DNPL 05

4 GeV ELECTRON SYNCHROTRON

Progress Report for the Period 1st November, 1966 to 31st May, 1967

Daresbury Nuclear Physics Laboratory
Daresbury, Nr. Warrington, Lancashire

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CONTENTS

1. INTRODUCTION

This progress report is concerned with an exciting period in the history of the Laboratory, namely the period during which the 4 GeV electron synchrotron, NINA, was first brought into operation. This occurred in December, 1966, when an energy of 4.5 GeV was achieved.

Regular running of the machine started in January, 1967 for investigations into its behaviour, for targetting and for determination of external photon beam lines. After Easter, a two-shift system of operation commenced, the machine being operated from 8.00 a.m. until 10.00 p.m. each day for 10 consecutive days followed by a 4 day maintenance period. About half the beaming time was allocated for machine start-up, synchrotron investigations, targetting and electron beam extraction work, the remainder being shared by the experimental groups.

During these early months of operation the activities of the Applied Physics and Machine Groups have been inextricably bound together, so no attempt has been made to report these activities separately in what follows.

2. THE COMMISSIONING OF NINA

As reported in DNPL 4, injection trials were carried out in early October, 1966, during which the ring magnets were energised at injection level from a d.c. supply. There followed a period of a few weeks during which the a.c. supply to the magnet network was commissioned and various other preparatory work completed, such as the commissioning of the personnel safety system.

On the 30th November, injection tests were recommenced, this time with an alternating field in the magnets. After adjustment of the pole-face windings the beam could be retained for up to 10 turns of the ring. Tests were interrupted by a vacuum failure caused by the beam from the injector which, during adjustment, produced local overheating of part of the flight path.

Tests were resumed on 2nd December, the injector beam being switched on at 2.00 p.m. At 3.30 p.m., shortly after the r.f. supply to the cavities was switched on, a beam of about 1 mA was accelerated, at first to 2.5 GeV and then to 3.3 GeV. The beam was lost, however, when an attempt was made to obtain 4 GeV, but was regained when the magnet current was reduced to the equivalent of 3.3 GeV.

On the following day, a further attempt was made to achieve 4 GeV. With the magnet current set to the appropriate value, the beam was lost after about 100 microseconds. This loss was so abrupt that it seemed clear that it was due to a stop-band, and, by re-adjustment of the quadrupole pole-face windings, another condition was obtained for acceptance into the initial orbits, but in this case the beam was not lost and could be accelerated to the full energy. After some optimisation of controls, a circulating current peaking up to over 10 mA was obtained at an energy of 4.1 GeV. Optimisation was made more difficult by instability of the injected beam.

As explained in the previous report, difficulties with the RCA 2054 triode meant that during this first commissioning, and for some months following, the r.f. power for accelerating the beam had to be obtained from the driver tetrode.

On Monday, 5th December, to check the stability of the various parameters, the machine was switched on with all controls at the same settings as before. The only adjustment necessary to obtain an accelerated beam was to the bias on the peaking strip which determines injection timing. Then the magnet current was slowly increased to the equivalent of 4.5 GeV. At this energy a large proportion of the beam was lost near the peak of the magnet cycle, as the peak power available from the driver, about 80 kW, was not sufficient to compensate for the higher radiation losses. However, about 0.7 mA of circulating current was accelerated to 4.5 GeV.

The only other investigation undertaken during this first period of running was to look for the effect of possible transmission line modes in the magnet power supply network on the running of the machine. The method of targetting and beam extraction used in NINA requires closed orbit distortions at high energy (or "beam bumps") produced by pulses applied to magnet back-leg windings. Such pulses can excite transmission line modes in the network which may effect the magnet field distribution at the next injection point causing loss of beam. The synchrotron was, therefore, run with a beam bump applied of such an amplitude as to give a 3 cm. displacement to the beam at maximum energy. It was found that the transmission line mode excited by the front of the pulse was sufficient to disturb injection conditions and prevent acceleration during the next three cycles. However, when the magnets and capacitors were isolated from earth, thus increasing the frequency of the transmission line mode, only one cycle was lost. It was clear that further investigation was needed to reduce the effect of these modes and this is reported in Section 3.6.

Following this investigation the machine was shut down for a few weeks, chiefly in order to improve the stability and performance of the linear accelerator. Early in 1967, regular operation of NINA was started and systematic investigations were then undertaken of the characteristics of the synchrotron. Some of this work is reported in the next section.

3. SYNCHROTRON INVESTIGATIONS

3.1 Introduction

A number of investigations into the behaviour of the synchrotron were undertaken during the period January to May, after which the machine was shut down for about one month. The time available for such investigations was limited in view of the requirements of experimental physics teams and the necessity to push ahead with beam extraction work. A number of initial operational troubles further restricted the amount of time which could be spent on the investigations. A further difficulty was that the beam injected into the synchrotron tended to be variable and to have a beat at about 3 c/s, the difference between the magnet network frequency and that of the a.c. supply. However, some useful results were obtained. The injection energy has been held at 45 MeV throughout this period.

3.2 Available Aperture

The pole-face windings which give dipole corrections to the field distribution at injection have been re-optimised a number of times. There are two sets of windings giving this correction. One alters the differential field between F and D magnets uniformly all round the ring and it was known from magnetic field measurements that a correction of this sort would be needed. The other set of windings is on F magnets only and arranged in triads. These cause a local distortion of the beam at low energies and by increasing the current in each triad until the beam is lost, in each direction, the effective aperture can be found and the optimum setting to give a central beam determined. Near the inflector the position of the injected beam has to be varied to match the displaced orbit. At each re-optimisation the pattern of currents in these windings around the ring has been the same, i.e. the peaks have been in the same places and there have been about 5 such peaks around the ring. (The nominal Q value is 5.25.)

It appeared from these investigations that the available radial aperture round most of the ring was about 14 cm.

Similar observations have been made in the vertical plane. In this case the corrections are made by means of Helmholtz coils. Again the pattern of corrections remains unchanged although there has been some reduction in the maximum amplitudes of the corrections.

3.3 Quadrupole Corrections

Provision was made in the pole-face windings for both quadrupole and sextupole corrections to the fields at injection. All running so far has been done without sextupole corrections. It is possible also to run with the D magnet quadrupoles at zero but it is always necessary to use the F magnet quadrupoles. At first a rather high F quadrupole setting was needed giving a ΔQ_r of 0.51, but this has been progressively reduced. A satisfactory beam has been circulated with ΔQ_r as low as 0.10 but the usual correction is about 0.24. ΔQ_v is always small.

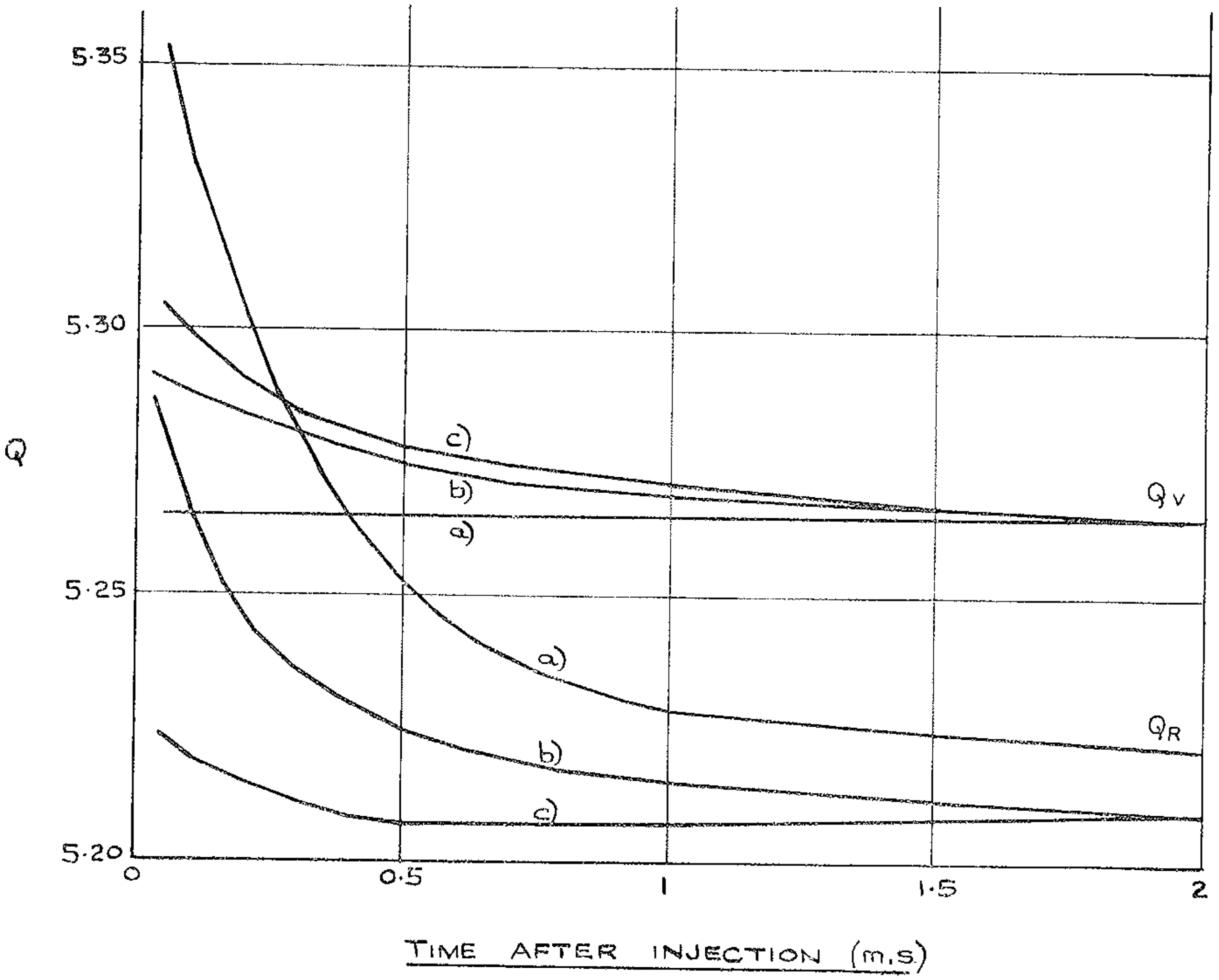

FIG. 1 VARIATION OF Q VALUES DURING THE CYCLE
(*a*) $\Delta Q_R + .28$, $\Delta Q_V - .05$
(*b*) $\Delta Q_R + .17$, $\Delta Q_V - .05$
(*c*) $\Delta Q_R + .10$, $\Delta Q_V - .03$

In the course of these investigations, use has been made of a special device for measuring Q values using r.f. deflecting fields at a frequency in the neighbourhood of 7 Mc/s in conjunction with beam position and total current monitors. This device is described in section 5.6.

Typical results of Q measurements throughout the cycle are shown in Fig. 1, for 3 settings of the F and D quadrupoles. These curves show that it is possible to obtain almost flat Q values from injection to high energy in both planes simultaneously. However, the highest accelerated current is usually obtained when Q_v is relatively flat at 5.265 and Q_r ranges from just under 5.5 near injection to its high energy value of 5.21.

3.4 **Momentum Acceptance**

For reasons not yet understood there appears to be a restriction in the momentum acceptance of the machine. This is thought to be relatively independent of r.f. capture effects, in that there appears to be loss of circulating beam over the first turn or two whether or not the accelerating field is applied.

There is a collimator slit between the two bending magnets in the injection path which controls the energy range of electrons entering the machine. Measurements have been made of the amplitude of beam current in the ring at the 5th turn and at high energy as this collimator slit width is varied. The results, shown in Fig. 2, are rather unexpected. They show a continuous reduction in the proportion of injected current accelerated as the slit is increased from a very small width. The loss with wide slits does not appear to be due to beam loading, which is beginning to be noticeable with 40 mA circulating beam, the maximum so far accelerated.

Not much increase in the high energy beam current occurs as the slit is opened wider than about 8 mm. This width corresponds to about ½% momentum spread for a beam of zero emittance. This apparent restriction on the momentum acceptance of the synchrotron is made more puzzling by the fact that it is possible to vary the magnetic field at injection over a range of 2½% between values where complete beam loss occurs and there is little change in the beam current over the middle 1% of this range. It is proposed to carry out a thorough investigation of the momentum matching system of the injected beam to try and find the cause of this anomalous behaviour.

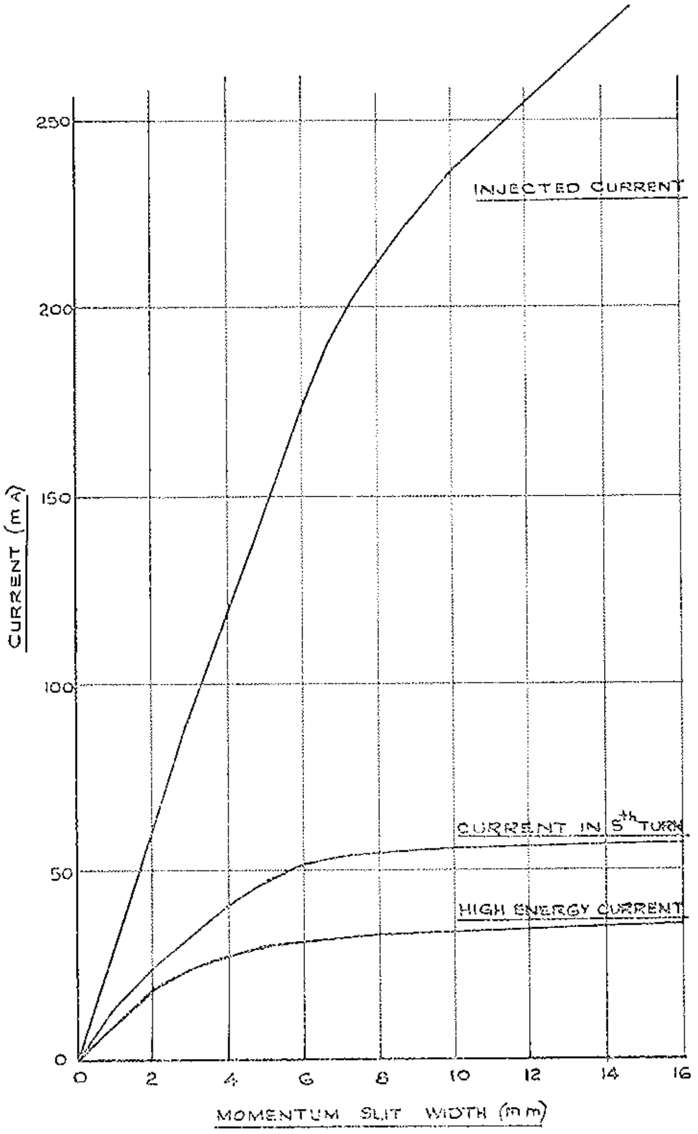

FIG. 2 VARIATION OF INJECTED AND ACCELERATED CURRENTS WITH MOMENTUM SPREAD AT INJECTION

3.5 **R.F. Capture**

Some experiments have been carried out to assess r.f. capture with the beam current small enough not to present cavity beam loading effects. A complex system of feedback controls, cavity detuning and frequency modulation will later be commissioned to compensate for beam loading. R.F. capture at injection was found to be insensitive to injection field amplitude. The optimum stable phase angle near injection was 22° but could be varied from 8° to 55° at which extremes the beam was just lost.

At present the injector produces 7 bunches per cycle of the accelerating field. It is possible to vary the relative phase of these bunches over about 90°. The effect of this variation on the beam current was assessed and it was found that there were two optima separated by about 50°, as expected, and the total swing of beam current amplitude was 14%.

3.6 **Delay Line Modes of Resonance**

It was found that the resonant magnet network of NINA, in common with those of other synchrotrons, exhibited modes of oscillation that involved the magnet inductances resonating with the stray capacitances from the magnet system to earth. When these "delay line" modes of resonance were excited, standing waves of current and voltage were observed in the magnet coils, and the magnet flux varied round the magnet circuit. This led to orbit disturbances, severe enough to cause loss of the electron beam in some cases.

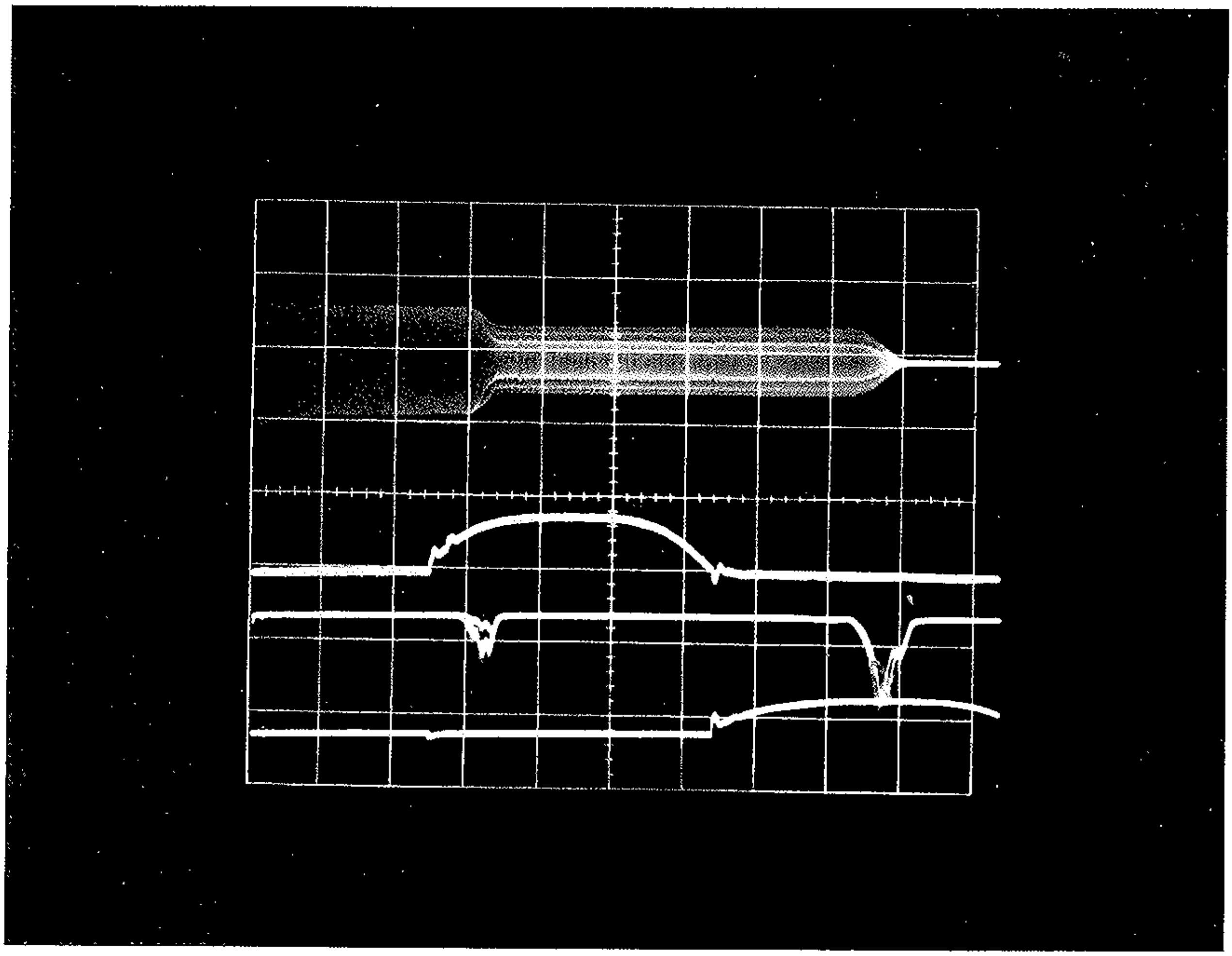

Fig. 3 Oscilloscope Photograph Illustrating Sharing of Beam Between Two Targets on the Same Cycle

(*a*) the circulating electron beam as function of time

(*b and d*) beam bump amplitudes

(*c*) spills from two targets

The oscillations were very strongly excited by the magnet flux excursions or "beam bumps", that are used to deflect the electrons at high energies, and it was found that the use of a large beam bump could cause the loss of beam for up to two subsequent acceleration cycles.

A system of damping loops was inserted which coupled magnets in different positions in the network, and extracted energy from the undesired resonance. It was found that the loops successfully increased the damping of the oscillations and improved the machine acceptance for the disturbed cycles after beam bumping. It is thought that a sufficiently large number of these loops will prevent the oscillation from disturbing the beam, and work to this end is proceeding at the moment.

The modes of resonance were also excited by the energy pulse that maintains the alternating current in the magnet power supply. When this pulse was triggered during the ascending portion of the magnet flux waveform, i.e. during the acceleration period, no beam disturbance was observed. However, when the pulse occurred during the flux descent, about 5 ms prior to the next injection instant, the beam acceptance at injection decreased by a factor of two. For this reason it was decided to operate the machine in the first of these two conditions.

3.7 Targetting

The first high energy photon beam was brought out into the Manchester experimental area during February and measurements were made of its intensity and its direction. The internal target was positioned so that the photon beam emerged clearly through the beam exit window without striking the r.f. cavity in the straight section following the target. When the collimators had been positioned in the beam it was then used for the first time by the Manchester team. The beam intensity was about 10^{10} equivalent quanta per pulse and the spill time was initially 100 to 200 μs but this was later improved to 500 μs.

Photon beams were brought out into the Daresbury and Liverpool experimental areas in March/April and their beam equipment aligned. The three beams can be brought out into the areas in sequence allowing the experiments to run in parallel.

Investigations have been carried out to try to find methods of improving the beam duty cycle to the experimenters. This can be done in two ways: (*a*) by improving the spill time, and (*b*) by sharing the beam simultaneously between two users.

Optimisation of the beam bump excitation currents have resulted in an improvement in spill times but the inflexibility of the bump generator is a limitation, and further improvements must await modifications to the beam bump supply.

Investigations showed that although two beams could be produced by energising two beam bumps simultaneously the angle of emission of the beams was altered considerably, making this technique impracticable. It was shown, however, that beam sharing during the same acceleration cycle was possible without any alteration of the beam directions providing the beam bumps did not overlap in time.

The photograph (Fig. 3) shows an example of this. The first spill is caused by a beam bump on to the Daresbury photon target and the second spill by a beam bump on to the Manchester target. The sharing ratio of beam intensity could be altered to give any desired value, e.g. in the example the ratio was 40% to Daresbury and 60% to Manchester. Although at present the spill time during the rise is rather poor this will be improved by shaping the beam bump waveform suitably. When an experimenter requires only low intensity and low energy and is prepared to tolerate some variation of beam energy during the spill this technique is of considerable interest.

4. BEAM EXTRACTION

4.1. Extraction Experiments

The extraction equipment, described in a previous report, was installed in one of the long straight sections in the ring at the beginning of March, 1967. In this part of the ring there is sufficient space for diagnostic equipment for measuring emittance and other properties of the extracted beam.

The first attempt to extract the beam was made on 10th April. Initial studies were carried out using two scintillation screens with television cameras relaying pictures to the Main Control Room. An intensity monitor of the same type as used in the ring, but using a narrow bend amplifier to give greater sensitivity, was used to give an estimate of spill time and intensity of the extracted beam. As a further check a simple Faraday Cup was constructed.

At first no correlation existed between the two types of beam intensity monitor, but it was then discovered that the beam of extracted electrons was not emerging along the expected line and hence not striking the Faraday Cup. When some repositioning had taken place, the two intensity monitors showed a reasonable agreement. In the early stages extraction efficiency was only of the order of 10%. On investigation it was found that a considerable beam loss was taking place in a part of the ring away from the extraction equipment. This was shown to be due to the residual ripple in the orbit due to an imperfectly compensated beam bump which, adding to the orbit distortion occasioned by the regenerator strip, caused the observed loss. As a preliminary step the ripple was reduced by using a second beam bump centred on a different magnet. This resulted in a threefold increase in extraction efficiency.

Initial studies were done at 3 GeV. The width of the emergent beam (at half intensity) in the horizontal plane was 1.45 cm at 8 m from the exit window, the equivalent figure in the vertical plane being 1.8 cm.

The conditions under which extraction could be achieved were found to be substantially different from those predicted. The theory indicates that extraction should be possible with little or no beam bump. In practice it was found that a large beam bump was required and that its amplitude was critical. It was also thought that the position and direction of the beam were not in agreement with theoretical predictions, but measurements showed that the field in the kicker magnet was lower than had been expected and this accounted for the discrepancy.

A modification to the beam bump system is to be carried out which it is expected will eliminate the ripple around the rest of the ring and so avoid the necessity for using two beam bumps. Further measurements of the properties of the extracted beam will be made.

4.2 The Faraday Cup

A Faraday cup has been designed to take the 10 microamps of 4 GeV electrons, an equivalent power of 40 kW, even if the beam is focused down to a small spot. Because of this, it is necessary to water-cool the central part of the cup, and choose the thickness and composition of the absorbing medium with care. This central part, comprising the first 25 radiation lengths, is made up of a number of water cooled plates, 9 in × 9 in. The first 10 radiation lengths of these plates are of copper aluminium alloy, 40% copper, 60% aluminium, having a radiation length of 3 cm. There are 12 plates of $\frac{1}{2}$ in thickness followed by 6 plates of 1 in thickness. The next 15 radiation lengths of absorber consist of copper plates, radiation length 1.5 cm.

The central water-cooled unit fits into a cylindrical lead block which has a 6 in diameter beam entrance hole. The block is insulated from ground inside an evacuated box. A guard ring is incorporated into the insulation system. Annular permanent magnets are used to deflect low energy secondary electrons produced from the input window, and also to reduce loss of charge as a result of back-scattered electrons.

Contracts for the various parts have been placed and delivery is expected early August of this year. Assembly will be carried out at the Laboratory.

5. THE R.F. SYSTEM

5.1 Introduction

During November the amplitude programme equipment, which accepts signals from the magnet and produces the correct r.f. envelope waveform, was commissioned, and at the beginning of December a beam was successfully accelerated, the maximum energy being restricted because only the driver amplifier was available.

The r.f. equipment requires little attention and the programme is not critical when the rest of the machine is tuned properly. A feedback loop round the amplifier ensures that the output is always a replica of the programme signal, and this enables the energy to be changed over a wide range without touching the r.f. controls. Cavity detuning at injection is available but so far has not been observed to affect the number of particles trapped. The frequency control feedback loop is, therefore, not required yet, but the hardware is installed and partly commissioned.

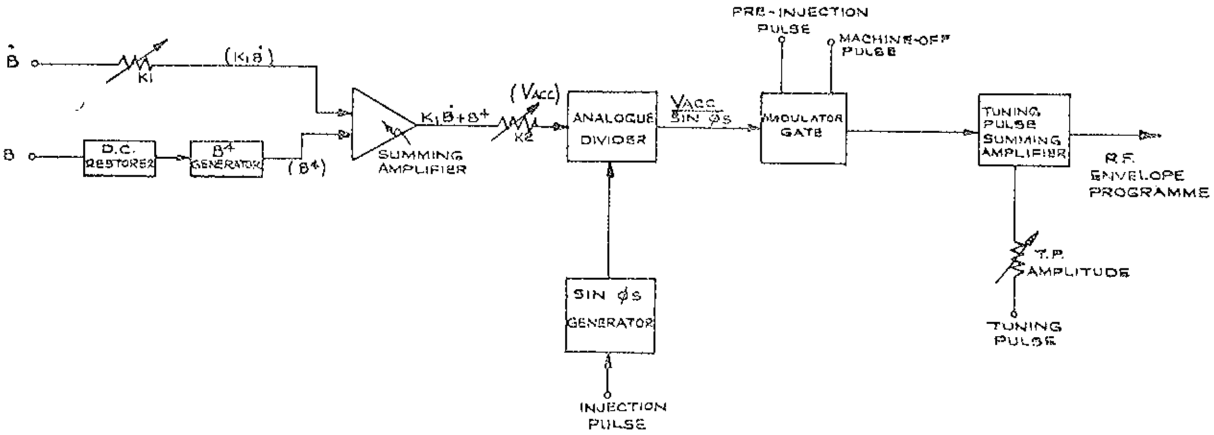

FIG. 4 BLOCK DIAGRAM OF THE R.F. AMPLITUDE CONTROL SYSTEM

By 26th May the 2054 triode amplifier was ready for use and details are given below. It will enable energies and higher currents to be obtained.

5.2 R.F. Amplitude Control

The programme generator is supplied with analogue signals representing B and dB/dt from the magnet, and also appropriate timing pulses.

The cavity voltage V_c is given by the following equation.

$$V_c = \frac{V_{acc}}{\sin \phi_s} = \frac{K_2 (K_1 \, dB/dt + B^4)}{\sin \phi_s}$$

Where V_{acc} is the r.f. voltage at the instant of transit of the electron bunch, ϕ_s is the phase angle between the instant of transit and the next zero-crossing of the r.f. voltage waveform and K_1 and K_2 are constants determined by the geometry of the machine. B, dB/dt, and ϕ_s vary during the acceleration cycle. The ϕ_s programme is generated within the r.f. programme equipment and is the variable controlled by the operator.

A block diagram is shown in Fig. 4 .The B signal is derived from a precision integrator in the magnet power supply, and the fourth power is obtained from an interpolation circuit using integrated circuit operational amplifiers. dB/dt is obtained directly from a back-leg magnet winding, and is fed through a variable-gain amplifier so that K_1 can be set correctly.

The sin ϕ_s variation is shown in Fig. 5. The programme generator has three controls which vary independently the level of ϕ_s at injection, the high energy level, and the rate of change from one to the other. These three controls are duplicated in the Main Control Room, and can be set by the operator. Injection level is set for optimum trapping, the high level value is set at the highest angle which does not cause loss of particles before peak energy. The slope is similarly set as steeply as possible for minimum average r.f. power.

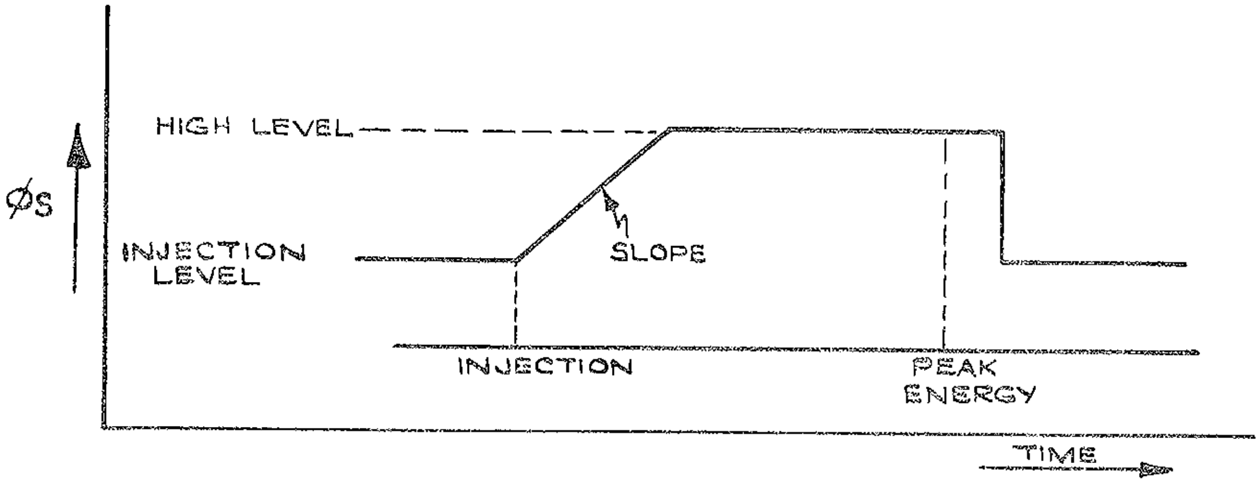

FIG. 5 VARIATION IN SIN ϕS

The B^4 and dB/dt terms are summed in an amplifier whose gain controls K_2 whilst V_{acc} is divided by $\sin \phi^s$ in a Hall probe divider. This works quite well, but the drift and noise are not quite as low as expected, and a circuit using only operational amplifiers in an interpolation quarter square multiplier circuit is being investigated.

The final V_c waveform is gated by the pre-injection and turn off pulses. The 100 microsecond period prior to injection allows the cavities to reach a steady state. A tuning pulse, about $\frac{1}{2}$ ms wide, is next added between acceleration pulses, and this final "voltage demand waveform" is fed as a reference to the feedback cricuits. The final overall accuracy of this waveform is within 1 % of peak output.

Non-linearities in the r.f. amplifier chain, and fluctuations in beam loading made feedback stabilisation of the cavity voltage essential if operation of the synchrotron is to be trouble-free and equally easy to operate at varying energies and currents.

Such a system has been developed and is being commissioned in two stages. First, the amplifier output voltage, obtain from a directional coupler in the waveguide feeder, is compared in a feedback loop with the reference waveform. This stabilises the power output, and so compensates for non-linearities, although not for beam loading. This system is working and enables the beam energy to be changed without touching the r.f. controls. The next stage, which is expected to be commissioned during July, is cavity voltage feedback which will stabilise the system against beam loading.

A block diagram of the feedback system is shown in Fig. 6. It is unusual in that the overall gain of the amplifier and detector is of the order of unity. This means that the feedback chain has a voltage gain equal to the loop gain. Also, since the reference signal must be applied before the compensatory networks to avoid a large overshoot, it turns out that the response time of a normal stabilised negative feedback circuit would be too long. A hybrid system has, therefore, been evolved in which the r.f. amplifier is driven open loop and corrections added by means of the feedback loop.

This block diagram will apply to feeder or cavity feedback, though amplifiers with different compensation must be switched in for the two cases. With cavity feedback, sophisticated protection will be required to ensure that the power output is not increased enormously under fault conditions; if, for example, the cavities are a long way off tune when switching on.

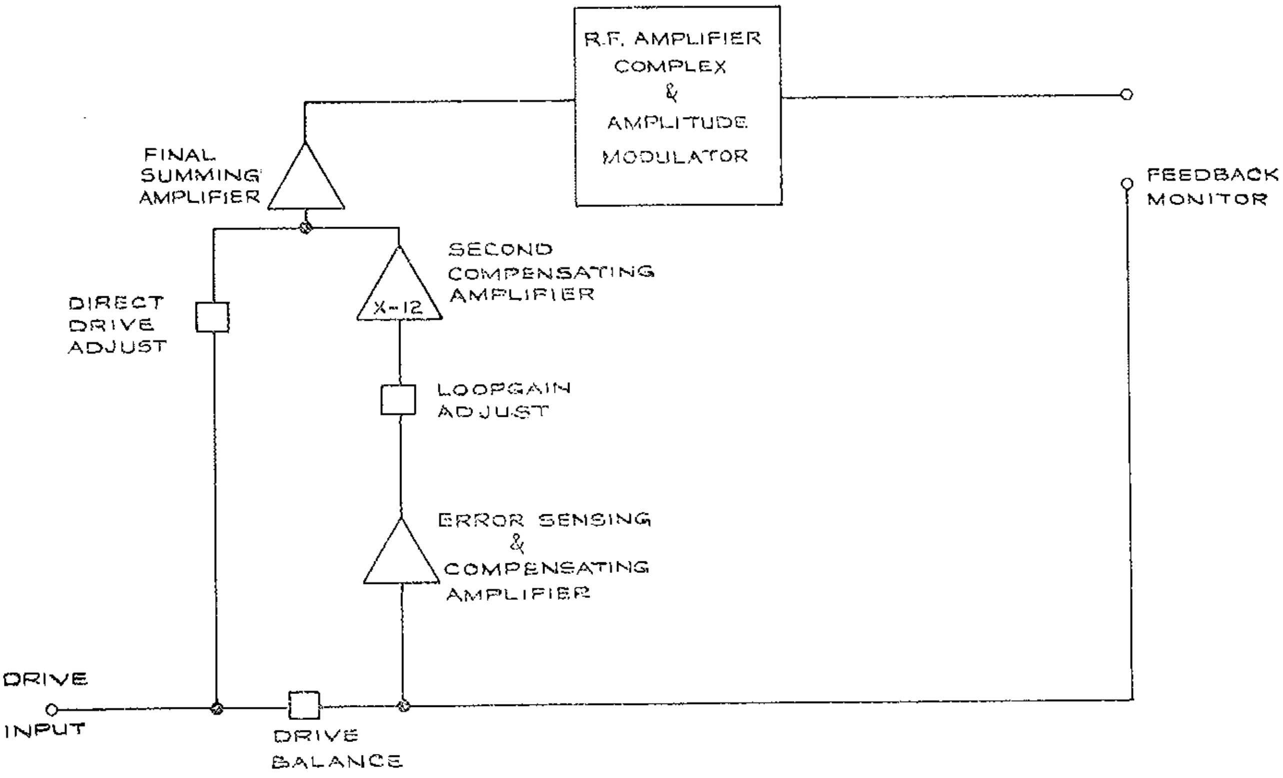

FIG. 6 BLOCK DIAGRAM OF THE R.F. FEEDBACK SYSTEM

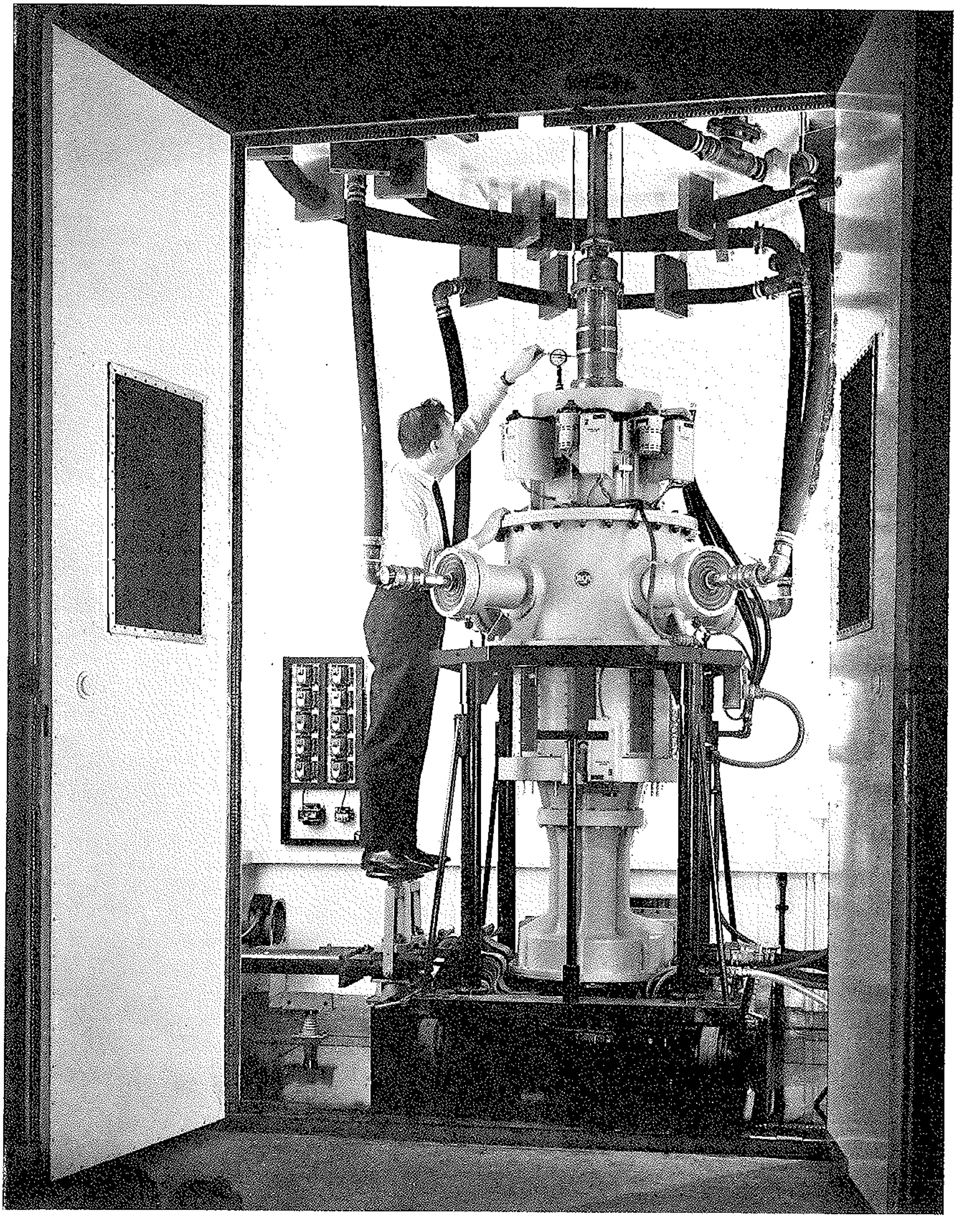

FIG. 7 THE 2054 HIGH POWER AMPLIFIER

5.5 The R.F. Phase Monitoring System

A useful addition to the existing r.f. monitoring system has been a means of measuring the phase of various points in the system at any arbitrary time during the r.f. programme cycle. The system makes use of a heterodyne technique, so that the phase information is carried at a much lower frequency, which makes for a simple and less critical arrangement than if 408 Mc/s signals were used directly.

An oscillator, stable to about 1 in 10^6 at a frequency 2.04 Mc/s less than the main frequency, is used to feed power to a resonant ring of low loss coaxial cable. The power required is about 1 watt, and the ring is approximately 740 feet in circumference. Spaced around the ring at required points are 6 directional couplers whose output ports are fed to the input terminals of 4 port hybrid junctions. In this way six approximately equi-amplitude and phase signals are derived for the heterodyne process. A balanced mixer, consisting of a 408 Mc/s hybrid and two broad-band Schottky diode detectors, is used to produce the required intermediate frequency. A switch enables the choice of a cavity signal or a waveguide feeder signal to be made. An integrated circuit 2.04 Mc/s tuned amplifier provides about 25 db of gain, with a bandwidth of 600 kc/s. Measurements can be made either in the Inner Hall or in the Main Control Room.

5.6 Betatron Q-value Measurement

An r.f. device, not part or the r.f. system, but commissioned and used during the period of the report, is the r.f. deflector for exciting betatron oscillations. By observing when resonant build-up occurs, as the frequency of the excitation is altered, the betatron oscillation frequency can be measured.

In the deflector, longitudinal current strips produce between them a deflecting magnetic field. By suitable shaping of the strip, and use of a ferrite yoke, the field is made uniform across the cross-section of the beam. The strips are shorted at one end and energised at the other by a pulsed r.f. power amplifier, the strips being resonated with a variable capacitance for power economy. Two such deflectors, each 1 metre long, and arranged to deflect horizontally and vertically respectively are placed end to end in one long straight section and fed centrally through a change-over switch from one amplifier. The frequency is about 7.2 Mc/s.

The beam deflection is seen by a beam position monitor further downstream, and, if enough deflection is applied so that some beam is lost, this can be clearly seen on the intensity monitors. A pulse length of 10-100 microsecond can be used, triggered at any point in the acceleration cycle. Results of experiments using this device have been given in Section 3.3.

6. THE MAGNET POWER SUPPLIES

The adjustment and setting up of the pulse power supply servo-system commenced in November, 1966. The six-phase charging rectifier output voltage contained a component at the mains supply frequency which produced a beat frequency in the magnets and affected the accurate control of the magnet alternating current. The problem was most severe for very small differences between the supply and magnet network frequencies so the latter was altered to 53 c/s. The resulting 3 c/s beat does not affect the ability of the servo-system to control the current. The network voltage was thus increased by 6% and the loading of the resonant capacitors was increased by approximately 20%, but these values are within the rating of the equipment.

The stability of the pulse power supply and the d.c. bias supply are such that the field gradient at injection, at levels of operation up to 4 GeV, are within the design value of ± 1% over periods of up to 8 hours.

However, as described in Section 3.6, delay line modes of resonance are excited which effect the magnet field distribution at the next injection time. It has now been found that if the energy pulse is applied during the acceleration cycle there is no disturbance to the beam and so this mode of operation has been adopted.

7. INJECTOR

7.1 General

During the period covered by this report work by M.E.L. on improvement of the performance of the linear accelerator continued; but from early January, when regular periods of synchrotron operation commenced, access by M.E.L. to the accelerator was restricted to maintenance periods. A long shutdown in May for the commissioning of the RCA plate modulator in the r.f. power supplies was allocated also for acceptance trials on the linear accelerator.

Some of the main difficulties encountered in the operation of the equipment are outlined below.

7.2 Electron Gun

The triode gun as first supplied was found to suffer from severe voltage breakdown but, after some modification, this limitation was overcome. This gun has now operated for several hundred hours.

7.3. Gun Modulator

This suffered from repeated breakdown of the 100 kV d.c. supply unit, partly attributable to being run with a current drain above its rating. Replacement by a conventional rectifier set is in hand and is expected in September. In the meantime a d.c. set has been borrowed from the Rutherford Laboratory.

The gun h.t. modulator uses a Machlett triode in an oil tank as the switch valve. The bushing through which the pulsed h.t. is brought out of the tank broke down and had to be completely redesigned.

7.4 Klystron Modulators

On the whole the klystron modulators have been reliable. The voltage pulses have been flattened to 0.3—0.4%. This residual unflatness is still considered to be the chief limitation on the achievement of adequate energy homogeneity during the pulse.

Some hum arises within the klystrons, possibly caused by the heaters, giving rise to a small 3 c/s beat in the output when the klystrons are pulsed at 53 p.p.s. M.E.L. have introduced hum-bucking circuits, operating via the clipper valve to reduce the effect of this on the beam energy. Even when this had been done, however, a variable amount of beat still showed up on the analysed current pulse, causing a similar variation in the synchrotron beam. It was demonstrated that the modulators caused considerable variation in phase currents in the main supply to the equipment at the beat frequency and that this provided a means of feedback to other parts of the equipment, principally to the gun modulator. It was decided to fit larger charging chokes in the main modulators to reduce these phase current variations. These are expected in July.

7.5 Klystrons

The CSF K.2049 klystrons used to supply the linear accelerator have behaved reliably. Contrary to expectation, however, the perveance has dropped continuously during life and has been the only cause of tube replacement. Since the information from C.S.F. was that the perveance would stay constant for up to 1,000 hours, no special provision was made in the modulators to compensate for changing impedance, with the result that the klystron voltage pulse progressively develops a droop which can cause further variation in energy during the pulse.

Troubles with the Eimac X.3029 drive klystron were outlined in the previous report. The unsatisfactory tubes have now been replaced free of charge and the new tubes are quite satisfactory. When the voltage pulse was flattened to 0.3% the phase variation across the klystron was flat within 1°.

7.6 Acceptance Tests

The tests carried out on the linear accelerator were in three parts covering energy homogeneity, emittance and stability respectively.

(*a*) **Energy homogeneity**

The mean value of the current pulse, over a period of 1 micro-second, falling within the energy band 40 ± 0.2 MeV, was measured and the maximum value was 570 mA for a total acceleration current of 920 mA. By critical adjustment it was possible to obtain conditions when the ripple on top of the pulse was within ± 5% of the mean value.

(*b*) **Emittance**

The emittance was measured using two traversing collimators and a quadrupole triplet magnet and it was concluded that 74% of the current fell within the specified value of 3.2×10^{-6} m-radians.

(*c*) **Stability**

An endurance test was carried out over a period of nearly 24 hours, during which there were no spontaneous trips of the accelerator equipment. The output current, within the required band of energy, was recorded.

The mean output current only varied by more than ± 5% for about 4% of the total time and some of this departure was attributable to the temporary gun h.t. set which was not fully stabilised against mains variation. The aim of the test was that there should be little if any adjustment of controls to maintain the analysed current constant. However, some adjustments were needed at infrequent intervals to the phasing conditions and to the current servo.

The variation of output current at the beat frequency of 3 c/s between the pulse repetition rate and the supply frequency showed as a variation of output usually of about 10% and at times considerably greater. This has been referred to above in Section 7.4.

In conclusion, the machine was considered acceptable with regard to beam current falling within the specified limits, although about 10% down on specification, and with regard to reliability during the 24 hour run, but it was considered that the stability should be improved and measures to do this were agreed with M.E.L.

7.7 The Chopper System

The equipment for modulating the beam from the electron gun at the synchrotron radio frequency, ordered with the linear accelerator in 1964, is still under development. Completion is expected later this year.

7.8 Positron Injection Equipment

The project for the acceleration of positrons in NINA has received financial approval, and the major items of equipment have been ordered. It is proposed to direct the electron beam from the M.E.L. linear accelerator on to a tungsten target at an energy of about 45 MeV. Emergent pairs will be focused by means of a short solenoid with a field of 15 kGs into a second linear accelerator. This accelerator will consist of 2 sections of corrugated waveguide, each 2.8 m long, fed from a single CSF klystron of 30 MW peak output power at 2856 Mc/s. The accelerator will be fitted with a solenoidal focusing system which will maintain a field of 3 kGs over the whole length. The energy gain given to the positrons will be 50 MeV so that their final energy will be about 60 MeV. The beam transport system into the ring has already been designed to handle a large emittance beam (4.1×10^{-5} m-radians horizontally and 2.3×10^{-5} m-radians vertically). It is expected that a current of about 10 microamperes peak will be injected into the synchrotron.

The linear accelerator has been ordered from Vickers Engineering Ltd. for delivery before the end of 1967, whilst M.E.L. are providing a modulator for the klystron identical to those made for the electron accelerator. Vickers are also making the focusing system for the accelerator. Design work on the rest of the equipment is well advanced.

A by-pass system for transporting the electron beam to one side of the positron accelerator has been designed using 4 bending magnets. When this is in use, the signal for the energy servo on the electron accelerator will be derived from a beam position indicator in the by-pass line where a good momentum separation occurs.

8. SERVICES GROUP

8.1 Mechanical and Electrical Sections

The installation of NINA was completed by November, 1966 and more effort was devoted to the support of the experimental teams in the form of a manufacturing service. This has now been extended to cover outside manufacturing and inspection. Contracts have been established with a number of companies so that an effective manufacturing service is available.

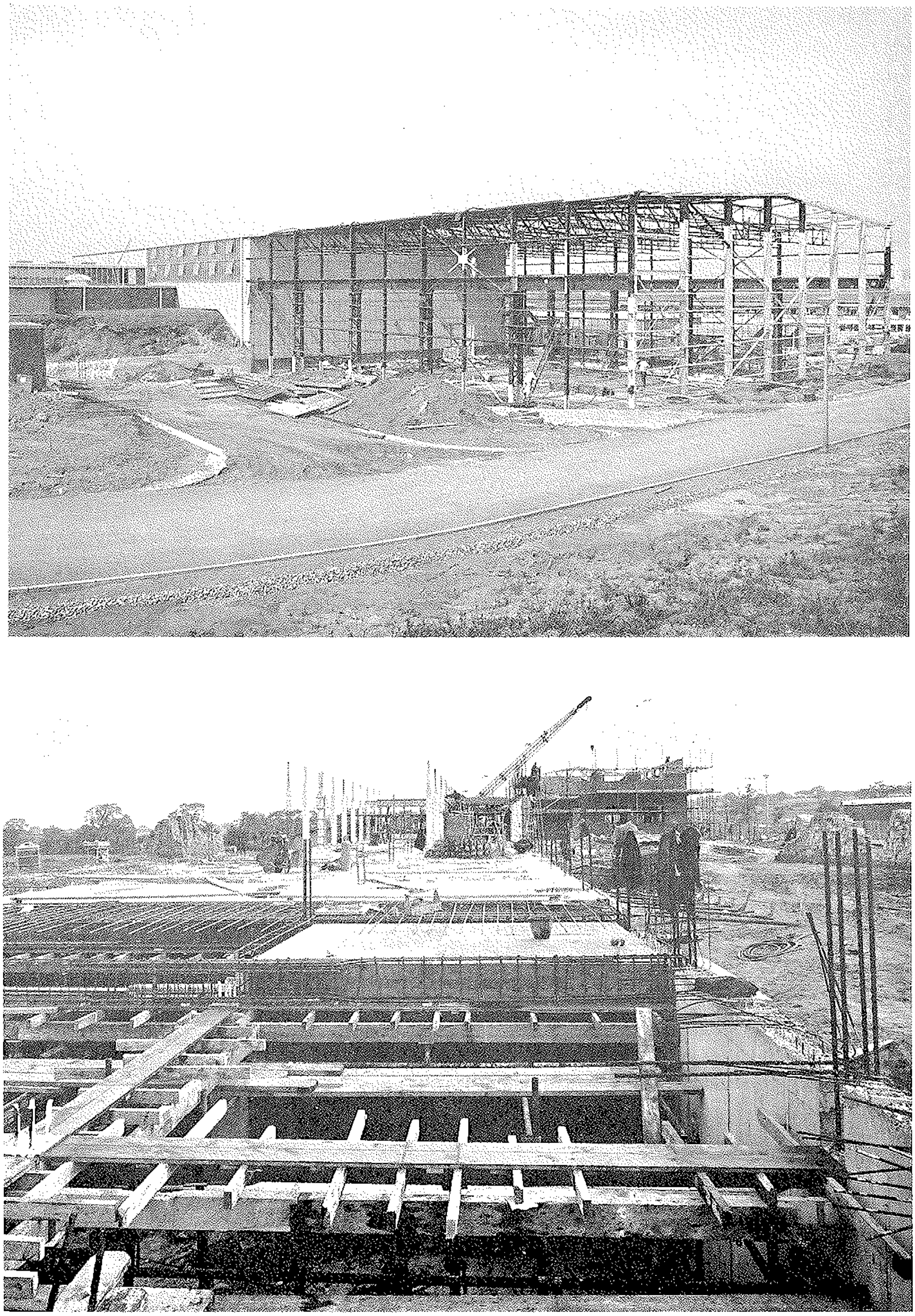

Fig. 8 New Building Progress in April, 1967
(*a*) the experimental hall extension
(*b*) the new laboratory and office block, and electronics building

Some of the more exacting jobs, designed in the Design Office, are manufactured in the Laboratory Workshop. Examples of these are the Quantameters and Secondary Emission Counter to be used with gamma and electron beams from NINA.

The electrical section has been engaged in producing numerous panels for the Experimental Group. Installation of electrical equipment is a continuous process and is proceeding satisfactorily. The installation within and external to the Plant Room has been finished.

Work on the second incoming feeder from the supply authority is in hand and should be commissioned by the end of the summer. This will give a twin feeder supply to the Laboratory of 10 MVA.

8.2 Building Development

Progress has been made with the construction of the new Laboratory and Office Block and the Experimental Hall extension and the first phase of the former, the Electronics Laboratory, should be ready for occupation by mid-September. The main block is programmed to be finished by April, 1968 and the Lecture Theatre unit by August, 1968.

The extension to the Experimental Hall is well under way and is due to be finished by January, 1968. This extension will greatly relieve the congested present hall. The new Plant Room, which is part of the Experimental Hall area is on programme and should be finished early in 1968. Fig. 8 shows building progress at April, 1967.

A new central stores building of 25,000 sq. ft. has been designed. This building will also provide storage for experimental equipment.

9. COMPUTER AND ELECTRONICS GROUP

9.1 Computing System

During March, an additional disk drive was added to the existing IBM 360/50 installation, and a Calcomp incremental plotter was commissioned.

The Operating System, which has been modified to provide detailed accounting and statistical information, now provides two FORTRAN compilers with user options for the choice of either fast compilations or fast execution. By the end of April two full shifts were operated daily and approximately 70% of all the work run was for program execution, as opposed to compilation or editing. About one hundred jobs are run each day.

9.2 Data Analysis Programs

A main activity of the group has been to get many of the established analysis programs for high-energy physics running on the IBM 360. One of the main successes has been that all the main CERN programs for track-chamber analysis, THRESH, GRIND, SLICE and SUMX now run at DNPL and they have been used by local groups. Some of these programs have been sent to high-energy physics centres in Europe and the U.S.A.

9.3 Electronic Instrument Loans

A pool has been established, within the Electronics Group, for the distribution and servicing of many of the standard electronic instruments used by the experimental physics teams. These instruments include fast electronic logic modules and scalers, and an important feature is the adoption of the NIM standard modular format for all new equipment where appropriate.

9.4 NINA Instrumentation

Three new modular systems are being constructed, to operate from the installed peaking strips, which will provide timing pulses for electron and positron injection. The existing magnet field and magnet phase systems are being modified to provide a machine cycle selector, capable of gating timing pulses and thereby facilitating beam sharing.

Five beam-bump pulse generators are now in commission for the magnet back-leg windings and for driving the electron beam extraction current strip and kicker magnet. Further pulse power supplies are being designed for use with the electron beam extraction systems.

9.5 **Current Integrators**

A completely solid-state current integrator has been designed to operate with the quantameters. These integrators are modular and they have both manual and remote control and indication. The integrator has a sensitivity of better than 10^{-9} A and there is zero dead-time. A prototype system has been built and tested, and it is now in use by an experimental team; a further five units are in production.

9.6 **Interface Equipment**

A system has been specified by the Group, for the automatic read-out of a set of 100 MHz scalers on to IBM-compatible magnetic tape. The system was built commercially and now operates successfully with an IBM 7330 tape transport. Up to 100 scalers can be read out by the system, which incorporates an automatic error detection and recovery facility. After intensive checking and reliability tests, reading the tapes generated on the IBM 360/50, the unit was handed to one of the NINA experimental groups.

10. EXPERIMENTAL PHYSICS GROUP

Beam Intensity Monitors

Photon beam intensities will be measured using quantameters built to a CEA design. Four of these instruments have been constructed and one of them has been calibrated at DESY against a Faraday cup using a 3 GeV extracted electron beam. A similar calibration will be performed on all four quantameters at Daresbury later in the year. Comparison of the DESY and Daresbury results should go some way towards the standardisation of the calibration of such beam intensity monitors in various electron laboratories.

The quantameters will not be suitable for use at high photon beam intensities because of saturation and heating effects. A water-cooled secondary emission quantameter now being designed, will be used under these circumstances. The S.E.Q. contains insulated copper absorption plates separated by gaps, as is the case in the gas-filled quantameter. It differs in that the beam intensity is measured by collecting secondary electrons emitted from the surfaces of the copper plates, the apparatus being maintained at high vacuum. The surfaces are gold plated in order to improve the stability of the device. The output current from the S.E.Q. is very much smaller than that from a gas filled quantameter, but the S.E.Q. has the advantage of not saturating at high beam intensity.

A thin foil secondary emission monitor has been constructed for use in the calibration beam line. The monitor contains 21 aluminium foils, each 0.0008 in thick. The current due to the secondary emission of electrons from the foils is collected from alternate foils while a polarising voltage is applied to the remainder. The high vacuum required in the monitor is provided by an ion pump.

Considerable effort is being applied to the development of techniques needed in the construction of beam monitor devices. Amongst the techniques involved are vacuum and electro-deposition of thin metallic layers and methods of mounting thin metal foils.

11. DARESBURY LABORATORY EXPERIMENT (Fig. 9)

The proposal by this group to study, simultaneously, wide angle electron and muon pairs was discussed in the last report. Briefly, the group plan to study symmetric lepton pairs produced at angles between 5° and 8° to the photon beam. These pairs have values of their invariant mass squared up to $(500\ \text{MeV})^2$ and will be studied using an arrangement having high angular and momentum resolution. In addition to providing a sensitive test of the validity of Q.E.D., the experiment will test the equivalence of the electron and muon propagators down to ~ 0.05 fermi.

One of the two identical spectrometers is now complete except for the muon range counter and assembly of the second is proceeding. Preliminary runs were made during April using a 3 GeV bremsstrahlung beam from NINA and a $\frac{1}{4}$ in Al target. Most of the scintillation counters were timed and their efficiencies measured as a function of bias. Using the spectrometer set for 1 GeV/c, the single electron rate, estimated using the threshold gas Cerenkov and shower counters, agreed with that expected. However, these counters have not been calibrated and this will be done by taking advantage of the very large cross-section for production of small angle electron pairs. A bending magnet placed immediately after the target will bend small angle pairs into the spectrometers and hence almost eliminate the contribution from the pion background which greatly exceeds the electron rate at larger angles.

DARESBURY GROUP EXPERIMENT TO STUDY THE PHOTOPRODUCTION OF ELECTRON AND MUON PAIRS

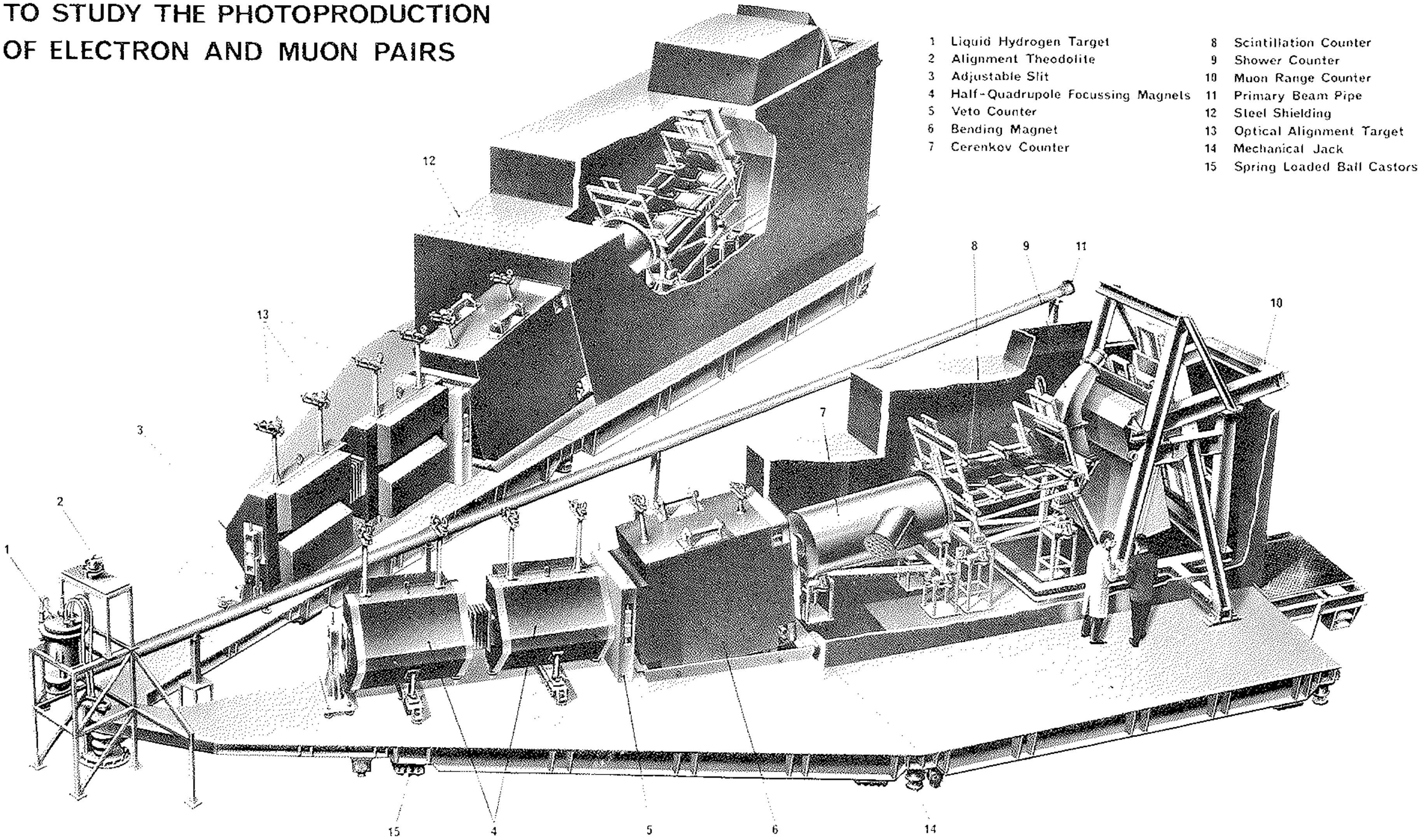

FIG. 9 ILLUSTRATION OF THE DARESBURY EXPERIMENT

Measurements of the background rates in the lead glass counters were inconclusive because of a lack of knowledge of their energy calibration. It is hoped to obtain this calibration by extracting very weak bremsstrahlung from the synchrotron and placing the lead glass directly in this beam. Preliminary tests indicate that this is feasible. It is necessary to have some means of equalising the gain of the 49 photomultipliers of the lead glass assembly and the direct bremsstrahlung will also be used for this purpose. The assembly has been mounted so that each one of the 49 blocks can be brought into position in the beam. Americium scintillator buttons at the end of each block serve as secondary references, and pulsed light sources will enable the time delays to be equalised.

The design of the next phase of the experiment in which a bending magnet and counter hodoscope will be used for momentum analysis of the protons, is almost complete. A gas Cerenkov counter is included in this design to discriminate against pions and electrons.

14. GLASGOW EXPERIMENT

In this experiment the polarisation of recoil protons from elastic e-p scattering will be measured. The experiment has been described in DNPL 3 and DNPL 4.

The rotating platforms for the magnetic spectrometers have been installed and the magnets will shortly be mounted on them. The parts for the 60 cm liquid hydrogen target have been fabricated and are awaiting assembly. This target will use a closed circuit refrigeration system maintained by a small cryogenerator. This means that no hydrogen reservoir is required and the total volume of liquid hydrogen in the system is only equal to the 0.75 litres required to fill the target.

All the physics apparatus which was constructed at Glasgow, namely the spark chambers, the photographic system, the scintillation counters and the associated electronic equipment, has been transported to Daresbury and is in process of being installed. The spark chambers were tested in a 200 MeV electron beam from the Glasgow synchrotron with satisfactory results. The shower counter was also tested in this beam and its energy resolution was as good as could be expected at this low energy. The mirror system was assembled at Glasgow and test photographs showed that the format was satisfactory. Some deficiencies were revealed in the fiducial crosses which define the co-ordinates of each chamber and these have now been improved. Some preliminary measurements of optical distortions were made, which showed that these are not large and it is anticipated that adequate corrections can be made in the computer analysis of the data. Work has started on the computer programmes for the analysis of data from the film, using the digitiser "Cyclops" at the Rutherford Laboratory.

15. LANCASTER/MANCHESTER EXPERIMENT

An introductory account of this experiment was given in DNPL 4. Briefly the proposal is to study the reaction $ep \rightarrow ep\pi^0$ by detecting both electron and proton and measuring both their momenta: this provides enough information to determine the mass of the unobserved neutral particle, its momentum and its direction, so that each event can be solved kinematically.

Detailed design work has been continuing. It is necessary for the proton spectrometer to be able to move not only over angles from 20° to 70° with respect to the beam in the horizontal plane, but also to be able to tilt vertically, up to angles of 30° to the horizontal. This has made for major design problems due to mechanical interaction of various components around the complicated pivot structure which is needed. Design has reached the stage where it has been shown that it is possible to make a structure which will enable both spectrometer platforms to be able to cover the angular range specified without any important loss of solid angle due to having to move the quadrupole magnets further away from the hydrogen target than was desired. Detailed design work is now in progress and the requests for construction will go out to tender in the near future.

Detailed design of the hodoscopes has been in progress. They have been planned so that, when a particle passes through a hodoscope, at least two counters will fire, forming a recognisable pattern. This redundancy will enable events to be sorted out in which extra counters fire due to random coincidence with the gate-opening time. Because of this redundancy and because of the low momenta of the protons to be detected, it is necessary for the counters to be thin: 2 mm thick in the momentum hodoscopes and

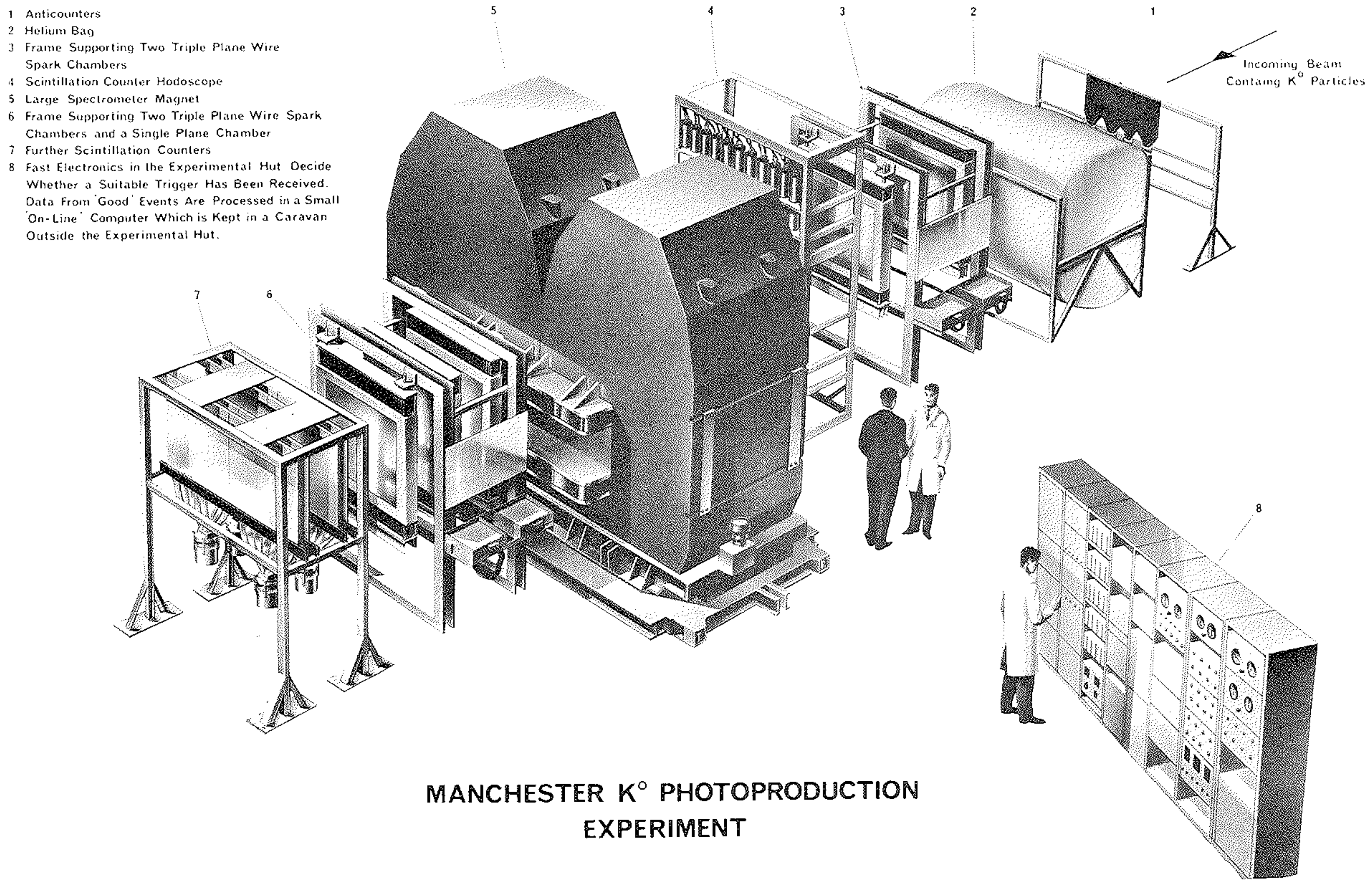

FIG. 10 ILLUSTRATION OF THE MANCHESTER EXPERIMENT

0.5 mm thick in two of the angle hodoscopes. A parasitic test run of counters of this thickness was made at the proton synchrotron Nimrod. Detailed construction of the hodoscope counters and their mountings is now in progress. To reduce the number of random coincidences between unrelated electrons and protons, it is planned to record the time interval between two counters, one in the electron spectrometer and one in the proton spectrometer, and then to correct this time for the different times of flight of protons of different momenta between hydrogen target and counters. Development work is in progress to make such a system with as good time resolution as possible. Tests are also being carried out to see if it will be possible to correct for different times of travel of light from different parts of these counters to the photomultiplier, using information from the hodoscopes about where each particle is passing through the timing counter. Present tests suggest that such a correction will make a useful improvement in the resolving time, and so reduce the background of accidental coincidences.

More detailed studies have been made of the kinematics of the reaction and how they interact with the apertures of the spectrometers. The analysis is rather complicated but is now understood in principle and being studied in practice. It has been found that a large amount of bookkeeping will be required in the computer.

It is now proposed to study first excitation of the N* (1236) to investigate virtual photoproduction of the smaller multipoles, but the earlier proposal to study π^0p masses from 1400-1600 MeV remains on the books for later attention.

16. A PROPOSED MAGNETIC SPARK CHAMBER COLLABORATION EXPERIMENT

A proposal has been submitted to the Nuclear Physics Board of the Science Research Council for a large magnet for spark chamber experiments on photoproduction using a tagged photon beam. It is envisaged that several university groups will collaborate with physicists at Daresbury in this work.

Above 1 GeV photon energy, photoproduction experiments are complicated as there is multiparticle production, there are several kinds of mesons and associated baryons produced and there are various decay modes. The proposed triggered spark chamber system should allow the study of all these phenomena, especially those involving strange particles, as well as a study of the mechanism of the photoproduction process.

The overall arrangement would be for a weak intensity electron beam, probably obtained by double conversion, to enter a thin radiator preceding a tagging magnet. The photons from the radiator would proceed to a cylindrical liquid hydrogen target, whilst the recoil electrons associated with these photons would be momentum analysed in the magnet and identified by a system of about 30 tagging counters along the focal plane. By observing coincidences between triggered events and the tagging counters, the energy of the incident photon causing the event can be deduced from the particular tagging counter which gave the coincidence.

The charged products from photoproduction in the hydrogen target would be analysed in an arrangement of spark chambers contained in the magnetic field (about 16 kGs) of a large magnet. This magnet would have a maximum gap of 75 cm, an effective pole width of 150 cm and a length in the incident photon direction of 120 cm. It would consume 2 MW at 8000 amps, would weigh about 130 tons and would have a flexible arrangement of holes or slots in the top pole yoke so that the tracks in the spark chambers could be photographed.

It is proposed that wide gap spark chambers be used initially with photographic recording. There may be an alternative arrangement using digital readout chambers or eventually streamer chambers operating with short high voltage pulses so that they would detect multi-particle tracks efficiently and isotropically.

Meson triggering counters would be located on either side of the tagged photon beam near the magnet exit. To avoid excess triggering on electromagnetic pairs the median plane would be left free of counters, since the pairs are confined to this plane.

The momentum resolution of the tagging system should be about $\pm$ 1.5% and that of the spark chambers also about $\pm$ 1.5%. Allowing for kinematic effects the resultant accuracy on the mass of, for example, the baryon from a two-body reaction should be about $\pm$ 15 MeV/c^2.

From the presently known cross-sections for strange particle photoproduction of about 2 to 5 μb the rate of data collection should be about one strange particle event per minute. The rate of pion production processes should be very high since their cross-sections are of the order of 100 μb.