and 25 MW peak at 25 kW mean. The Laboratory have negotiated for six of these valves to be provided on a batch guarantee basis. The accelerator uses two valves and since each valve has two output connections from the final cavity no high power divider is necessary. High power phase shifters are needed, however, and these are to be of the 3 db coupler type.

The driver klystron is the Eimac X.3029, also used in the Stanford project, and this in turn is fed from a frequency multiplier supplied with 407.88 Mc/s power from the same source as will be used for the synchrotron r.f. accelerating system.

Since the high power klystrons are only about 40% efficient the modulators have to supply about 80 MW peak power. Four pulse forming networks are used, which are charged through a choke and discharged through the primary of a pulse transformer which combines the four pulses. The switch valve used is the CX.1159.

In order for it to meet the specification the r.f. pulses applied to the accelerator must be flat, for at least one microsecond in the middle of the pulse, to about 0.1% and also stable from one pulse to the next. This is to be achieved by a combination of two techniques, appropriate selection of tapping points of the coils of the pulse forming networks and the use of clipper circuits. Similar considerations apply to the drive klystron modulator, though in this case the chief reason is the avoidance of phase modulation effects.

Two closed cooling circuits are used on the equipment, one of which is controlled in temperature to a fraction of a degree for the cooling of the corrugated waveguides. The operating temperature may be set between 28° and 52°C to give some measure of tuning to the linear accelerator. Heat exchangers transfer the heat to the Laboratory raw water circuits.

Ten Ferranti 15 l/sec pumps will be used to maintain vacuum in the equipment, roughing out being done by a Pfeiffer turbomolecular pump.

The injector is to have its own control room, housing not only the linear accelerator controls, but also the controls for the beam transport elements between the injector and ring, for the linear accelerator test system and for the inflector. Essential controls are to be transferred to the main synchrotron control room.

A layout of the basement of the linear accelerator building is given in Fig. 11. The klystrons and modulators are housed on the floor above, immediately over the accelerator.

At the end of October 1965, the production position on the linear accelerator was as follows. All sections of the accelerator waveguide had been manufactured and tested, and were aligned in the M.E.L. test shelter ready for beaming tests. The drive system was fully commissioned and the high power klystrons had been run up to 30 MW r.f. output without difficulty. Various sections of corrugated waveguide had been outgassed and powered up to 15 MW without breakdown occurring, and the first section had accelerated a beam of up to 2 A without pulse shortening.

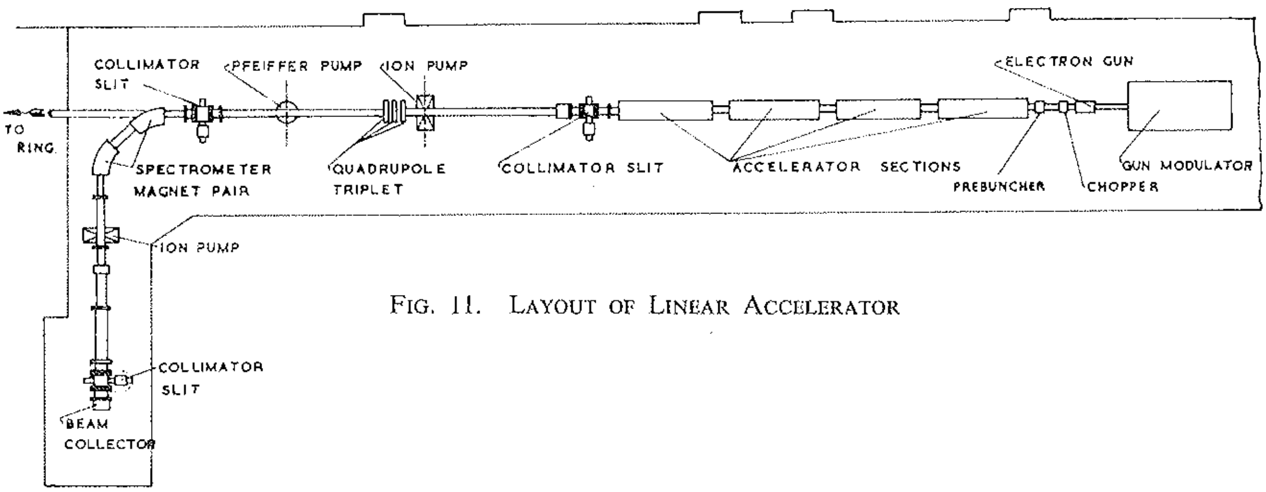


FIG. 11. LAYOUT OF LINEAR ACCELERATOR

These tests were carried out using temporary controls and an interim diode gun. The machine was then shut down in order that the permanent control racks could be connected in, and commissioning from these racks has commenced. It is hoped to run the complete accelerator during November and to dismantle it for shipment to Daresbury before the end of the year.

The additional work to provide a beam chopped at 408 Mc/s has proceeded as far as a basic design, but considerable development work remains to be done.

6.2. Injector Test System.

In order to test whether the linear accelerator gives the required performance a test system has been devised to measure emittance and energy spectrum. Emittance is to be measured by an arrangement consisting of two collimator slits and a quadrupole triplet. The latter is positioned between the slits at a distance equal to the focal length. Thus, a sample of the beam determined by the first slit may be analysed for divergence by scanning with the second slit.

The spectrometer consists of two 45° bending magnets spaced at such a distance that the focus in the plane of bending occurs at a point nearly 5 metres from the second magnet, thereby ensuring good resolution. A collimator slit at the focus will transmit a beam with 1 % energy spread if the gap is about 10 cm.

At the end of October 1965, the magnets and the quadrupole triplets, all made by Mullard, had been delivered. The collimator slit assemblies, made by Torvac, had also been received. All the interconnecting vacuum pipes and pumping system were on order. Work had been completed on shaping the fringe fields of the spectrometer magnets.

The bending magnets will be left in position when the synchrotron becomes operational so that the injector may be run on its own, at any time, with the beam diverted into a specially shielded "beam dump" area.

6.3. Injection Path.

The possibility of accelerating positrons has been anticipated in the design of the injection system. In order to obtain the maximum possible current, it is necessary to use the full aperture of the synchrotron in the most efficient way, since the emittance of the positron source is greater than the acceptance of the synchrotron, and the energy spectrum is very wide. This requires an injection system that puts each

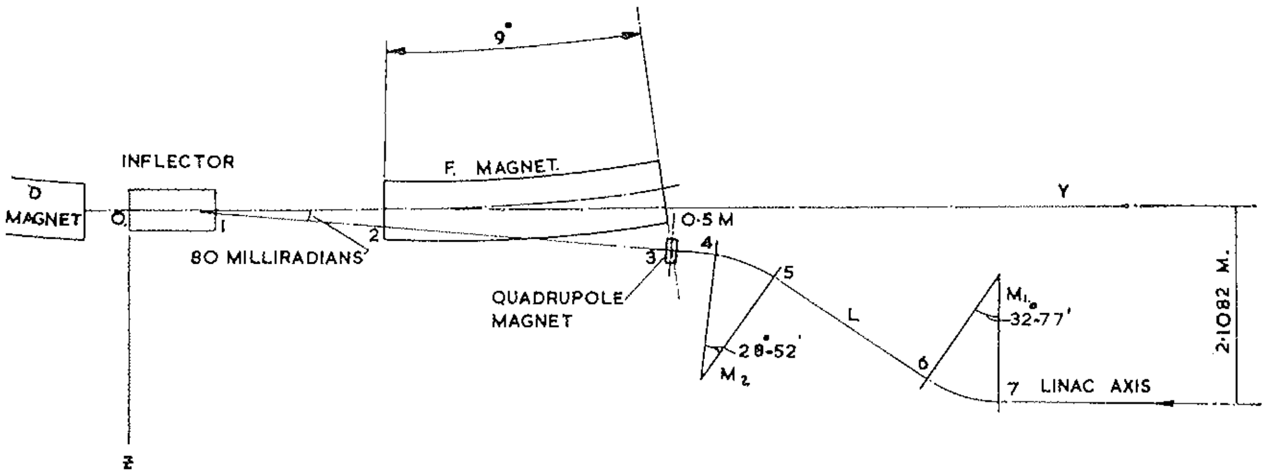


FIG. 12. (*a*) ARRANGEMENT OF INJECTION PATH

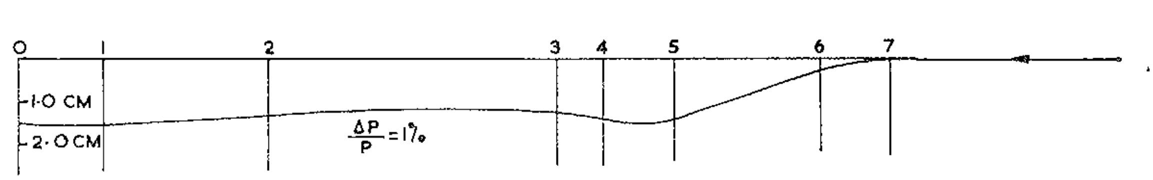


FIG. 12. (*b*) TRAJECTORY OF PARTICLE WITH MOMENTUM 1 % HIGH

positron into the orbit appropriate to its energy and emittance. Such matching is not new, but previously it has been possible to separate the functions of emittance and momentum matching. With the requirement for matching an emittance of up to 4×10^{-5} m.rad., and a momentum error of up to 2%, the use of separate matching systems in series would require excessively large apertures in the matching elements.

A number of schemes to overcome this difficulty were investigated, and one that seemed to show promise used a momentum matching system which included a momentum cross-over. With such a system, it should then be possible to place an emittance matching element at this cross-over without affecting the momentum match. However, in practice, such an element could not be effectively a "thin lens", and the system would have been difficult to set up and critical of adjustment. The present scheme, shown in Fig. 12, uses an inflector with a gradient in the magnetic field, which varies 2% per cm radially. This, with a single quadrupole, provides sufficient emittance matching to keep the aperture through the momentum matching system within reasonable bounds. The emittance match is completed by means of quadrupole triplets between the injector and the bending magnets. Fig. 12 shows the departure from the central path for a particle of momentum 1% high.

The parameters for the bending magnets and quadrupoles have been settled, and delivery of the former is expected during November.

6.4. **Inflector.**

As explained in DNPL.1, the magnet lattice to be used is "Focusing-Long straight-Defocusing-Short straight". This order was chosen to give the best arrangement for targetting and extraction of the electron beam, but it introduces some difficulties at injection. To inject the beam into a long straight, it must either pass through the fringe field of an F magnet, or the angle of inflection must be large. Computations showed that the non-linear fields in the fringe region would cause an increase in the emittance of the injected beam, particularly in the vertical plane. Although this might be tolerated for the injection of electrons, if the emittance of the linear accelerator is within the specified limit, the situation is different for the injection of positrons, where any increase of emittance will result in a reduction of the accepted positron current. Therefore the relatively large inflection angle of 80 milliradian was chosen, to keep the distance travelled through the fringe field to a minimum.

The inflector must provide a magnetic field of about 250 gauss over a length of 1 m. to give the required 80 milliradians deflection for 60 MeV positrons. This field must remain constant for the orbital period of the synchrotron, 0-736 microsec, and then fall to zero in as short a time as possible. The field must also have a constant gradient over the full aperture needed for the positron beam. The field will be provided by 50 rectangular ferrite frames, energised by two strip conductors. The ferrite frames are shaped on the inside to give the required field gradient.

The pulsing of the inflector presents a difficult problem, since a current of about 1000 A is needed. This current must be constant to about 1% during the pulse, and then fall to zero, without overshoot or ringing, in about 0.1 microsec. Consideration was given to the use of the conductors as a delay line by the addition of periodic lumped capacitors, but it was found possible to achieve close to the required performance without this complication. The design of the pulser has been developed by A.E.I. Limited, under a contract with DNPL and a simplified circuit is shown in Fig. 13.

To understand the operation of the circuit, assume the pulse forming network is charged up to +5 kV and that V_3 is not triggered. A half-sine-wave of current will flow through the relatively large inductor L, until the charge on the PFN reverses to about −5 kV, when the diode V_4 ceases to conduct. If thyratron V_1 is then triggered, a pulse of current will flow through the inflector coil. This will continue until the voltage across the PFN again reverses, since the resistance of the circuit is small. Just before this occurs, valve V_3 is triggered, applying +25 kV to the cathode of V_1. This stops the current flow through V_1 and the inflector very rapidly. Although V_1 is rated to stand 20 kV inverse voltage, it will not stand more than −5 kV if the voltage is reversed in as short a time as 0.1 microsec and the capacitor C_2 is chosen so that, by the time the current flow in V_1 has stopped, the voltage across C_2 has fallen to 5 kV. At this point, V_2 conducts, until the PFN is recharged to +5 kV, and the cycle is repeated.

Tests with a prototype of this circuit fed into a model of one quarter of the inflector have shown that it is possible to obtain a flat-top pulse with a fall time of less than 0.1 microsec. The "ringing" after the pulse was slightly larger than acceptable, but some of this may be attributable to the monitoring system.

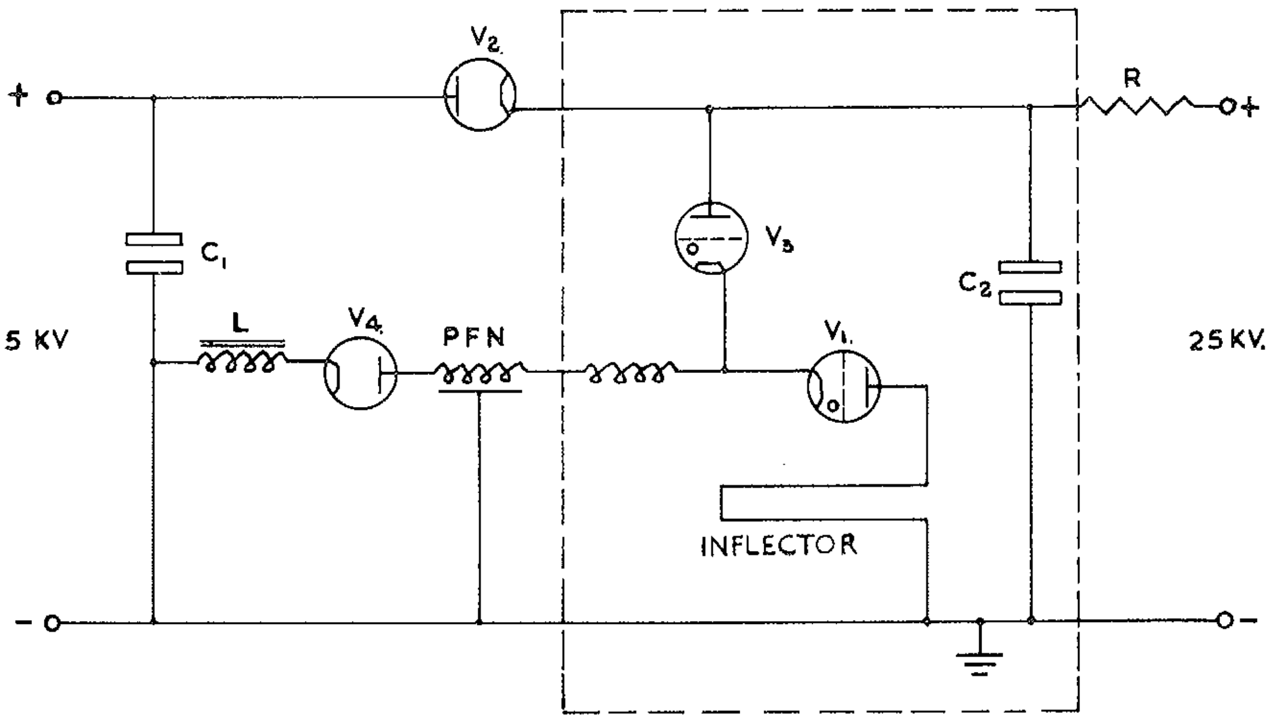


Fig. 13. Schematic Diagram of Inflector Modulator

Since this is very dependent on the exact layout, further work on this will be necessary when the actual pulser is available.

The inflector will be effectively in 4 sections, with the components shown within the dotted line of Fig. 13 repeated for each section.

The vacuum box to house the inflector has been ordered from Fairey Engineering Limited and the ferrite frames from Mullard Limited. A contract has been placed with Staveley-Smith Controls Limited for the construction of a pulser to the A.E.I. design, together with all the control circuits. Delivery is expected in February 1966.

7. CONTROL AND INSTRUMENTATION.

7.1. General.

The broad outline of the system of control of NINA has been decided. Many of the finer details have been committed to paper, and construction and installation work is well under way. However, a lot of detail points inevitably await the completion of design and development of some of the main components of the accelerator. Development work on most of the instrumentation systems is also in progress.

7.2. Main Control Room.

Most parts of the accelerator will be provided with local detailed controls and monitors, but the more important of these will be duplicated in the main control room. In this control room the equipment will be housed in standard 6 ft racks arranged in bays. The racks are separated by 6 in wide cable termination panels. The arrangement is illustrated in Fig. 14, which shows the allocation of racks for the remote monitoring and limited control of the various accelerator components. Certain controls which it may be necessary to adjust during running of the accelerator are grouped together in racks 18-21, which form a main control position.

Various common services, such as personnel safety, are also housed in some of the racks and an allocation has been made for future developments. A control computer, discussed later, is to be housed in the control room. It will be operated either automatically by programme, or by push buttons from the control centre, except when programmes are being entered or tested. Urgent computer communications to or from the shift engineer will be made by means of a printer keyboard on his desk.

Beyond the computer, racks become more closely associated with experimental work; some dealing with beam targetting and beam transport are shown in the figure. The rest of the room is allocated for control equipment for the experiments.

Building work on the control room has been completed. Most of the racks have been installed together with some minor items of equipment. The bulk of the installation and cabling remains to be done. The floor of the control room is made of 2 ft square sections supported at the corners and there is an 18 in cavity underneath. Any stretch of the floor may easily be lifted for installation of cables.

7.3. **Cabling.**

Because of the large diameter of NINA, cable runs may be up to 250 yards and the total amount of cable at present involved is about 100 miles. The work of scheduling and specifying these runs has almost been completed and installation is proceeding.

Coaxial cable, type UR.43, and sheathed and screened pvc insulated multicore cables (DEF 10 types C and R) are to be used as standard. The radiation resistance is considered adequate except in the immediate vicinity of the beam orbit, where hyperlon or mineral insulated cables are to be used. Crimped connectors are being used throughout and terminations for multicore cables are usually $\frac{1}{4}$ in tab and "push-on" type.

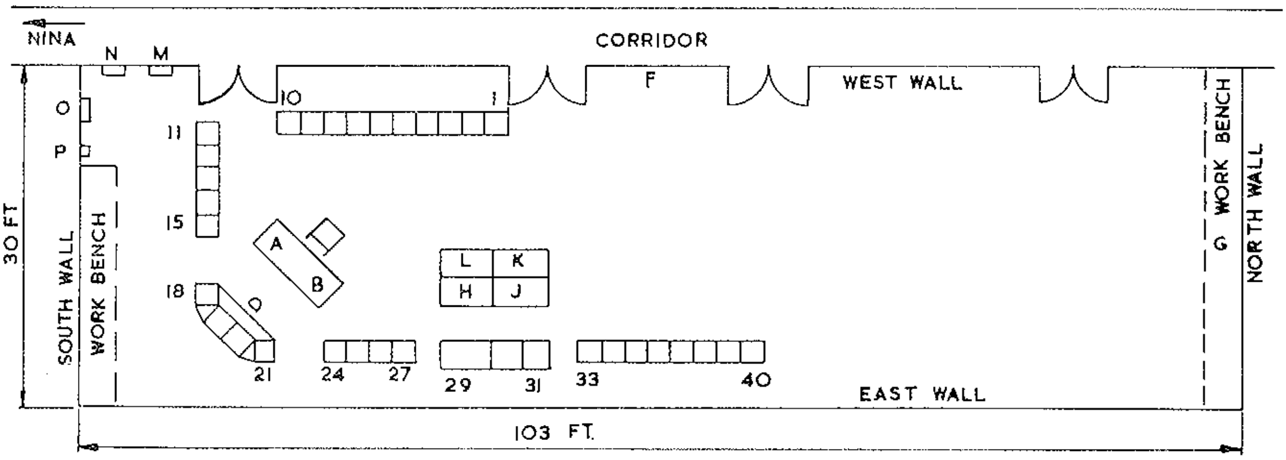


FIG. 14. CONTROL ROOM LAYOUT:—

Rack	1	Water	Racks	14 & 15	Beam Sensing
	2	Vacuum		18—21	Main Control Centre
	3	Injection		24	Beam Steering
	4	Spare		25	RF Waveguide Control
	5	Timing		26	RF Programme Control
	6	Health Physics		27	RF Amplifier Control
	7	Public Address		29—31	Computer/Logger
	8 & 9	Personnel Safety		33	Computer Input/Output
	10	Television		34—36	Development Work
	11	Magnet		37—40	Beam Handling
	12 & 13	Magnet Power Supplies			

A	Table with Telephone
B & H	Computer Printer/Keyboard
J	Card Read/Punch
K	Card and Tape Store
L	Tape Punch and Read
M & N	L. S. Telephone Exchange

7.4. **Controls Computer.**

A digital computer is being installed as part of the NINA instrumentation to assist in the operation of the accelerator. It is expected that its use will avoid the necessity for a multiplicity of specialised pieces of hardware, and it will provide a central data handling system for all parts of the accelerator equipment. This centralisation will enable the data to be processed as a whole or in combination, as well as in detail. Time division multiplexing to common equipment enables the data handling processes to be of greater complexity than is otherwise possible. Since the form of the processes will be controlled more by computer programme than by hardware, developments made necessary by changing ideas or conditions will rarely involve the upheaval of modifications to installed hardware.

The following processes are planned to be supplemented and extended by use of the computer:—

(*a*) Data logging
(*b*) Limit warnings
(*c*) On-line control.

The permanent data log for the accelerator will be kept on a punched paper tape. In this form subsequent computer analysis is easily possible. Printed records will be made only infrequently or when demanded, but it is planned to keep 10 hours of detailed back history of accelerator conditions stored in a volatile manner on a magnetic disc. This information will be available on demand.

A computer has the advantage over normal alarm limit warning devices in that it can easily consider the effect of other related measurements on a measurement that might be indicating an off-limit condition. In this way unnecessary warnings will often be avoided. On the other hand, the computer may frequently be able to give an early prediction that a limit is being approached, since it can have the past history available from which to detect a trend.

It is not planned to use the computer for on line control until some experience on its use and in the behaviour of NINA has been gained. The computer will, however, be delivered with a number of digital outputs capable of exerting control. Wherever possible the remote control circuits of accelerator equipment are being designed to be capable of control by these outputs.

A type 1800 computer has been ordered from I.B.M. It is due for delivery in January or February of 1966. Its brief specification is as follows:—

Fast store	—	8 k words
Cycle time	—	4 microsec
Word length	—	16 bits
Backing store	—	512,000 words on a magnetic disc
Interrupt levels	—	12 (with 16 events at each level)
External interrupt inputs	—	32
Digital inputs	—	5 16-bit words
Digital outputs	—	2 16-bit words
Analogue inputs	—	192 at 0.5 V f.s.d.
Scanning speed	—	100 points per second.

7.5. **Communications.**

On a large accelerator good communication between the various locations of the many pieces of ancillary equipment is essential. On NINA a variety of systems is being employed for reasons of greater reliability and suitability for different applications. The systems being installed are as follows:—

(*a*) A public address system with 30 loud-speakers and 2 battery operated transistorised amplifiers each of 200 W output.

(*b*) Loud-speaking telephones capable of automatic duplex operation. Many will have alternative hand sets. Two 20 line exchanges, each having two speech channels are being installed, one being reserved for machine operation, the other for physics experiments. It will be possible to link the two systems if necessary.

(*c*) A network of 6 core cables is being provided for setting up *ad hoc* communications as required. Telephone sockets are being positioned in all likely locations into which portable handsets or noise cancelling head sets may be plugged.

(*d*) The Laboratory has a P.O. licence for simplex radio telephone channels operating at 169.25 Mc/s and 169.35 Mc/s. A 5 W base station and six 0.2 W portable sets are already in use. Contact can be made throughout the site, even within the ring tunnel.

(*e*) Closed circuit television is to be installed in the ring tunnel near the main entrance and the injection point. These are remotely controlled and are principally for safety surveillance. In addition cables are being provided so that a more simple type of camera can be set up as required around the accelerator.

(*f*) Normal P.O. telephones, operating through the Laboratory exchanges will be installed.

All of this equipment is now to hand and installation is in progress. It is being pressed because of its value in installation work.

7.6. **Personnel Safety System.**

A comprehensive interlock system has been devised to avoid a beam being circulated in the ring whilst any person is within the radiation shielding. Its installation and manufacture is in progress.

The system is designed in form as follows:—

(*a*) Warnings will be broadcast over the public address system instructing personnel to retire from the radiation areas.

(*b*) Two men will search the areas. Their search will be made effective by locking doors and having a photo-electric detection system to make sure that no one can elude them. They will have to prove the thoroughness of their search by pressing push buttons and shutting doors in a prescribed routine in order for a preliminary interlock to be closed.

(*c*) All doors will then be locked and their keys placed in interlocked key presses.

(*d*) All access points will be electrically interlocked permitting machine operation only if the barriers are closed.

(*e*) Audible and visual warning of imminent start-up will be given by the loud-speakers and 160 flashing red lights. Emergency stop buttons will be located near to each of the lights.

It will be possible to give a small number of people access to the radiation areas for a limited period without destroying the search procedure interlock. The supervision of this procedure will be carried out remotely from the control room by electrical means, closed circuit television being used to give an additional safeguard.

The interlock logic circuits employed throughout this system will use solid state and magnetic core devices in a fail safe configuration. The types chosen have been used on the experimental reactor DIMPLE, are available commercially and are about to be delivered.

7.7. **Installed Radiation Detectors.**

A total of 12 radiation detectors will be used to monitor the radiation outside the screening walls. They will give both local warnings of high levels and a central display in the main control room. The detectors for this work use a simple logarithmic d.c. amplifier driven by TPA ionisation chambers filled with hydrogen at 20 atmospheres. Delivery of the equipment is expected shortly.

It was felt that the units used should be the simplest available device that would work from pulsed radiation sources, rather than one of the complex detection systems that are necessary to obtain invariably accurate measurements of radiation hazards under all conditions. A local calibration will therefore need to be applied to each unit when setting the alarm levels.

7.8. **Electronic Development.**

Quite a number of the instruments and electronic devices needed to operate NINA cannot be bought and need to be specially designed. Work is therefore in progress in the Controls Group Laboratories on several lines of urgent work. The aim is to develop and construct the systems named below in time for the commissioning of NINA.

(*a*) *Beam Sensing System.*

This is being devised to measure the intensity of the circulating beam and its vertical and radial deviation from the correct orbit in ten positions. A magnetic induction system will be used and the gap formed by the inflection system in the circumferential plot of the beam intensity can be made to produce an a.c. signal of frequency 1.36 Mc/s for measurement. The position sensing device has passed through its final stages of laboratory prototype testing and is in the hands of a manufacturer. It is a development of a C.E.A. design and takes the form of an assembly of aluminium conductors of about 1 in diameter. The conductors are arranged as the edges of a rectangular box and thus form pairs of loops at the sides and above and below the beam. Currents caused to circulate in these loops by the beam can be sensed by "current transformers" placed round the conductors at one end. These current transformers employ magnetic dust core toroids and their signals can be used to show deviations of the beam from the central position. The prototype has been tested using a wire carrying a pulsed current. It appears to be able to sense deviations of beam path as low as 0.003 in for a circulating beam current of 30 mA (1 micro-amp mean). The sensitivity varies directly with beam current, but even allowing for this, adequate sensitivities should be available for low currents that will exist during the commissioning period.

(*b*) *Timing Pulse Systems.*

Timing pulses for synchronising the injector and r.f. equipment will be generated by peaking strips in one of the magnet gaps. Electronic equipment for processing these pulses is being developed. For pulses arranged to occur at high beam energies, two systems are being developed. One will be timed by the magnetic field level. This will employ a counting system to integrate the output from a voltage to frequency converter that has a magnetic pick up coil as its input device. The other will be timed by magnet current phase. It will also employ a counting system but the driving source in this case will be an oscillator locked to a harmonic of the magnet frequency by means of a servo system.

(*c*) *Multiple Display Systems.*

It is often convenient to be able to display in a single place the measurements made of the behaviour of pieces of identical equipment that are used in large numbers. On NINA two examples are the currents in the vacuum pumps of which there are about 50 and the currents in the pole face windings and the Helmholtz coils (45). Time division multiplexing circuits are therefore being devised so that these groups of measurements may be displayed collectively on cathode ray tube screens. Scanning will be performed by reed relays into storage condensers at about 50 points per second. To avoid flicker on the C.R.T. screens, the condensers will be scanned by transistor switching circuits at a rate of about one complete scan per millisecond. A logarithmic amplifier will be introduced into the system for vacuum pump currents in order to produce a more useful display.

(*d*) *Beam Steering Power Supplies.*

It has been necessary to develop special d.c. power supply equipment for the pole face windings and Helmholtz coils used to steer the beam at low energies. These require currents of long-term stability in the region of 1 % of their maximum rating, and they need remote controls giving variation from zero to full rating in both positive and negative directions. Although a large fraction of the 50 c/s induced voltage in the pole face windings will be bucked by a special magnet used as a bucking transformer, some alternating voltage will remain, and this will be an additional complication. The ability to control and stabilise the wide range of currents has been given to those units by the well tried method of using series transistors. This simple technique has been found to have advantages over the several other possible means of current control. Twenty-four double power supply units are now in production under contract. Prototypes made in the laboratory are being used as models. A number of other special power supply units are also being constructed in the laboratory.

(*e*) *Pulsed Power Supplies.*

Work has just started on the development of units for the production of pulses of current to pass through back leg windings on some of the magnets. Beam position control at high energies in connection with target systems and the like is the objective of this work. The units will take the general form of lumped constant lines with pulsing circuits using silicon controlled rectifiers.

8. ACCELERATOR DEVELOPMENT.

8.1. Targetting.

With the magnet arrangement to be used, if a target is placed near the end of an F magnet, the photon beam can be extracted in the long straight following, without the need for a special branched vacuum chamber in the D magnet. To enable targets to be used in such a position, on the outside of the orbit, "beam bumps" are to be provided. These beam bumps are local distortions of the equilibrium orbit caused by pulse currents in back leg windings on some of the F magnets. In order to avoid the excitation of transients in the magnet system by the application of these pulse currents, it is proposed to use a system extending over three half wavelengths of the betatron oscillations, giving three bumps of relative amplitude $-\frac{1}{2}$, $+1$, $-\frac{1}{2}$. If all the magnets affected were within a single group, the net excitation would be zero, but since they spread over more than one group, there is some resultant transient, but this is not expected to be large enough to be troublesome.

The pulse currents for the back leg windings will be of the type using a pulse-forming network charged from a d.c. supply and discharged by an s.c.r. through the windings. Pulse lengths from 1 to 3 milliseconds will be provided.

8.2. Beam Ejection.

A system for the ejection of the electron beam has been settled in outline, and detail design is proceeding. The basic principle is the same as that used elsewhere, in which the betatron oscillations in the beam are increased by the non-linear field produced by a current strip parallel to the beam, until they are of sufficient amplitude to cause the electrons to pass the other side of the strip. The field they experience here, being of opposite sign, causes a further perturbation of the orbit, which brings them subsequently into a "kicker" magnet, where a high field deflects the electrons onto a path which comes out of the synchrotron. In the case of NINA, it has been found possible to mount the current strip and kicker magnet together in a long straight, on the outside of the orbit. Computations show that about 70% of the circulating beam should be extracted over a period of about 1 ms, giving an external beam of small emittance (less than 10^{-5} m.radian).

9. PHYSICS APPARATUS.

9.1. Measurement Techniques.

The laboratory allocated to the group has been equipped and is in use. Work is concentrated on:

(*a*) multiplate and wide gap spark chambers and ancillary devices such as Marx generators;

(*b*) scintillation counters, for which a standard housing exists in prototype form;

and

(*c*) Cerenkov counters; preliminary studies being directed towards a threshold counter for detecting high energy electrons.

A study has been completed in collaboration with the universities of Manchester, Liverpool and Glasgow of available fast counting systems with a view to the selection of a standard system for use by resident and visiting experimental teams. As a result of this study the M100 fast modular logic system of Edgerton, Germeshausen and Grier has been adopted and orders have been and will be placed to provide a stock of equipment sufficient to fill the needs of teams proposing to carry out experiments at NINA.

9.2. Experimental Quadrupoles, Magnets and Power Supplies.

Tenders have been invited for the quadrupoles given in Table I.

Diameter of inscribed circle cm.	*Aperture* cm.	*Effective length* cm.	*Max. field gradient* kGs/cm.	*Power* kW	*No. to be ordered*
29	10.2 × 40.8	105.6	1.104	400	6
29 (H.Q.)	~10.2 × 20.4	105.6	1.104	200	2
16	5.7 × 22.8	104.3	1.972	400	4
16 (H.Q.)	~ 5.7 × 11.4	104.3	1.972	200	2
35	12.6 × 50.4	66.0	0.915	400	2

H.Q. = half quadrupole.

Six bending magnets are to be ordered with a gap 16.8 × 51 cm, 1.300 m. long with a maximum field strength of 21 kGs and a power requirement of 400 kW. Also two bending magnets with detachable pole pieces are proposed so that they can be constructed either with a constant field or with a desired field gradient. These magnets are to have an aperature of 10 × 40 cm and length of 1.077 m. with a field gradient of 0.5 kGs/cm. when used with shaped poles and a field strength of 15 kGs when used with parallel poles. The power requirement is 200 kW each.

Power supplies are required for the magnets and quadrupoles and tenders have been obtained for these. The requirement so far planned is for six 400 kW units, four 200 kW units, six 100 kW units and four 25 kW units. All these supplies are to be stable to 0.01 % over a 12 hour period.

10. SERVICES GROUP.

Siting of the Laboratory together with brief descriptions of buildings was given in the previous report DNPL.1 and the layout of the buildings is shown in Fig. 15. Apart from the computer building, which came on a later programme, all buildings are virtually finished and good progress has been made on the work of finishing off the external areas. Grassing is almost complete and later in the year a vigorous tree and hedge planting programme is planned.

The photograph, Fig. 16 is a view of the site in October 1963 and Fig. 17 shows the site in April 1965.

In DNPL.1 reference was made to the work of the United Kingdom Atomic Energy Authority's Engineering Group. The task of completing such a considerable civil engineering work is in no small way due to their excellent design, construction and contractual work. To have constructed approximately £1.5M of work from November 1963 to June 1965 is to their credit, and, to add to it, that they kept well to the cost estimate and the programme is but an indication of how successful has been the co-operation of themselves and the main contractor with the client.

10.1. Accelerator Buildings.

This complex building contains the Electron Hall, Inner Hall and the Magnet Ring Building. The latter is temperature controlled to ±1°C in order to maintain stability of the magnet foundations and the magnet structure. The automatic air conditioning plant which regulates the temperature has been commissioned and is working satisfactorily. Some influence of draughts from the underground service corridors had to be reduced by isolating these corridors where they entered the lower part of the Magnet Ring building.

Work of the survey of the magnet foundations and check work on the survey monuments continues. This work is to assess the effects of the following:—

(*a*) the placing of earth mounding on the top and side of the Magnet Ring Building; and

(*b*) the introduction of over 5,000 tons of concrete shielding blocks which form a tunnel for the magnet structure in the Electron Hall.

The shielding blocks have been installed at this stage in order that accurate positioning of the magnets may be carried out with the ultimate load in the building. Because of access required for installation purposes it is not possible to place the shielding blocks in their final position but this will be done in May-June 1966. In order to conserve floor area it is now proposed that part of the outer concrete shield be replaced by cast iron.

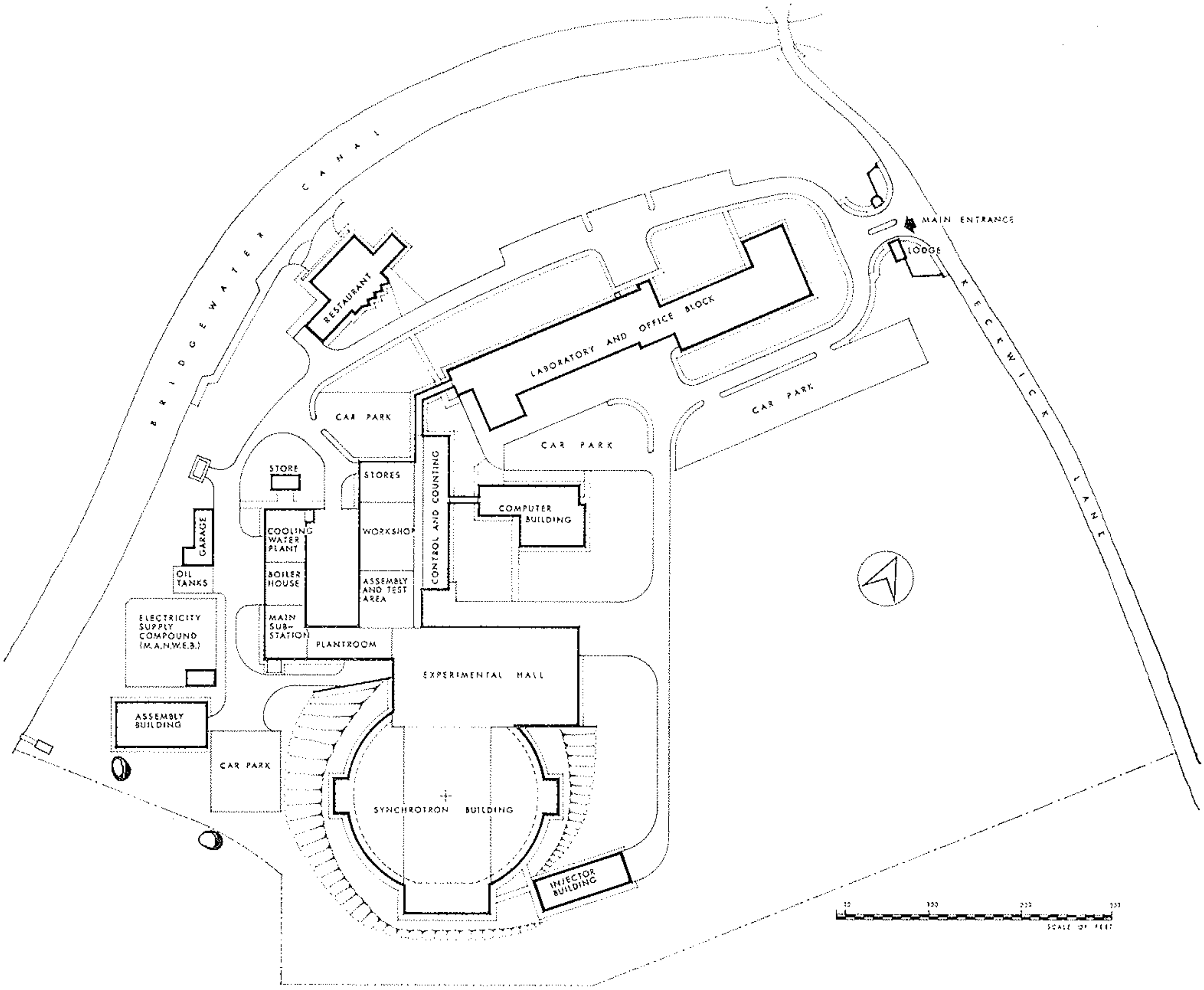
The Electron Hall is being used as a temporary assembly area for the erection of the magnet units.

10.2. Service Buildings for the Accelerator.

The installation of the first phase of the electrical supply 4,000 kVA is now complete. Work is in hand to increase this to 10,000 kVA and a d.c. supply of 4 MW will be available for experimental purposes.

A small 250 kVA diesel generator set is being installed. The main function of this set is to provide a standby supply to the main cooling water pump in order to provide fire protection for the magnet power supply plant.

The cooling water plant which uses water from the Bridgewater Canal is now commissioned. At this stage plant to provide approximately 3,500 g.p.m. of canal water has been installed, though the head and return main have been designed to cope with approximately 5,700 g.p.m. which will provide for the ultimate cooling load of approximately 15,000 kVA.



DARESBURY NUCLEAR PHYSICS LABORATORY

FIG. 15. LAYOUT OF BUILDINGS AT DARESBURY

Some of the canal water is distributed through the accelerator and other buildings to cool air conditioning plant, air compressors, local plant heat exchangers, etc. The rest of the canal water will be circulated through heat exchangers in the plant room. The secondary cooling systems use demineralised water and provide cooling for the magnet coils and the experimental equipment. All this plant including the demineralised water treatment plant is situated in the water cooling plant room.

In order to prevent algae growths in the main carrying the canal water it is necessary to carry out frequent chlorination tests. As residual chlorine in the return mains would probably prove injurious to the fish life it has to be removed by the addition of sulphur dioxide. Extreme care in the operation and control of this plant and frequent analyses of the water are necessary in order to prevent any pollution of the water, the Bridgewater Canal being a "mecca" for local anglers.

FIG. 16. THE SITE IN OCTOBER 1963

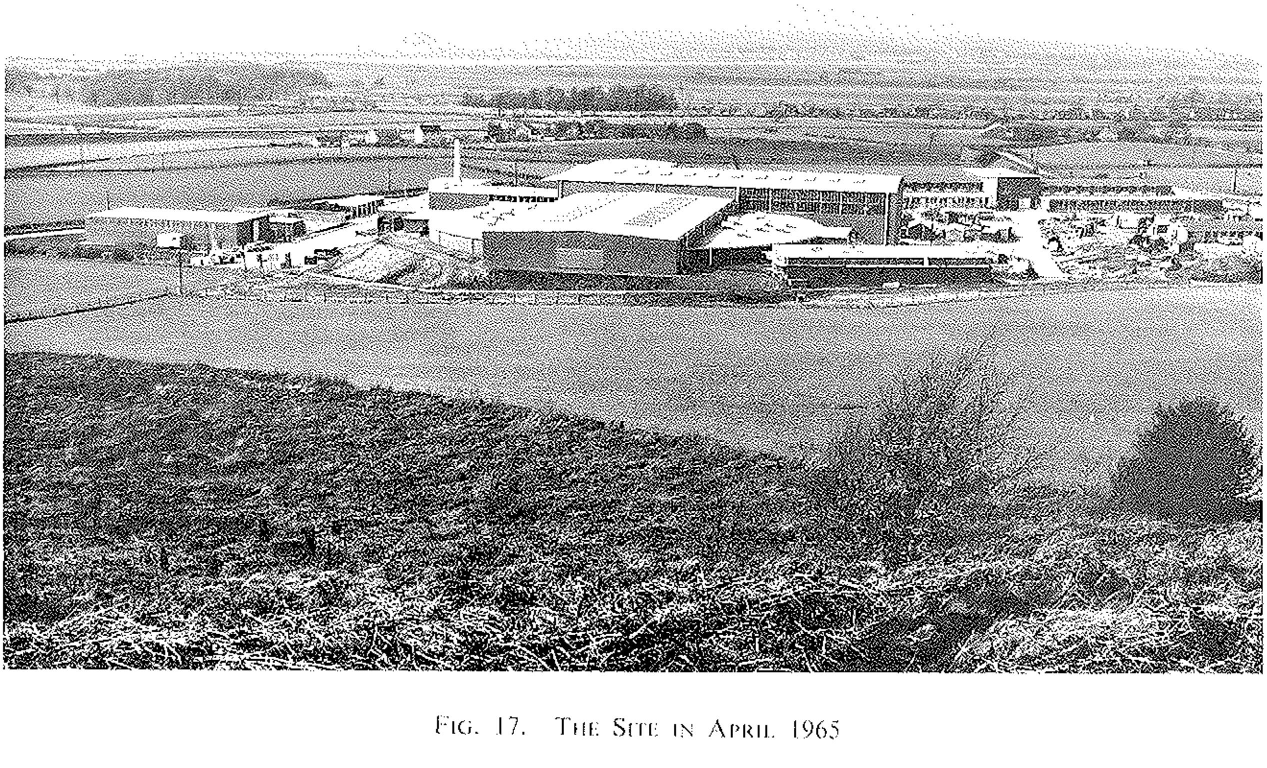


FIG. 17. THE SITE IN APRIL 1965

The boilers and associated plant are now fully operational. A high pressure hot water system is used for the main distribution from the boiler house to the various buildings. Some buildings use the high pressure hot water system directly for heating whilst, in others, the supplies call for a low pressure system or heater batteries on a plenum system.

10.3. Research Services Buildings.

This group contains the Control Room, Workshop, Stores and Assembly area. The former is a single storey building and is isolated from the latter by a corridor. The Control Room is complete and installation of the control equipment has started. In the Workshop and Stores area the installation of machine tools and other equipment is complete and both areas are operational.

10.4. Laboratory and Office Block.

Part of this building has been occupied since the end of 1964 and the complete building was finished in the summer of 1965. On the ground floor are a series of laboratories, in which experimental work connected with the RF, injection and vacuum systems is proceeding, as well as the development of experimental physics equipment. A number of laboratories are reserved for use by visiting University teams.

At one end of the block is a Library, which is gradually being stocked with a useful range of technical and scientific books and journals, and a large room used for lectures and conferences.

10.5. Further Building Development.

Two new buildings have been designed, one to house a computer and its associated equipment and the other for the testing of hydrogen targets. The computer building is to be adjacent to the main Control Room, to which it is to be linked, and will consists of a single storey building of about 5,000 square feet floor area. The computer room itself is to be an open-spanned room and fully air-conditioned. At present the site is being prepared and completion of the building is expected in August 1966.

10.6. Design Services.

The Group Design and Drawing Office is fully occupied and is backed up by a small team of engineers who up to date have been mainly employed in the technical work associated with the design of the whole laboratory. This work has eased off and more engineering effort has been made available to the Experimental Groups. Such work involves target design, magnet design, beam lines, etc.