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Rutherford Laboratory Report

The Work of the Rutherford Laboratory in 1966

Edited by
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THE WORK OF THE RUTHERFORD LABORATORY IN 1966

Rutherford High Energy Laboratory
Chilton, Didcot, Berkshire.
May 1967

Contents

Summary

The previous report covered the period 1 October 1964 to 31 December 1965. The present report follows on and covers the work of the Rutherford Laboratory during 1966.

During the year the Nimrod programme fully recovered from the effects of the alternator breakdown and from January 1966 onwards Nimrod was operational at 7 GeV. During the year 4850 hours were available for High Energy Physics at a mean beam intensity of $1{\cdot}08 \times 10^{12}$ protons per pulse. Seven experiments involving electronic techniques were completed: four of which used extracted proton beams. Two bubble chamber experiments were completed and over 3·5 million pictures were taken.

In December approval was given for construction to proceed on a new experimental hall which will more than double the available experimental space.

The year has seen a steady advance in the work of the Proton Linear Accelerator. In response to the demand for machine time the target room has been modified so that time taken in the setting-up of experimental equipment has been appreciably reduced. Machine development has included substantial improvements in both polarized and unpolarized ion sources and in duty cycle modifications. During the year the PLA was operated for a greater time and the percentage of lost time was less than in any previous year, a total of 5605 hours being available to the experimenters.

During the period of this report the Variable Energy Cyclotron operated for the first time with both internal and external beams. The machine successfully reached its design specification and by the end of the year an active research programme was beginning to develop.

The Orion/DDP coupled computer system for on-line experiments ran successfully until mid-September when it was closed down and replaced by an IBM 360/75 computer.

The CRT flying spot digitiser for spark chamber film successfully measured 30, 000 events for the $K_2^0 - 2\pi^0$ experiment. The HPD flying spot digitiser was brought into operation with the Orion computer and after modifications is being recommissioned for the IBM 360/75 computer.

During the year the Saclay 80 cm Bubble Chamber has been operated for long periods and the Heavy Liquid Bubble Chamber successfully completed its first experimental run. The assembly of the 1·5m Hydrogen Bubble Chamber continued and the first cool-down to liquid nitrogen temperature took place during November. The construction of the Helium Bubble Chamber was completed and it has been successfully cooled down to liquid helium temperatures. A feasibility study of a high precision bubble chamber using a superconducting magnet is in progress.

Despite the increased exploitation of Nimrod and the PLA, radiation exposures have been maintained at moderate levels. No genuine whole-body exposures greater than 1·5 rem occurred during 1966.

This brief summary outlines the main achievements of the Laboratory in 1966, which, together with many other items, are treated in detail in the following pages. As in the previous report the work is reported in a number of sections, each devoted to the activities of one of the six Divisions of the Laboratory.

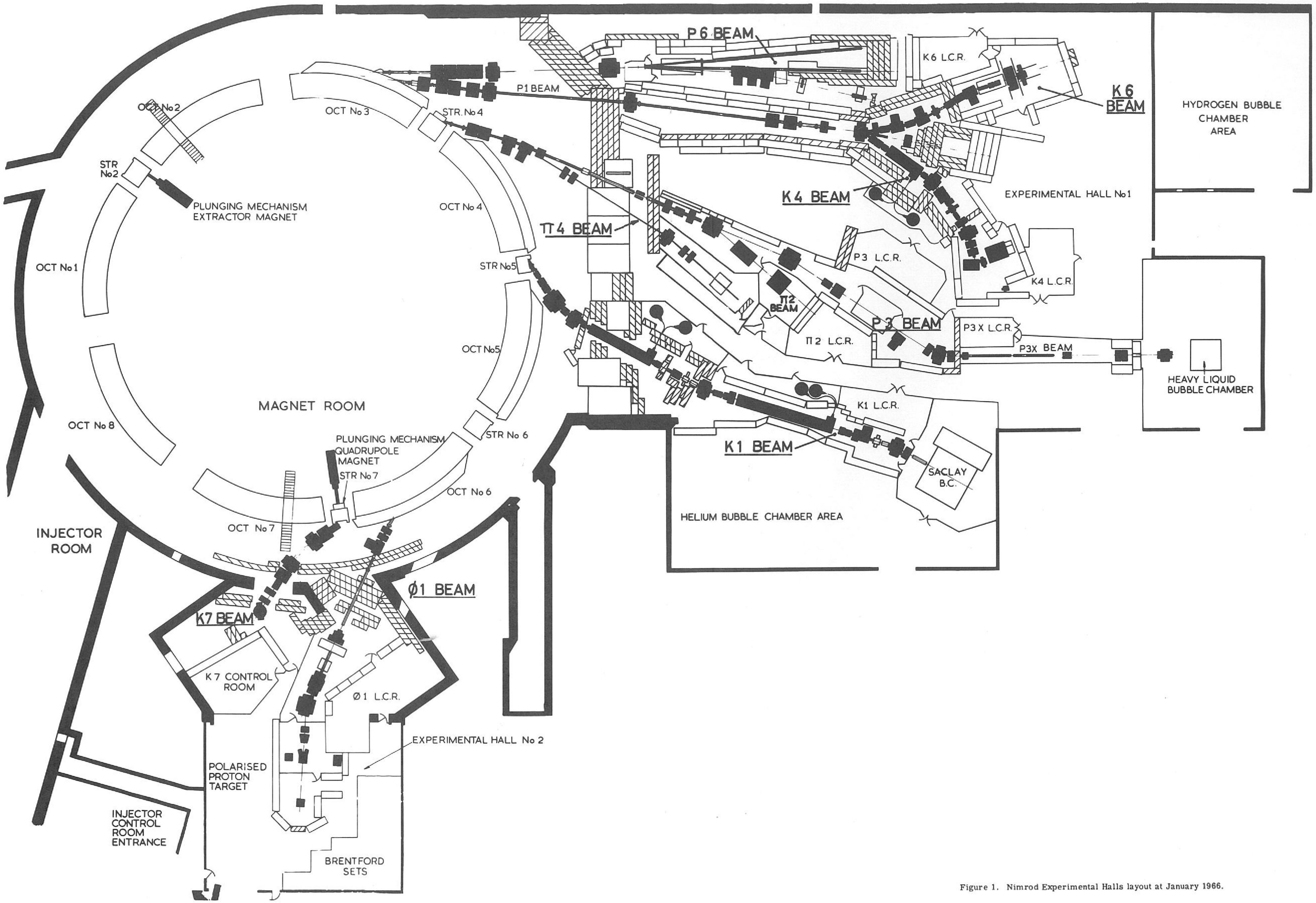

Figure 1. Nimrod Experimental Halls layout at January 1966.

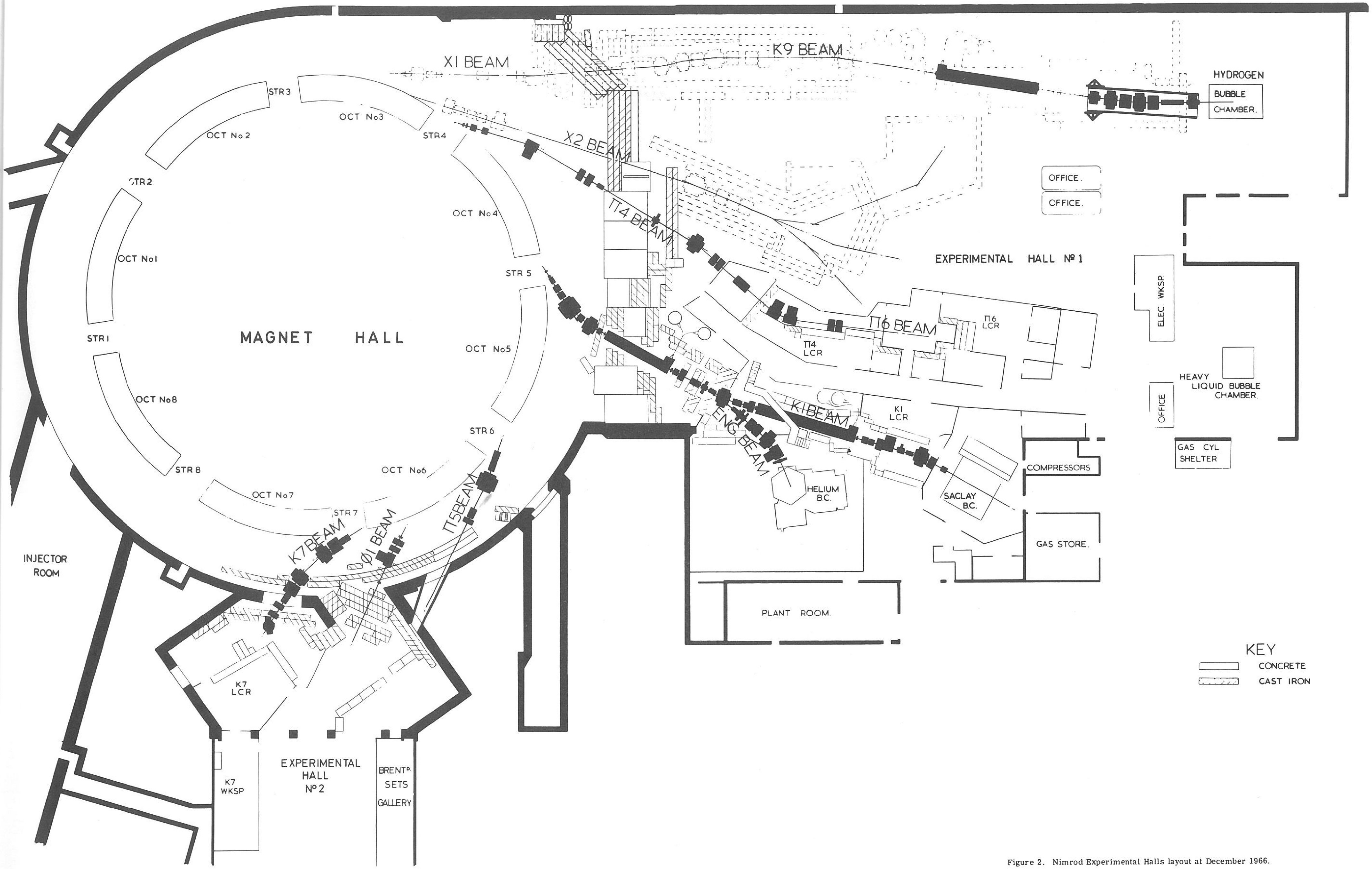

Figure 2. Nimrod Experimental Halls layout at December 1966.

Characteristics of Beam Lines

Beam Number	Beam Length (Metres)	Maxm. $\Delta p/p$	$\Delta\Omega$ (msterads)	Particle	Momentum (GeV/c)	Yield/Pulse quoted for $5 \cdot 10^{11}$ on internal tgt or 10^{11} on external tgt with $\Delta p/p = 1\%$ FWHH	Comments
$\pi 2$	~43	1·5%	0·67	π^-	1·6 - 2·8	$2 \cdot 5 \times 10^3$	Counter beam from internal target
P1 External Proton Beam	not relevant	0·2%	0·2	p	2 - 7·8	$\sim 5 \times 10^{11}$	Used for K4 and K6
P3	~56·5	6%	1·4	π^-	1 - 4·5	10^4 at 2·5 GeV/c	Counter beam from internal target
P3X	92·5	½%	0·15	π^+	0·5 - 1·1	500 at 1 GeV/c	Bubble chamber beam, separation by degrader
P6	~46·5	0·2%	not known	p	2·85 - 7·8	5×10^{10}	Counter beam, inefficient external proton beam
K4	20	4%	3·2	K^+	0·7	125 stopped	Separated stopping counter beam from P1
K6	19	1·2%	1·0	π^- K^-	0·6 - 2·75	π^- 4×10^4 K^- 15 - 150	Counter beam from P1
$\pi 4$	~38	1·7%	1·95	$\pi^\pm$	1·13 ± 10%	π^- 2×10^5 π^+ 2×10^5 p ~ 8×10^5	Counter beam from internal (octant) target. Different target position for + and - particles
$\pi 5$	34	2% ⊬	0·75	π^-	1·5 - 4·0 *	2 GeV/c - 3×10^5	Counter beam from internal target ⊬ design optimum * first doublet can be moved to reduce lower momentum limit to 1 GeV/c

Beam Number	Beam Length (Metres)	Maxm. $\Delta p/p$	$\Delta\Omega$ (msterads)	Particle	Momentum (GeV/c)	Yield/Pulse quoted for $5 \cdot 10^{11}$ on internal tgt or 10^{11} on external tgt with $\Delta p/p = 1\%$ FWHH	Comments
$\pi 6$	~58	1%	0·22	$\pi^\pm$	1·13 ± 10%	π^- 7×10^4 π^+ 7×10^4 p~3×10^5	Counter beam refocused $\pi 4$ unscattered beam
K1	~55	1%	0·15	K^-	1·3 - 2·2	1·5 to 1·8 GeV/c - 5 to 10	Separated bubble chamber beam from internal target
K7	15·8	10%	0·72	π^- K^-	0·6 - 2·5	K^- 3×10^2 π^- $2 \cdot 5 \times 10^5$	Counter beam from internal target
K9	61·2	1%	0·185	$\pi^\pm K^\pm$ p	$K^\pm$ 2 - 3 $\pi^\pm$ - 6 p - 7·5	2 GeV/c~4 K^-, 39 K^+ 2·5 GeV/c~10 K^- 2 to 4 GeV/c:- $\pi^\pm$ in range 0·6 to $5 \cdot 0 \times 10^4$ p in range 5 to 15×10^4	Separated bubble chamber beam from X1. First stage of momentum resolution and recombination, followed by a single separation stage Solid angle and momentum bite more accurately expressed as $\int_{-0 \cdot 5\%}^{+0 \cdot 5\%} \Omega$ eff d $(\Delta p/p) = 0 \cdot 185$ msterad × % at 2 GeV/c
$\phi 1$	~30·5	2%	1	π^-	1·3 - 1·8	1·56 GeV/c - $1 \cdot 5 \times 10^5$	Counter beam from internal target
X1 External Proton Beam	not relevant	0·2%	0·2	p	Up to 7·8		Used for K9
X2 External Proton Beam	not relevant	0·2%	0·2	p	Up to 7·8		Used for K11, K12, K13, K14

HIGH ENERGY PHYSICS DIVISION

January, 1966 saw Nimrod fully operational at 7 GeV for the first time since the failure of the alternators in February, 1965. Throughout the year, the machine provided 4, 850 hours for High Energy Physics at a mean beam intensity of $1{\cdot}08 \times 10^{12}$ protons per pulse. Seven experiments involving electronic techniques were completed: four of which used extracted proton beams. Two bubble chamber experiments were completed and over 3·5 million pictures were taken during the year.

No significant C (charge conjugation) violation was found in the decay $\eta \rightarrow \pi^+\pi^-\pi^0$, so the nature and origin of the CP (charge conjugation x parity) violating interaction responsible for the decay $K_L^0 \rightarrow 2\pi$ remain unknown and there has been no clear indication of CP violation in any other process. The result of the measurement on the decay $K_L^0 \rightarrow \pi^0\pi^0$ does, however, suggest that the CP violating amplitude with $|\Delta I| > \frac{1}{2}$ may be comparable with that for $|\Delta I| = \frac{1}{2}$.

The experiment to measure K-nucleon total cross-sections produced evidence for a new resonance $Y_0^*(1698)$ and the $N^*(1405)$ was seen in the p-p inelastic scattering experiment.

The 6 GeV/c K^-p bubble chamber film taken at CERN has proved a fruitful source of information on the phenomenology of high energy interactions and two new resonances, the $K^*(1400)$ and the $Y_1^*(1700)$ have been observed.

Sonic spark chambers, wire chambers with a ferrite core read-out and optical spark chambers with a vidicon system for digitisation, have all been used successfully on Nimrod. Two groups are developing a magnetostrictive read-out for wire spark chambers and a CRT film scanner - an automatic scanner for film of optical spark chambers - has gone into production. A new system of electronics developed by the Rutherford Laboratory electronics group was used in the experiment on K^--p polarization studies. It employs tunnel diodes and integrated circuits; is currently capable of rates up to 200 Mc/s and was designed to handle information from many channel scintillation counter hodoscopes.

Two of the nine electronic experiments on Nimrod used small local computers and two used the on-line link to the DDP 224 for immediate monitoring and preliminary checking of data.

The rebuilding of the 150 cm British National Bubble Chamber has continued throughout the year, and the 80 cm Helium Bubble Chamber has been commissioned.

The results of several experiments were reported at the International Conference in High Energy Physics held at Berkeley in September.

Figures 1 and 2 show the arrangement of beam lines in the experimental halls in January and December, 1966 respectively.

Composition of the HEP Teams using Nimrod						
	Physicists		Research Students		Support Staff*	
	Electronic Techniques	Bubble Chambers	Electronic Techniques	Bubble Chambers	Electronic Techniques	Bubble Chambers
Visitors⁺	61	38	44	28	13	21
Resident Rutherford Laboratory staff	17	5	0	0	19	11
Totals	78	43	44	28	32	32

* Includes only technical assistance directly concerned with experiments on Nimrod and does not include engineering support.

⁺ Staff from collaborating Universities, AERE Harwell and Saclay Bubble Chamber Group.

Experiments at Nimrod

Number	Experiment	Beam Line (Figures 1, 2)
	Electronic Techniques	
1	A measurement of the width of the η and a search for the S^0 meson.	ϕ1
2	An investigation of the production of Nucleon Isobars in p-p collisions for incident protons in the range 2·8 - 7·8 GeV/c.	P6
3	$\pi^{\pm}$ - p differential elastic cross-section measurements	π2
4	$K^{\pm}$ and $\pi^{\pm}$ nucleon total cross-sections from 600-2700 MeV/c.	K6
5	A study of the decay of the K^0_L meson into two neutral pions.	CERN
6	A study of the angular distributions of the charged decay modes of the f^0 meson.	P3
7	A study of the leptonic decay modes of K^+ mesons.	K4
8	A measurement of the Ke_2 branching ratio.	K4
9	A measurement of the partial width for the decay $\phi^0 \rightarrow e^+ + e^-$.	ϕ1
10	Polarization effects in π^--p and K^--p elastic scattering.	K7
11	A study of the β-decay of the Σ^- hyperon.	π4
	Bubble Chambers	
12	An experiment to study the $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$ decays of the η meson.	K1
13	A study of the decays of η mesons produced in the Heavy Liquid Bubble Chamber.	P3X
14	Low energy π-π interaction studies from Ke_4 decays.	CERN
15	A study of K^-- p interactions at 3·5 and 6·0 GeV/c.	CERN
16	A study of K^-- p interactions in the range 1·25 - 1·85 GeV/c.	K1
17	A study of K^-- d interactions in the region of 1·5 GeV/c.	K1
18	Single and double pion production in p-d collisions at 2·0 GeV/c.	K1
19	A survey of π^+-p interactions in the range 0·6 - 1·05 GeV/c.	K1
20	A survey of π^--p interactions in the region of 0·5 GeV/c.	K1

Experiment 1

Imperial College,
Rutherford Laboratory.

A Measurement of the Width of the η Meson and a Search for the S^0 Meson.

The analysis of a neutron time-of-flight investigation of η production in $\pi^- + p \rightarrow \eta + n$ close to threshold has been completed and indicates an upper limit on the width of the η of 0·9 MeV.

No evidence for S^0 production was found. The upper limit that can be placed on the cross-section is consistent with the results of other experiments.

Experiment 2

AERE, Queen Mary College London,
Rutherford Laboratory.

An Investigation of the Production of Nucleon Isobars in p-p Collisions for Incident Protons in the Range 2·8 - 7·8 GeV/c.

The experiment was performed at incident momenta of 2·85, 4·55, 6·06 and 7·88 GeV/c. In the reaction

$$p + p \rightarrow p + X$$

knowledge of the incoming and outgoing proton momenta and scattering angle determines the invariant mass of the recoiling system X. Resonance behaviour of the group X is revealed by a peak in the momentum spectrum of the detected proton. The use of several incident momenta and a range of scattering angles (22 to 144 milliradians) allows a systematic investigation of the production of various nucleon isobars as functions of the kinematical variables s - squared total centre of mass energy and t - squared four momentum transfer. The range of s was from 7·3$(GeV)^2$ to 16·7$(GeV)^2$ and t varied from 0·03 to 0·8$(GeV)^2$.

An extracted beam of 10^9 to 10^{10} protons per pulse was focused on to a 10 cm liquid hydrogen target. Scintillation counter telescopes and a magnetic spectrometer consisting of three 1-metre bending magnets in series (figure 3) analysed the fast scattered proton. The proton beam intensity was recorded by an ion chamber, which had been calibrated in an aluminium foil activation using the reaction $^{27}Al(p, 3pn)^{24}Na$.

The following qualitative features were apparent in the data:

(1) The production of the 1236 MeV nucleon isobar can be seen at all but the largest momentum transfers.

(2) The two $T=\frac{1}{2}$ nucleon isobars at 1518 and 1688 MeV are seen at the three higher incident momenta. The change in the production cross-section of these isobars with angle is not so rapid as that of the $T=\frac{3}{2}$ 1236 MeV isobar.

(3) The data are consistent with the existence of an isobar of mass around 1410 MeV which is produced strongly at small angles but whose production decreases rapidly with increasing angle and therefore becomes masked by the neighbouring 1518 MeV isobar.

The variation with t of the differential cross-sections for the various isobars are shown in figure 4. The uncertainties to be assigned to these cross-sections are in the region $\pm$ 20% to $\pm$ 30% with an additional $\pm$ 13% uncertainty in the absolute scale of the cross-section which arises from uncertainties in the calibration of the ion chamber. The data have been fitted using the expression

$$\frac{d\sigma}{d|t|} = Ae^{-b|t|}$$

A reasonable agreement is obtained with the data for the production of the 1236 MeV isobar ($T=\frac{3}{2}$) assuming pion exchange using either the absorption model or a Regge pole model, figure 5. Pion exchange does not appear to account for the production of the $T=\frac{1}{2}$ isobars (1410 MeV, 1518 MeV and 1688 MeV). The production of the latter has features which are characteristic of domination by the Pomeranchuk trajectory.

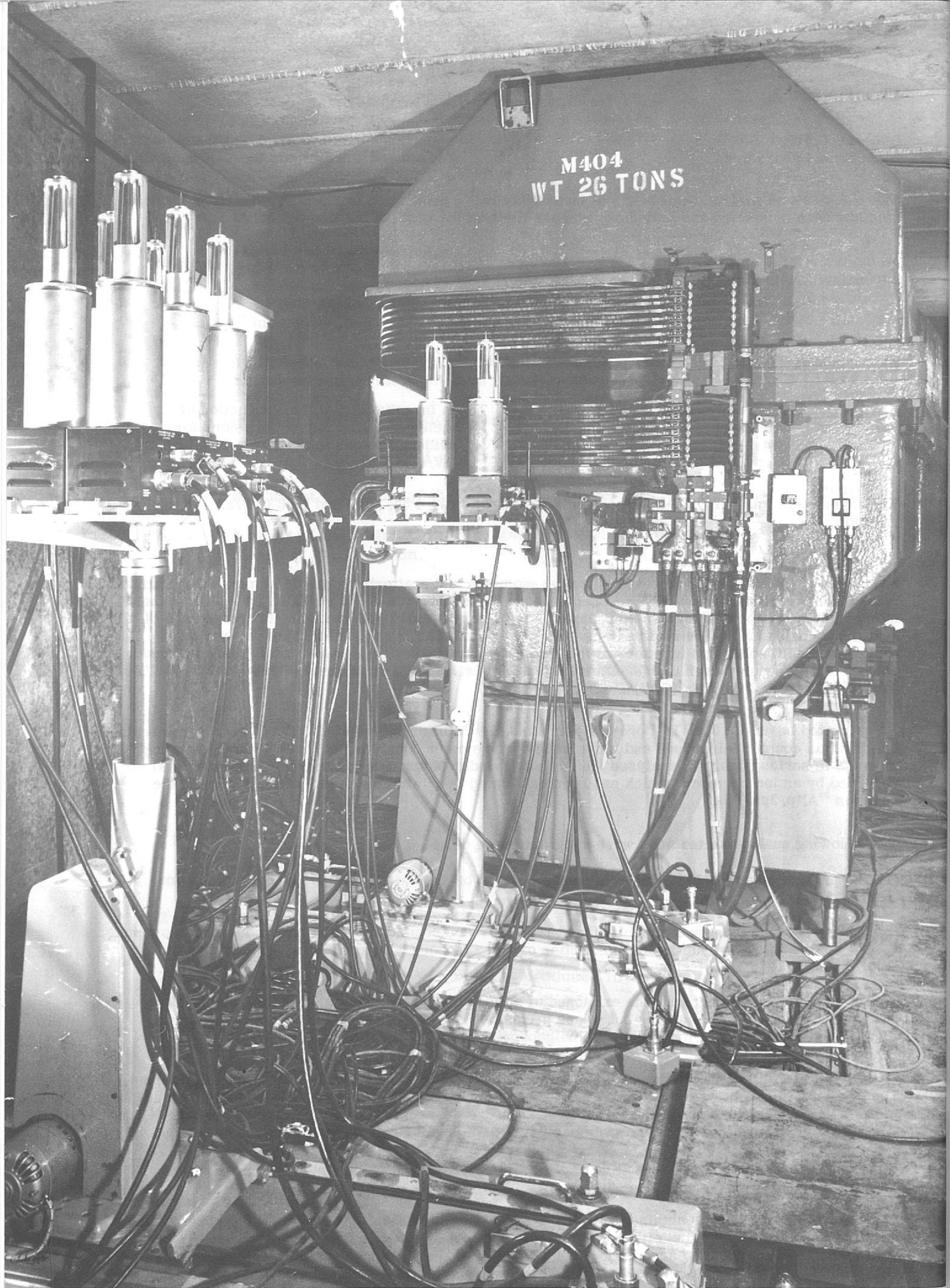

Figure 3. The counter hodoscopes and spectrometer magnets used in the experiment to study the production of nucleon isobars in p-p collisions.

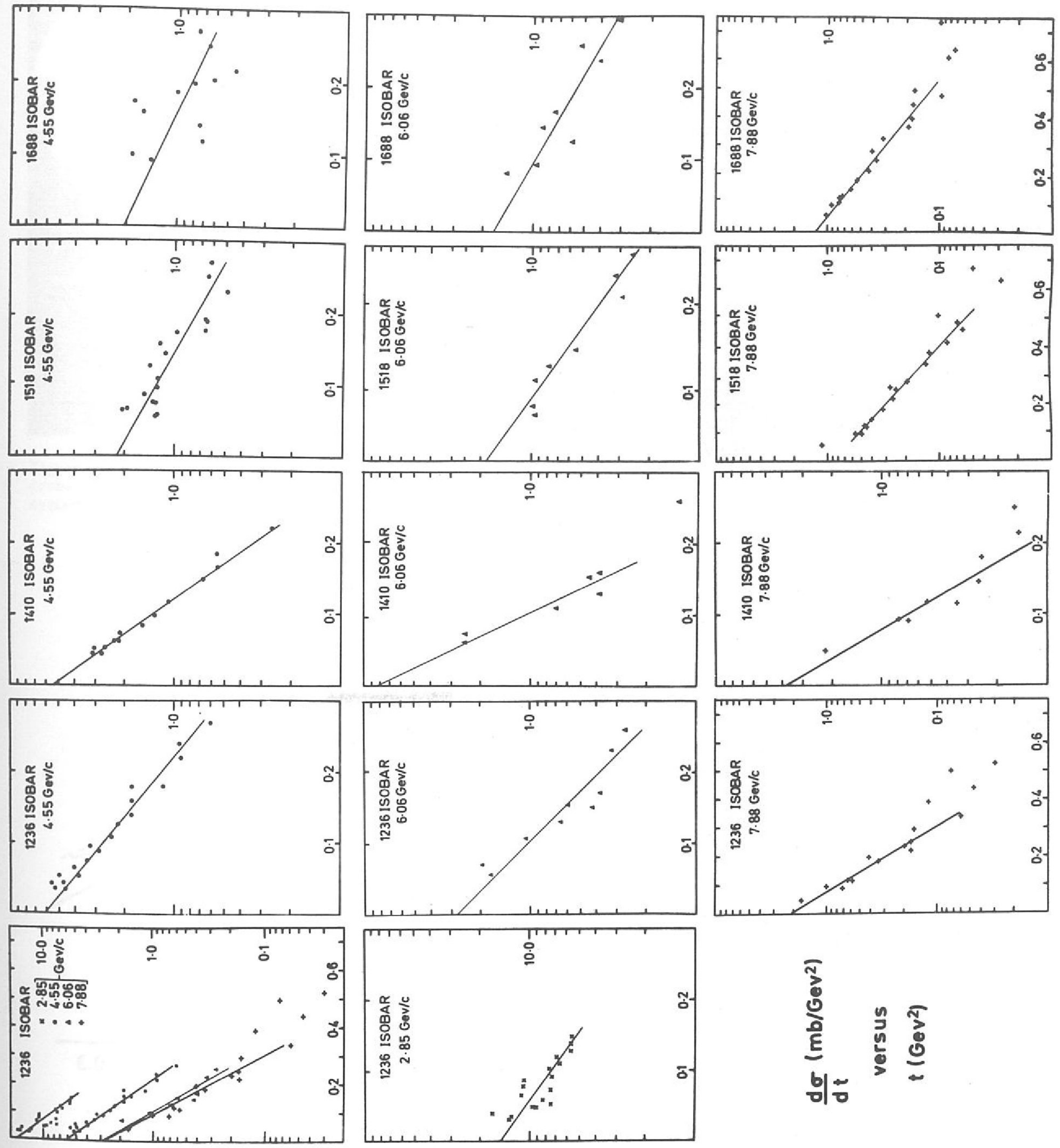

Figure 4. The differential cross-sections for the reactions p + p → p + N* expressed as dσ/d|t| in millibarns per GeV², against |t| the modulus of the squared four momentum transfer in GeV².

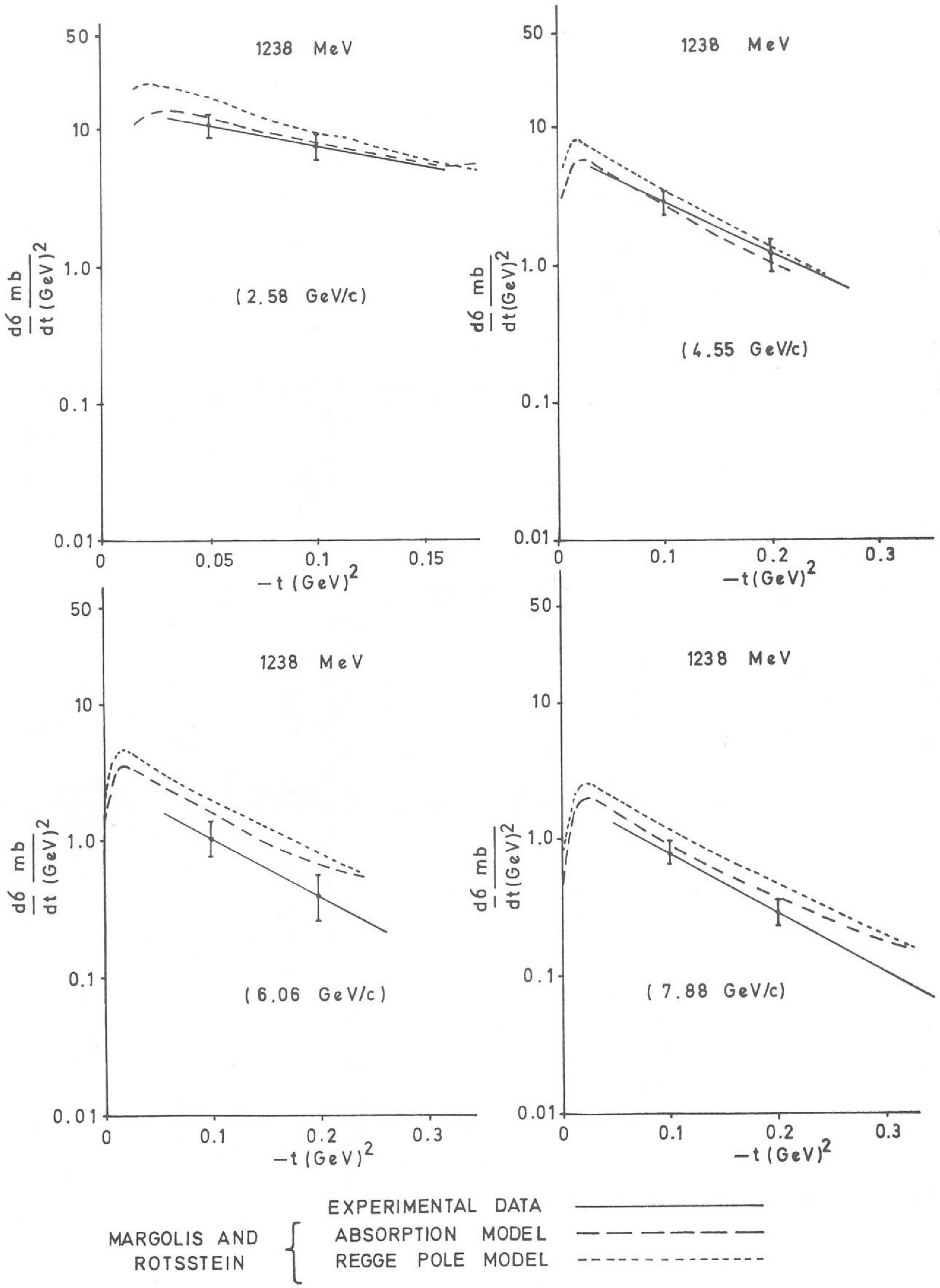

Figure 5. A comparison of the experimental data with the theoretical fits of Margolis and Rotsstein to the process $p + p \rightarrow p + N^*$ (1238 MeV)

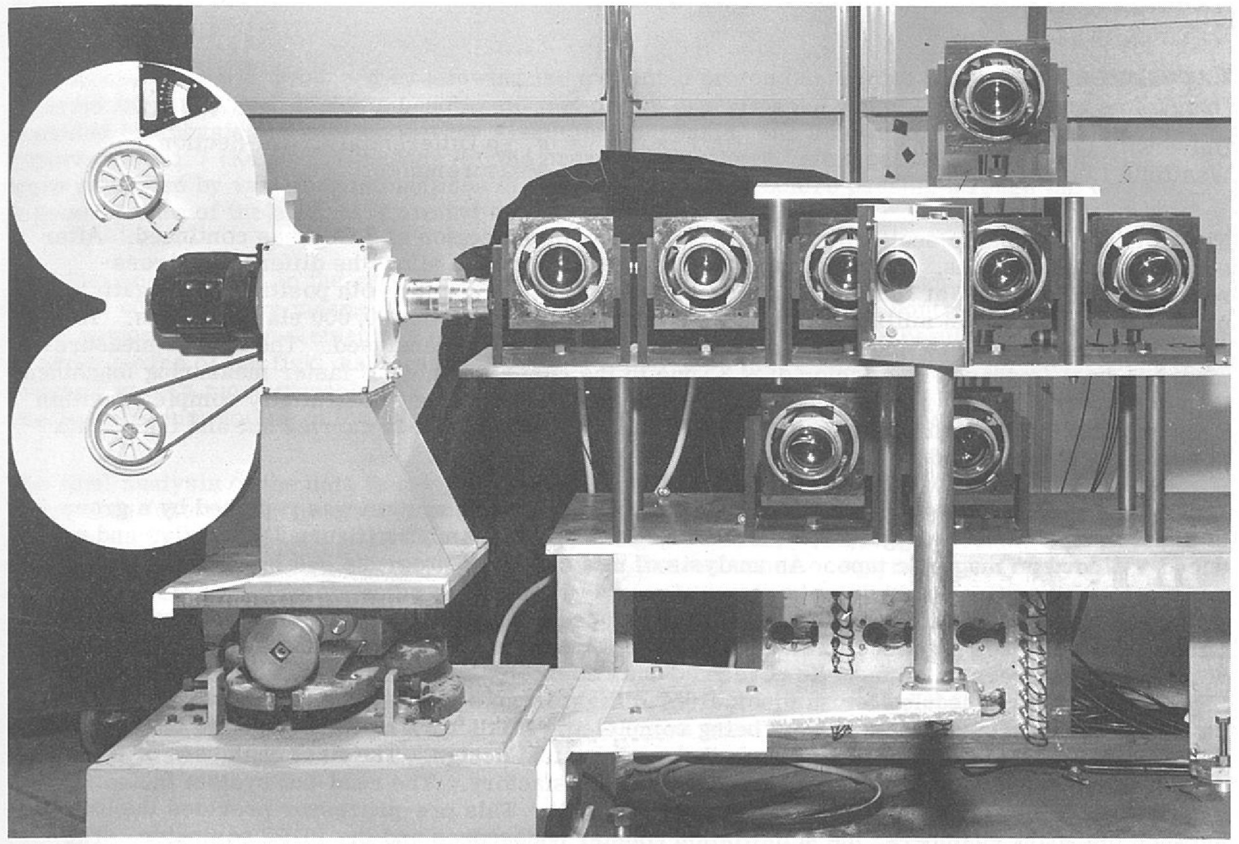

Figure 6. A battery of eight vidicon cameras used to scan the spark chambers during part of the $\pi^{\pm}p$ differential cross-section measurements. The camera on the left of the picture was used to check the operation of the vidicon system.

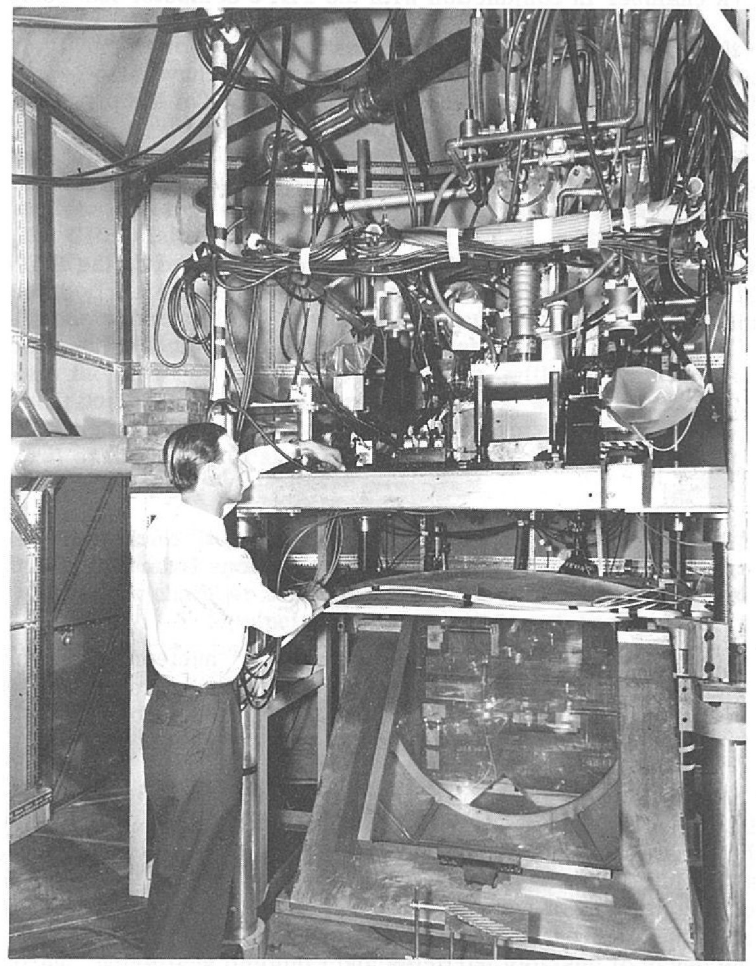

Figure 7. A view of the apparatus used in the $\pi^{\pm}p$ differential cross-section measurements. The spark chambers are photographed by means of the large mirror which can be seen beneath the apparatus.

Experiment 3

University College London,
Westfield College London.

$\pi^{\pm}$-p Differential Cross-Section Measurements.

The work on the elastic scattering of pions on protons in the region of 2 GeV has continued. After several successful runs, sufficient data has been accumulated to allow the differential cross-sections to be obtained at 10 momenta between 1·7 and 2·8 GeV/c for both positive and negative pions. In all, about 0·5 million pictures were taken containing about 60,000 elastic events. To date, the film for seven π^- momenta and ten π^+ momenta has been analysed. The rate of measurement has been improved by a factor of ~ 3, due to the commissioning of faster measuring machines. It is anticipated that the measuring and computing processes will be substantially completed within a few months. A preliminary interpretation of the π^- results has been carried out and the π^+ data is currently being considered.

During some of the running periods, the photographic recording system was replaced by a group of eight vidicon cameras (figure 6) which scanned the spark chambers (figure 7) directly, and produced a record on magnetic tape. An analysis of this data is in progress.

An automatic spark chamber system is being developed for use in future experiments by the UCL Group. Initially it is proposed to study K^-p elastic scattering. The system is based on the use of wire spark chambers with magnetic core read-outs connected on-line to a small computer. The K^-p experiment is scheduled for summer, 1967. Eight large spark chambers are required; these have been designed and are at present being completed. Much work has been done on the electronics required for pulsing the chambers and on their mechanical design. The first chambers of the final design are at present being tested and are proving satisfactory. The read-out system including a digital pre-processor has also been designed and built. This pre-processor provides the link between the spark chambers, the scintillation counter hodoscopes and the PDP8 computer. The information from the spark chambers and the hodoscopes is reduced into a form which can be fed into the computer in a manner which is both economic in time and computer storage space. About 800 integrated circuit elements are mounted on 200 printed circuit cards. Testing of the complete unit, including a spark chamber in conjunction with the PDP8 computer has been completed.

Work has been done through the year on the programs necessary for the analysis and monitoring of the data by the computer, which arrived in April. Programs have also been written for testing the electronics of the complete system and the visual monitoring of the progress of the experiment by means of oscilloscope displays.

A magnetic tape deck is used for the storage of partially analysed data in a form suitable for later processing by a larger computer.

However, a small percentage of the data will be completely analysed on the PDP8 and can be displayed in the form of a histogram on the oscilloscope to facilitate the early detection of faults and biasses in the experiment.

Experiment 4

Birmingham University,
Cambridge University,
Rutherford Laboratory.

$K^{\pm}$ and $\pi^{\pm}$ Nucleon Total Cross-Sections from 600 to 2700 MeV/c.

The aim of this experiment was to look for structure in the $K^{\pm}$ nucleon total cross sections over an incident kaon momentum range of 600 - 2700 MeV/c and to improve the statistical accuracy available on the corresponding measurements for incident $\pi^{\pm}$ mesons over the same range. The accuracy aimed at was $\pm$ 1% for the K measurements and $\pm$ 0·1% - 0·2% for the pions.

The technique used was the conventional one of measuring the attenuation of a beam of mesons by liquid hydrogen and deuterium targets. In order to achieve the maximum possible accuracy, great care was taken in the construction of the targets and in particular it was arranged that the condition of the target liquids should be both stable and accurately measurable. Corresponding precautions, such as the continuous monitoring of counter efficiencies, were taken with the electronics used to record the particles. Other corrections to be made to the raw data such as the effects of energy loss in the target, the decay of unstable particles and Coulomb scattering, were determined either by direct experiment or by computer calculation.

The meson beam was produced by allowing the extracted proton beam from Nimrod to strike an external target, placed inside a bending magnet on the experimental floor. The particles so formed provided two physically independent but simultaneous beams, one for this experiment and one for experiment No. 7 (K4). The mesons for the present experiment, after collimation and focusing, were identified by various combinations of Cerenkov counters before passing through the targets. A general view of the apparatus around the targets is given in figure 8.

The data accumulated in the scalers was punched out on to paper tape and then fed into a remote DDP 224 computer, by means of a teletype link positioned near the local control room. The computer performed some elementary calculations on the data, returning the results to the experimental floor by means of the link, and produced another paper tape in a format suitable for subsequent processing by a more powerful computer. The immediate calculations were of great value in checking the functioning of the experimental apparatus and the internal consistency of the data.

The final analysis of the data is not yet complete but preliminary results have shown several interesting features. The most important of these is the establishment of a previously unreported strange particle resonance in the K^-- p system, designated as $Y_0^*(1698)$, figure 9. The results of the present experiment are entirely consistent with the resonance occupying one of the unfilled places in an SU(3) multiplet, some of whose other members are already known. Other important conclusions to be drawn from the data obtained, are (1) the confirmation of structure in the K^-- p and K^-- n systems previously reported or suggested by a group at Brookhaven, and (2) the verification of small maxima in the K^+-p and K^+-n total cross-sections in the momentum region just above 1 GeV/c. The pion data does not show any new features, but it is expected that the greatly increased accuracy which will finally be available will enable more accurate and reliable dispersion calculations to be made.

Experiment 5

Aachen University (Germany),
AERE, CERN, Rutherford Laboratory.

A Study of the Decay of the K_L^0 Meson into Two Neutral Pions.

The observation of the decay $K_L^0 \rightarrow \pi^+ + \pi^-$ in 1964 by Cronin et al, which was confirmed by experiments at the Rutherford Laboratory and CERN, showed that CP symmetry was violated (CP symmetry requires that the physical laws remain unchanged if particles are replaced by antiparticles and the co-ordinate system is reflected through the origin). A multitude of theoretical papers were published explaining the CP violation by several types of model, which included: (1) C violation in the strong interaction, (2) C violation in the electro-magnetic interaction, (3) CP violation in the weak interaction (the major amplitude in the weak interaction has an isotopic spin charge of $\frac{1}{2}(\Delta I = \frac{1}{2})$ but there is some evidence for a small $\Delta I = \frac{3}{2}$ amplitude; the CP violation could be in either, or both, amplitudes), (4) CP violation in a completely new "super-weak" interaction specifically invented to explain the $K_L^0 \rightarrow \pi^+ + \pi^-$ decay. Evidently, with information from only one experiment, many theories are possible. What was urgently needed was a further experiment measuring an independent CP violating process. Such an independent process of considerable value is the decay of $K_L^0 \rightarrow \pi^0 + \pi^0$. Several of the theoretical models of CP violation make specific predictions about the neutral mode branching ratio.

An experiment aimed at measuring this branching ratio was carried out at CERN by a team from the Rutherford Laboratory and AERE joined by physicists from Aachen University and CERN. The experiment used a $5\frac{1}{2}$ ton spark chamber array to detect the four γ-rays coming from the decay process $K_L^0 \rightarrow \pi^0 + \pi^0 \rightarrow 2\gamma + 2\gamma$. The principle of this experiment was to detect all four γ-rays, determining their energies and directions from the spark chamber information and recombining the γ-rays kinematically to see if they, in fact, fitted the decay chain assumed above. The most serious background comes from the allowed process $K_L^0 \rightarrow \pi^0 + \pi^0 + \pi^0 \rightarrow 2\gamma + 2\gamma + 2\gamma$ which accounts for approximately $\frac{1}{3}$ of all K_L^0 decays and is several hundred times more frequent than the CP violating process of interest. Unfortunately, this background process has a higher probability of throwing four out of six γ-rays into the spark chambers than the wanted decay mode has of throwing four out of four γ-rays into the spark chambers. This meant that a very large fraction of events showing the required four γ-ray topology were in fact $K_L^0 \rightarrow 3\pi^0 \rightarrow 6\gamma$. An important addition to the apparatus was a large funnel of scintillator counters and steel plates, surrounding the decay region and forming a γ-ray detector. The trigger requirement for firing the spark chambers was that four (or more) γ-rays entered the spark chamber system, but none were detected by the γ-ray funnel. Background six γ-rays events of the most dangerous kind, in which four γ-rays went into the spark chambers and the other two γ-rays went elsewhere (i.e. into the funnel) were thereby considerably reduced.

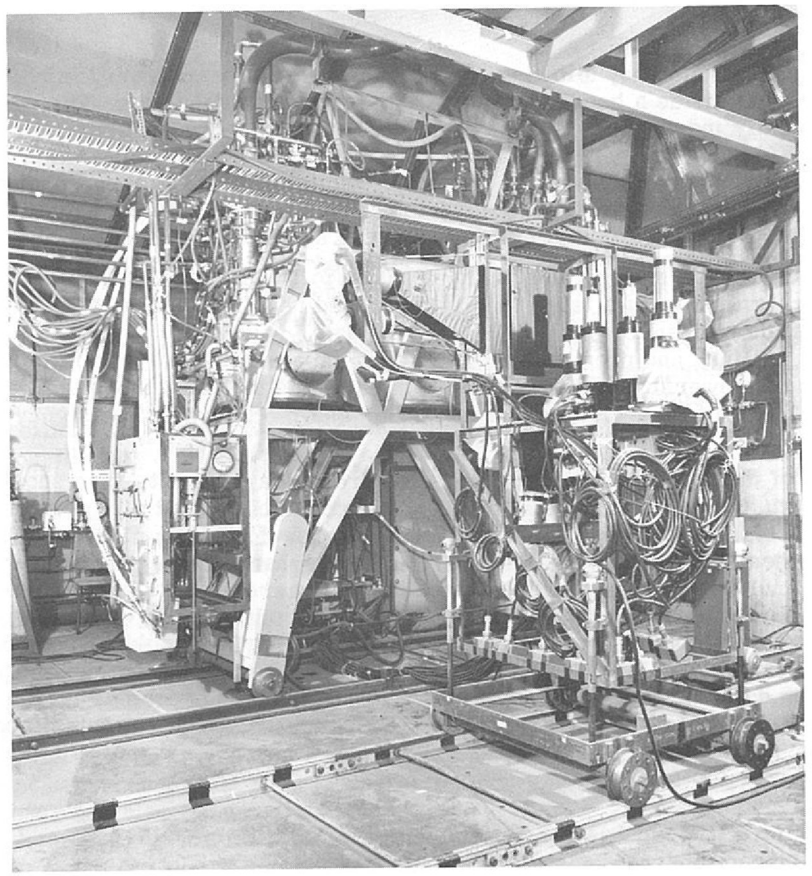

Figure 8. A general view of the apparatus used in the K-nucleon total cross-section measurement.

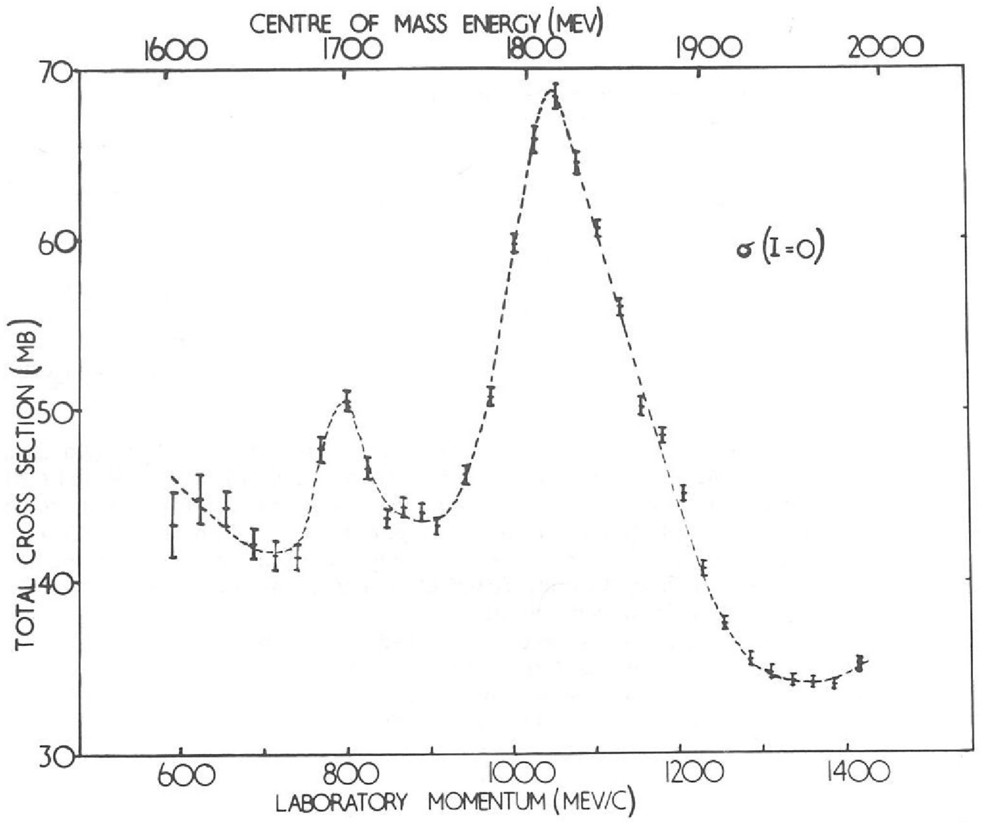

Figure 9. The values of the cross-section for I = 0, σ (I = 0), obtained from the relation σ(I = 0) = 2σ (K^--p) - σ(K^--n) using σ(K^--p) and σ(K^--n), the unfolded K^--n cross-section. The errors are purely statistical.

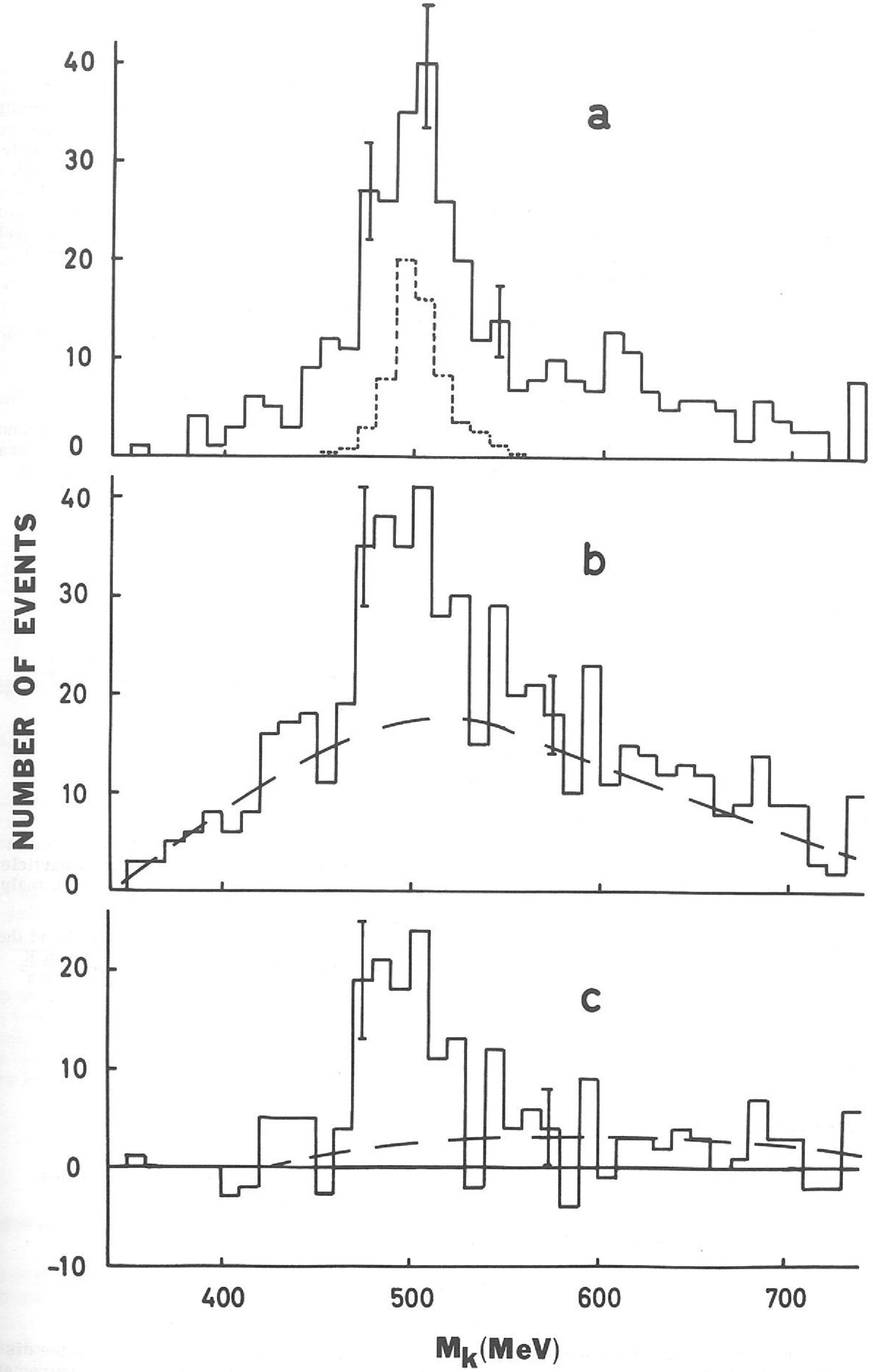

Figure 10. a) Experimental mass distribution for regenerated events. The dotted histogram is the 2π spectrum shape calculated with the Monte-Carlo program.

b) Experimental mass plot for free decay events. The dotted line is the background spectrum shape calculated with the Monte-Carlo program for $3\pi^0$ decays.

c) Experimental mass plot for free decay events with the Monte-Carlo spectrum subtracted. The dotted line is a fit by eye to the residual background.

A total of 190, 000 pictures were taken with the equipment in this mode. 15% of these pictures have now been analysed. The pictures were first scanned to select ones in which four γ-rays could be seen in the spark chambers. The selected events (approximately one third) were carefully measured and the resulting data was analysed in the Atlas computer to see if the event was kinematically consistent with the assumption that the four γ-rays resulted from the decay of two neutral pions. The two π^0s were, in turn, kinematically combined to form a single particle of mass (M), momentum (P), and direction of motion θ (to the beam). Genuine $K_L^0 \rightarrow 2\pi^0$ events should yield a value of M close to the mass of the neutral kaon (498 MeV) and θ close to zero (experimental errors cause small inaccuracies in M and θ). Figure 10 shows the resulting mass distribution. The peak centred at 498 MeV is proof of the existence of $K_L^0 \rightarrow 2\pi^0$ decay. The background is a residue of $K_L^0 \rightarrow 3\pi^0$, which passed the various selection criteria.

The input K_L^0 beam intensity was determined by regeneration of K_S^0 mesons with 30 gm/cm² of carbon placed in the K_L^0 beam. The resulting well known $2\pi^0$ decays of K_S^0 were observed with the same equipment and figure 10 shows the resulting mass spectrum.

A branching ratio: $K_L^0 \rightarrow 2\pi^0 / K_L^0 \rightarrow$ all decays = $(3{\cdot}3 \,{}^{+\,1\cdot8}_{-\,1\cdot1}) \times 10^{-3}$ was obtained from the data. The decay $K_L^0 \rightarrow 2\pi^0$ is the second observed process demonstrating CP violation. The measured branching ratio eliminates some of the many theoretical models invented to explain the $K_L^0 \rightarrow \pi^+ + \pi^-$ decay. For example, the super-weak theory is excluded and the CP violation is at least in part due to a $\Delta I \geqslant \frac{3}{2}$ amplitude.

Experiment 6

AERE, Southampton University, University College London, Rutherford Laboratory.

A Study of the Angular Distributions of the Charged Decay Modes of the f^0 Meson.

During July and August measurements were made on the study of the reaction

$$\pi^- + p \rightarrow n + \text{missing mass}$$

for pion momenta between 3·1 and 3·6 GeV/c.

An array of neutron detectors gave the energy and direction of the recoil neutron and was used in the trigger criterion. Sonic spark chambers provided data on the trajectories of charged particles. The equipment was operated on-line to the DDP 224/Orion computer system and subsequent analysis is being performed on the Atlas computer.

Approximately 40% of the data has been analysed. The $\pi^+\pi^-n$ final states are well resolved and the f^0 resonance is observed. Evidence is also seen for K^+K^- n final states indicating a small $\frac{K^+K^-}{\pi^+\pi^-}$ branching ratio for the f^0 decay.

Experiment 7

Oxford University.

A Study of the Leptonic Decay Modes of the K^+ Mesons.

The experiment is concerned with the decay modes

$$K^+ \rightarrow \mu^+ + \nu_\mu + \pi^0 \; (K\mu_3)$$

$$K^+ \rightarrow e^+ + \nu_e + \pi^0 \; (Ke_3)$$

which account for about 8% of all decays. The purpose of the experiment was to measure the distribution of energies of the e^+ or μ^+ and of the π^0 and the polarization of the μ^+. Such measurements would make possible an investigation of the structure of the interaction in relation to Unitary Symmetry models of the weak decay processes. In addition, the measurements will give information on two further questions.

(1) Are μ and e coupled in identical ways to systems containing strange particles?

(2) Is the interaction invariant under time reversal?

The K^+ mesons were produced in a target placed in the extracted proton beam from Nimrod. They were defined in momentum and separated from π^+ mesons and protons by a system of quadrupoles and bending magnets and a region of transverse electric field. The K^+ came to rest in a small spark chamber constructed from beryllium plates and the momentum of the e^+ and μ^+ measured by a system of sonic spark chambers and a magnet, the data being recorded on magnetic tape. The subsequent $\mu^+ \rightarrow e^+$ decay and the gamma rays from the π^0 muons were detected in visual spark chambers.

The setting up of the beam was completed early in 1966, just after Nimrod returned to full energy. Data was collected in two runs, one in the Spring and one in the Summer. About 420, 000 pairs of photographs were taken and the corresponding sonic spark chamber information was accumulated on magnetic tape. The latter was analysed in a preliminary manner in the course of data taking and indicated the correct functioning of the apparatus. A complete analysis of this data is now proceeding. The measuring of the useful photographs is also under-way. There is clearly a large amount of measuring to be done and, on completion, there should be for analysis, on a conservative estimate:

22, 000 Ke_3 10, 000 $K\mu_3$	decays with only the lepton momentum measured.
7, 000 Ke_3 5, 000 $K\mu_3$	decays fully reconstructed.
2, 000 $K\mu_3$	reconstructed decays having $\mu \rightarrow e\,\nu\,\nu$ decays suitable for polarization analysis.

Experiment 8

Oxford University.

A Measurement of the Ke_2 Branching Ratio.

The Ke_2 decay mode $K^+ \rightarrow e^+ + \nu$ is predicted to have a branching ratio of about $1{\cdot}6 \times 10^{-5}$ and a measurement of this quantity will confirm or refute the assumptions on which this prediction is based. These are:

(1) That the μ^+ and e^+ are equally coupled to strange particles and that the form of the weak interaction is (V-A) as it is in the case of non-strange particles.

(2) That there is no pseudoscalar coupling in the weak interaction.

The apparatus of the K decay experiment (experiment No. 7) was modified to make it suitable for the detection of this decay mode and in a run during September, 80, 000 photographs and the corresponding magnetic tape data were obtained. From this data the world's largest sample of Ke_2 decays has been extracted and a figure for the branching ratio will be available as soon as all corrections have been made.

Experiment 9

Imperial College, Rutherford Laboratory.

A Measurement of the Partial Width for the Decay $\phi^0 \rightarrow e^+ + e^-$.

A neutron counter and spark chamber study of $\pi^- + p \rightarrow K^+ + K^- + n$, close to threshold, showed clear evidence for ϕ meson formation and permitted an estimate of the production cross-section. This was found to be 0·16 microbarns for each 1 MeV/c step above threshold in the centre of mass system. The selection system was then modified to be sensitive to $\phi^0 \rightarrow e^+ + e^-$ and in all about 2×10^5 photographs were taken, on and just below the ϕ mass, in which 2 charged particles entered lead plate spark chambers and gave some evidence for multiplication. These photographs are now being scanned for possible examples of $\phi^0 \rightarrow e^+ + e^-$. Based on current ideas of ω - ϕ mixing about a dozen events are anticipated.

Experiment 10

Oxford University,
Rutherford Laboratory.

Polarization Effects in π^--p and
K^-- p Elastic Scattering.

A study has been made of the elastic scattering of negative pions and kaons on polarized protons as a function of the momentum of the incident particles. In the case of pions the range of momentum actually covered was from 0·65 GeV/c to 2·14 GeV/c and measurements were made at 50 closely spaced momenta within this range. Because of the much lower intensity of kaons in the beam, measurements for these particles were restricted to 8 momenta in the region of 1·15 GeV/c and 1·35 GeV/c. In all cases, results were obtained simultaneously in 4 momentum channels and measurements were made at 16 scattering angles for each momentum. The aim of this work was to provide data for a careful analysis of the scattering processes involved and, for both particles, these measurements represent a substantial contribution to the total available information.

The polarized proton target, which was designed and constructed by the General Physics Group, consists of a 3 in. long crystal assembly of lanthanum magnesium nitrate (chemical formula: $La_2Mg_3(NO_3)_{12}.24H_2O$) in which the spin directions of the free protons in the water of crystallization can be made to point in the same direction. This means that a scattering experiment using this target is sensitive to effects, arising from the proton spin, which average to zero when an unpolarized target, such as liquid hydrogen, is used. The target crystal contains only 3% by weight of hydrogen so it is necessary to detect the elastic proton scatters amongst a background of scatterings from all the heavier nuclei in the crystal. Figure 11 shows a plan view of the arrangement of scintillation counters, located in the 4 in. gap of the polarized target magnet, which was designed to do this. The arrangement of light-guides and photomultiplier tubes to detect the light output from the scintillators is not shown in the figure. The registration and processing of the output pulses from the scintillation counters was carried out using the "tunnel logic" circuitry developed by the electronics group and used for the first time in this experiment. This system consists of printed circuit logic units which are capable of handling counting rates of up to 200 megacycles/sec. About 1,000 of these units were used to construct a fast logic network which rejected all but potential elastic scattering events. The output from this network was connected on-line to a PDP5 computer in which a further rejection of unwanted events took place. In addition, the computer was programmed to assign the remaining events to one of four momentum channels and to separate the events into coplanar and non-coplanar categories. The latter provided a measurement of the background from non-hydrogenous scattering processes.

The collection of experimental data is complete and this data is now being analysed.

Experiment 11

AERE, Queen Mary College London,
Rutherford Laboratory.

A Study of the β-decay of the
Σ^- Hyperon.

The application by Cabibbo of SU(3) to the weak interactions of hadrons led to an attractive explanation of some of the discrepancies between theory and experiment which existed in a theory based on a Universal Fermi Interaction of the form (V-A), i.e. equal amounts of vector and axial vector currents. Notably, it explained why the hyperon leptonic decays which involved a change of strangeness occurred with branching ratios roughly an order of magnitude smaller than predicted by the UFI. In addition, the Cabbibo theory of weak interactions made the following predictions for the form of the interaction in the decays

$$\Sigma^- \rightarrow n + e^- + \bar{\nu} \quad (V + \cdot 35A) \qquad (1)$$

$$\Xi^- \rightarrow \Lambda + e^- + \bar{\nu} \quad (V - \cdot 16A) \qquad (2)$$

These two predictions are significantly different from the (V-A) form and provide good tests of the theory.

The present experiment is an attempt to measure the angular distribution of the decay electrons about the spin direction of the Σ^- hyperon in reaction (1) above. This should have the form $(1 + \alpha \cos\theta)$ and the relative amounts and sign of the vector and axial vector currents may be determined from the measured value of α.

In the reaction

$$\pi^- + p \rightarrow \Sigma^- + K^+$$

the Σ^- hyperons produced will have a polarization $P(\theta_\Sigma^*)$ perpendicular to the production plane and hence the form of the measured angular distribution will be $(1 + \alpha P(\theta_\Sigma^*) \cos\theta)$.

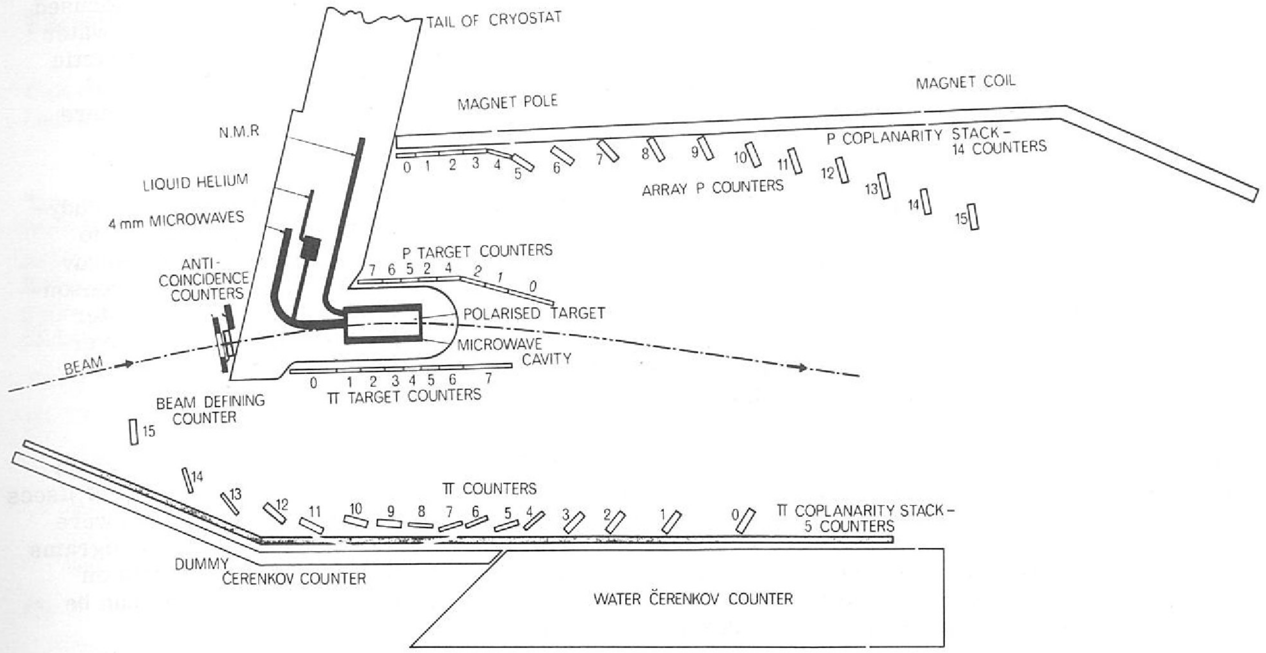

Figure 11. A plan of the counter hodoscope used in the measurement of polarization effects in K^--p and π^--p elastic scattering.

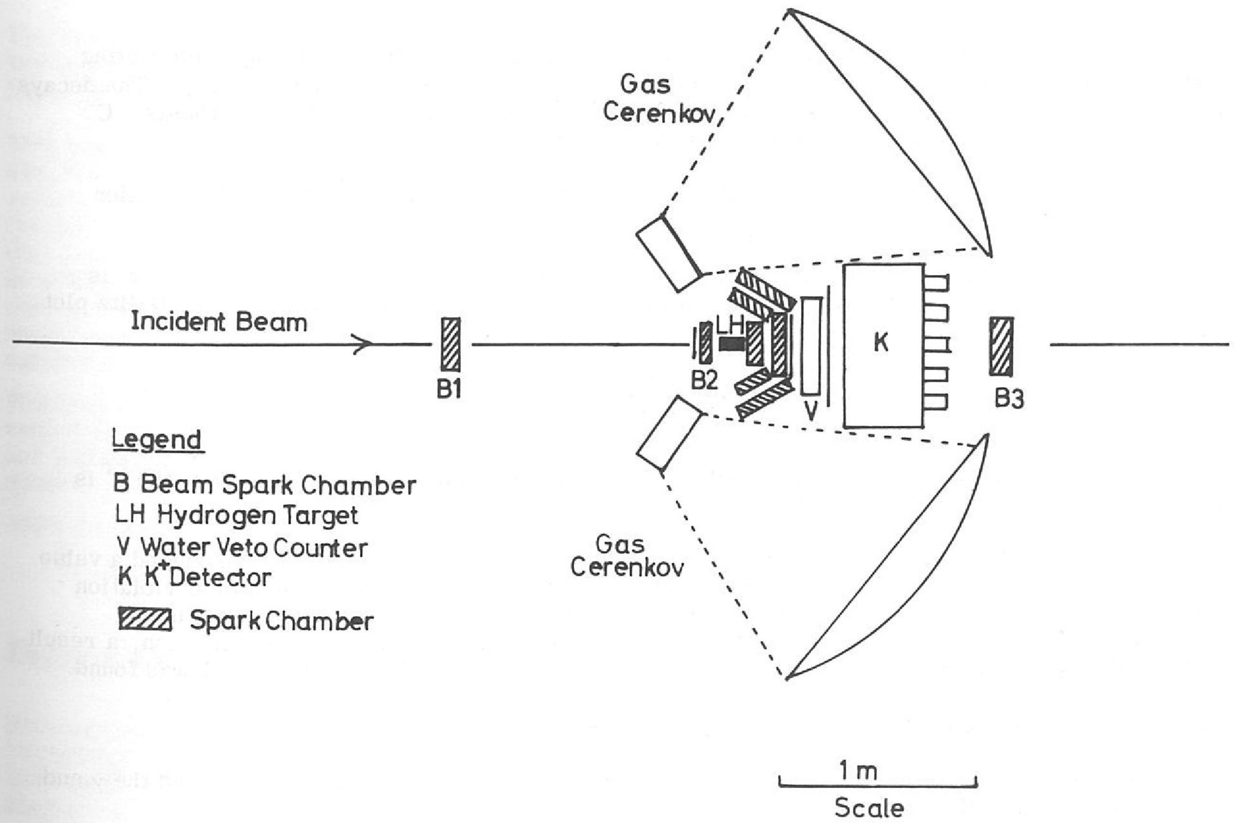

Figure 12. A schematic diagram of the experimental apparatus used in the study of the β decay of the Σ^- hyperon.

The experimental set up is shown in figures 12 and 13. A beam of 1·13 GeV/c π^- mesons is focused on to a 10 cm liquid hydrogen target. The K^+ mesons are slowed down and stopped in a large water tank and identified by their subsequent decay $K^+ \to \mu^+ + \nu$ in which the μ^+ is sufficiently relativistic to give a Cerenkov pulse in the water whereas the incident K^+ was not. The time distribution of the Cerenkov pulses should show a lifetime characteristic of the K^+ meson ($\sim$ 12·2 μsecs). There are two K^+ tanks, one above and one below the beam.

The branching ratio for reaction (1) is $\sim 1{\cdot}3 \times 10^{-3}$ so the main problem in the experiment is studying the β-decay against the potential background from the normal decay $\Sigma^- \to n + \pi^-$. In order to reduce the chance of a π^- simulating an e^- the electron detector is a one atmosphere gas Cerenkov counter filled with freon 12. A large parabolic mirror ($\sim$ 64 in. diameter) is used to give a reasonable solid angle and to focus the Cerenkov light on to a bank of 12 photomultipliers. The counter has been tested in a 180 MeV/c negative beam on the synchrocyclotron at the University of Liverpool. Its efficiency for electrons is $\sim$ 90% and for pions $\leqslant 2 \times 10^{-5}$. The electron detectors are placed on the left and right hand side of the beam.

Wire spark chambers will be used to see the trajectories of the incident pion, the K^+, the electron and in $\sim$ 5% of the events, a short Σ^- track. Each wire is connected to a ferrite core and $\sim$ 100 μsecs after the chambers have fired the 30, 000 cores are interrogated in order to determine which were 'set' by the currents in the sparks. This information is fed into a PDP8 computer which histograms the number of sparks per gap and cores set per spark, displays the event and writes the data on magnetic tape. The PDP8 is also linked with the IBM 360/75 via the DDP 224 so that data can be read from the tape and passed on to the 360 for detailed analysis.

The full electronic trigger - with the exception of the gas Cerenkov counters - has been set up, and the pion spark chambers and associated data handling tested extensively. Data taking should commence in Spring, 1967.

Experiment 12

Saclay, Rutherford Laboratory.

An Experiment to Study the $\pi^+ \pi^- \pi^0$ and $\pi^+ \pi^- \gamma$ Decays of the η Meson.

It has been suggested that C-violation in the electromagnetic interaction of strongly interacting particles might be responsible for the CP violation observed in the long-lived K^0 decay. The decays $\eta \to \pi^+ \pi^- \pi^0$ and $\eta \to \pi^+ \pi^- \gamma$ have been proposed as convenient ways to test this hypothesis. C violation would imply a difference between the π^+ and π^- energy spectra.

The Saclay chamber was exposed to a 0·82 GeV/c π^+ beam from Nimrod and using the reaction

$$\pi^+ + d \to p + p + \eta$$

a study has been made of the η decays. The Dalitz-Fabri plot for 765 decays of $\eta \to \pi^+ \pi^- \pi^0$ is shown in figure 14. The quantity under investigation is the right-left asymmetry in the Dalitz plot given by:

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

where N_+ and N_- are respectively, the number of events for which the kinetic energy of the π^+ is larger or smaller than that of the π^-.

An experiment in the Columbia-Brookhaven National Laboratory Bubble Chamber produced a value of A = 0·072 ± 0·028 for the decay to $\pi^+ \pi^- \pi^0$. This value is consistent with a maximal violation of C since the expected value of A is only $\sim$ 5%. The result of the present experiment is A = -0·06 ± 0·039. The two results suggest there is no significant evidence for C violation, a result confirmed by a spark chamber experiment at CERN where a value of A = 0·003 ± 0·01 was found.

The value of A obtained for the $\pi^+ \pi^- \gamma$ decay is - 0·04 ± 0·08.

The experiment has produced accurate measurements of the energy spectra of the π^0 and the γ and a new value for the relative branching ratio.

Figure 15 shows on interesting event where the decay mode has been identified as $\eta \to \gamma\gamma$. Both γ's have been converted, one internally and the other in the chamber filling.

Experiment 13

University College London,
Oxford University.

A Study of the Decays of η Mesons Produced in the Heavy Liquid Bubble Chamber.

Tracks were first observed in the 1·4 m Heavy Liquid Chamber in October, 1965 and it was ready for an engineering run in early 1966. A degrader separated π^+ beam (P3X) of 930 MeV/c was prepared to make maximum possible use of this run, by producing a good sample of η mesons. Because of the high interest in η decay and because of early detection of a few electron positron pairs of high invariant mass (near 500 MeV) the run was extended and a total of about 600, 000 pictures were taken in freon.

Three experiments from the same film are at various stages of analysis.

(1) The production of electron-positron pairs of high invariant mass (UCL- Oxford).

The whole of the film has been scanned for pairs of high mass and nine pairs with a mass (350 - 650 MeV) have been found. The observed cross-section for $\pi^+ + n \to p + (e^+ e^-)$, 650 MeV $> M_{e^+e^-} >$ 350 MeV, is 0·07 ± ·02 μb/bound nucleon. It is concluded that the effect can be satisfactorily accounted for in terms of inverse electropion production via intermediate vector mesons, i. e. $\pi^+ + n \to p + \rho^0$; $\rho^0 \to e^+ e^-$.

(2) A search for the decay mode $\eta \to \pi^0 e^+ e^-$ (UCL - Oxford).

The search for this decay mode was made automatically during the scan of the previous experiment. An event was found in a region where background is not negligible. No event has been found in the equally large region where background is negligible. Better limits will be set on the rate $\eta \to \pi^0 e^+ e^-$ when the analysis is finished.

(3) The branching ratio $\eta \to 3\pi^0$ (UCL).

The experiment requires a separate scan to look for five and six γ-ray events and this is just beginning.

Experiment 14

University College London,
University of Wisconsin,
LRL, Berkeley.

Low Energy π-π Interaction Studies from Ke_4 Decays.

This experiment was transferred to CERN because of the Nimrod alternator failure in 1965. The aim is to collect 300 examples of the Ke_4 decay mode of the K^+-meson: $K^+ \to e^+ + \pi^+ + \pi^- + \nu$. This sample represents four times the current world statistics and because of the small branching ratio involved, stopping 12 million K^+-mesons. The interest in this decay scheme centres on the fact that it is unique in providing the only known situation where the interaction between two pions may be studied without interference from other strongly interacting particles. An analysis of angular correlations among the four decay products leads to an estimate of the difference between the S and P wave phase shifts in low energy π-π scattering; a parameter of great importance for testing various model-dependent theories.

The Heavy Liquid Bubble Chamber is ideally suited for performing this experiment as its short radiation length induces the electron to radiate and curl up in characteristic fashion. It thus allows one instantly to distinguish the Ke_4 from the τ-decay which occurs with over 1, 000 times the frequency.

Analysis of the 575, 000 pictures is well advanced and results will be available early summer, 1967.

Experiment 15

Birmingham University, Glasgow University, Rutherford Laboratory, Oxford University, Imperial College, Max-Planck Institute Munich.

A Study of K^--p Interactions at 3·5 and 6·0 GeV/c.

The film for both exposures was obtained using the Saclay 80 cm and the British National 150 cm Bubble Chamber at CERN.

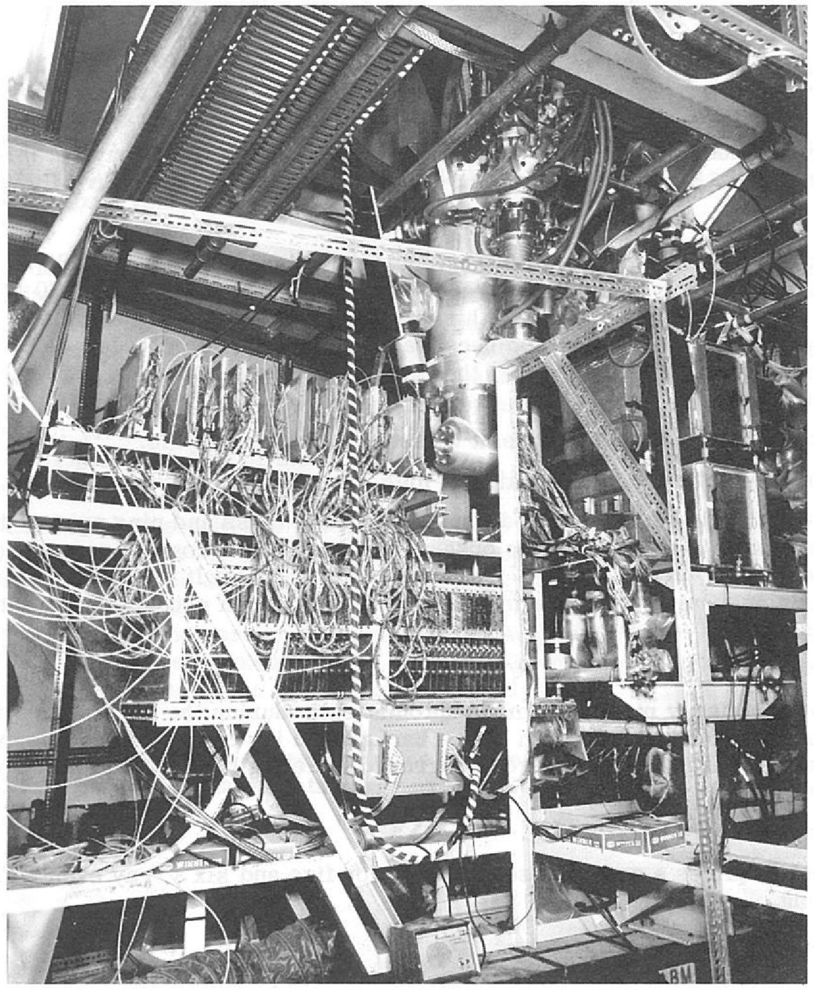

Figure 13. A view of the apparatus of the experiment on the $\Sigma^- - \beta$ decay, showing some wire spark chambers, the hydrogen target and the K^+ detection system.

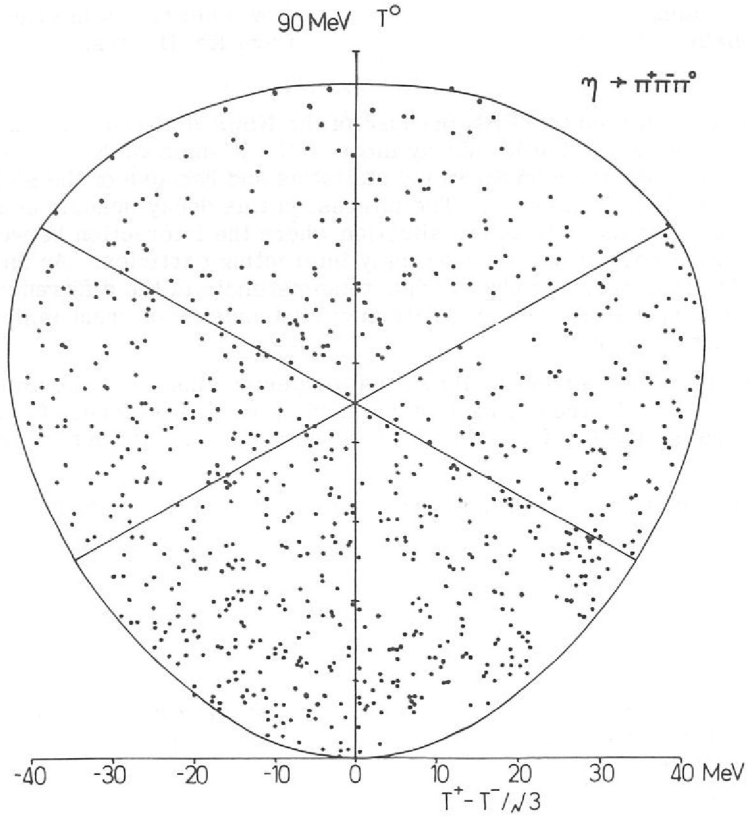

Figure 14. A Dalitz plot of the 765 $\eta \to \pi^+\pi^-\pi^0$ events. T^0, T^+ and T^- are the kinetic energies in the η centre of mass for the π^0, π^+ and π^- respectively.

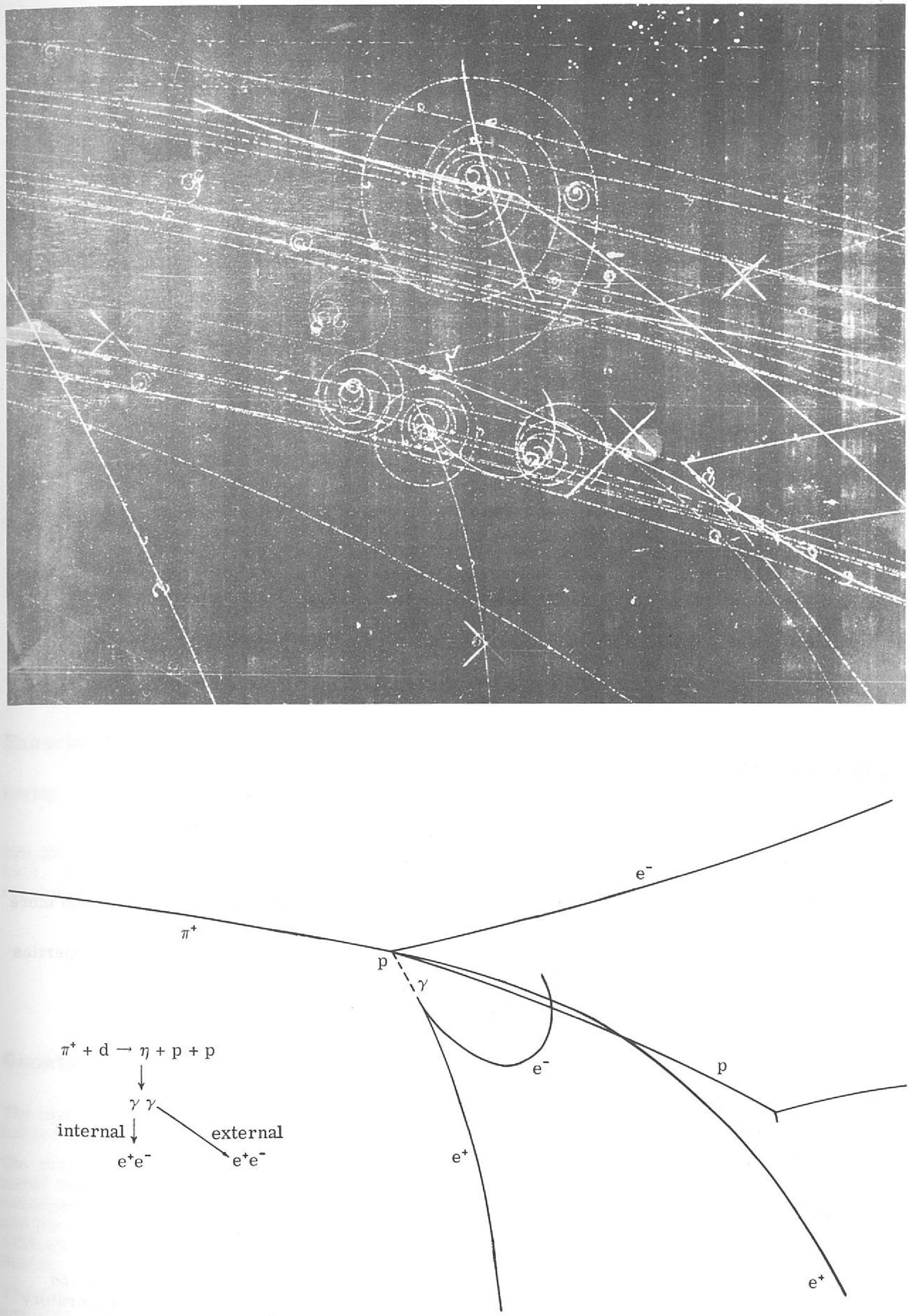

Figure 15. An $\eta \to \gamma\gamma$ event, in which both the γ's have converted, photographed in the Saclay 80 cm Chamber.

Work has continued on the analysis of the film and much detailed information is now available on many two and three body production processes and their analysis in terms of Absorption or Regge pole exchange models. Two body production at 3·5 GeV/c is described adequately by the Absorption model, but Regge pole exchange is needed to explain the 6 GeV/c results. At 6 GeV/c there are large numbers of final states with three or more bodies. These appear to arise from a double peripheral mechanism in which two particles or resonances are produced by exchange with the K^- and proton and one or more particles are produced isotropically between the K^- and proton. Several three body channels have been analysed in this way.

The $K^*(1320)$ and $K^*(1400)$ are produced at 6 GeV/c and decay modes $K^*\pi$ and $K\omega$ are clearly seen. There is evidence for the existence of a new resonance, the $Y_1^*(1700)$ decaying mainly as $\Lambda\pi$.

Six good examples of Ω^- decay have been analysed and with these and the American events, some estimates of the lifetime and branching ratios of the Ω have been obtained.

Experiment 16

Saclay, Rutherford Laboratory.

A Study of K^--p Interactions in the Range 1·25 - 1·85 GeV/c.

A total of 1·48 million pictures have been taken at Nimrod using the Saclay Chamber. These were spaced evenly over 13 energies, ranging from 1·25 to 1·85 GeV/c and will provide a detailed study of all Y^* states occurring by formation reactions in this range. The known states $Y^*(1915)$, $Y_1^*(2030)$ and $Y_0^*(2120)$ will be studied in decay modes such as $\Sigma^{\pm}\pi^{\mp}$, $\Lambda\pi^0$, K^0n and $Y^*\pi$.

Film taken corresponds to about 1 event per microbarn cross-section at each energy, so that typically 1,000 resonance events per channel per energy will be available. This should be sufficient to determine spins and parities for the known resonances and also to search for any new Y^* resonances in this mass range.

Experiment 17

Birmingham University,
Glasgow University,
Imperial College.

A Study of K^-d Interactions in the Region of 1·5 GeV/c.

235,000 photographs have been taken in the Saclay Chamber at a momentum of 1·65 GeV/c and more will be taken at 1·45 GeV/c in the Spring of 1967.

The analysis of the photographs already taken is proceeding with a view to measuring the properties of the $Y_1^*(2030)$ resonance, using the pure I=1 states obtained in K^-n reactions such as

$$K^- + d \to p_s + \Lambda^0 + \pi^-$$

where p_s is the spectator proton.

Experiment 18

Cambridge University.

Single and Double Pion Production in p-d Collisions at 2 GeV/c.

There were three reasons for doing this experiment. First, the nucleon-nucleon cross-section measurements made by a counter group from Cambridge University and the Rutherford Laboratory showed a rapid rise in the T=0 cross-section in this energy region, and further investigation of this behaviour seemed desirable. Second, the possible N_1^* (1405) should be produced strongly at this energy, perhaps allowing a study of its decay modes; and finally, analysis of the spectator proton momentum distribution and comparison with results already obtained at Cambridge in an anti-proton-deuterium bubble chamber experiment at 1·67 GeV/c should indicate the extent to which the impulse model holds in this energy range.

The 80 cm Saclay Chamber filled with deuterium was exposed to protons from the K1 beam at Nimrod. In total, about 65,000 pictures were taken (the chamber expansion being arranged to give two pictures per machine burst), and these were approximately equally divided between proton momenta of 1·84 GeV/c and 2·14 GeV/c, the latter being the maximum momentum obtainable with the K1 beam line.

The film has been completely scanned at Cambridge for three and four prong events corresponding to the reactions.

$$pn(p) \to (p)pp\pi^- \quad (1)$$

and

$$pn(p) \to (p)pn\pi^+\pi^- \text{ or } (p)pp\pi^-\pi^0 \quad (2)$$

Some 6,000 events have been measured on conventional machines and analysed by the CRAB system of programs on the Cambridge Titan computer. When the analysis is complete, data will be available on the following (approximate) numbers of events.

	Reaction (1)	Reaction (2)
1·84 GeV/c	1600	350
2·14 GeV/c	950	500

Experiment 19

Imperial College,
University of Oxford.

A Survey of π^+-p Interactions in the Range 0·6 - 1·05 GeV/c.

The analysis of 208,000 pictures taken in the Saclay Chamber is proceeding. The object of the experiment is a study of the dynamics of $N^*(1238)$ production by pions, including interference effects.

Experiment 20

Saclay, University of Oxford.

A Survey of π^--p Interactions in the Region of 0·5 GeV/c.

229,000 pictures have been taken in the Saclay Chamber and more will be taken in the Spring of 1967. It is hoped that a study of the $\pi^+\pi^-$ interaction well below the ρ-threshold may lead to a partial resolution of the present confusion with π^+ - π^- enhancement, such as the σ meson.

Electronics Group

Counter Electronics

The high speed logic system (the Tunnel System) mentioned in the 1965 report has been developed further and the results obtained from experiment No.10 have confirmed the high hopes of the system.

Our previous experience with the RL series of electronics indicated several weaknesses which would limit the extension of conventionally packaged transistor electronics to higher speeds. The necessary fan-out to obtain high logic power at high speed is incompatible with discrete transistors and the constructional techniques associated with them. The large size of the units presented difficult timing problems when cascading many stages of logic with alternative routes. The Tunnel System was developed to overcome these limitations.

The gain-bandwidth figure of merit of tunnel diodes is typically 5 times that for transistors and the use of these devices allows a large number of fan-outs to be obtained with logic delays of the order of one nanosecond. The elements are constructed on cards approximately 2 inches square (figure 16a) and are mounted in crates, each holding 62 cards. Figure 17 shows the equipment used in experiment No.10 where approximately 800 cards were used. This experiment ran throughout the year, with a total data collection time of over 1500 hours and the final performance indicated that no significant loss of reliability had resulted from the introduction of this novel system.

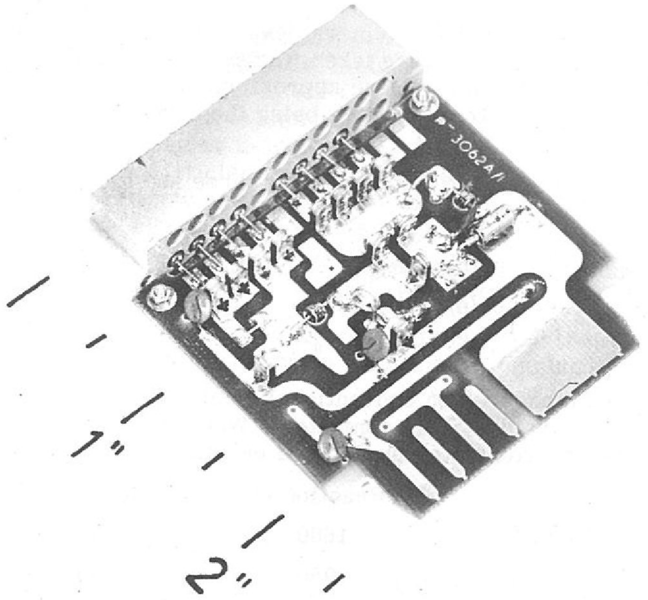

Figure 16(a). An OR gate in the tunnel diode system. The circuit is shown on the opposite page in figure 16(b).

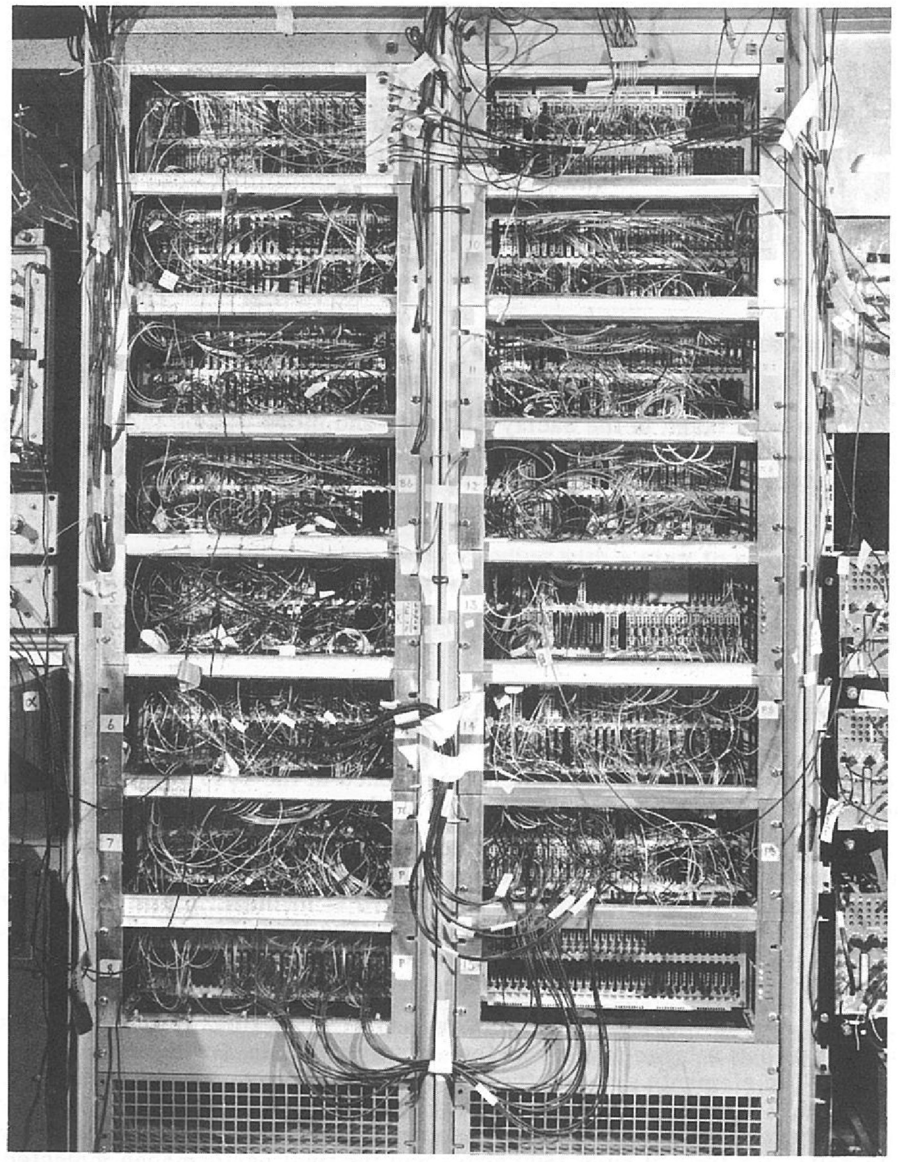

Figure 17. The tunnel diode system used in experiment No. 10.

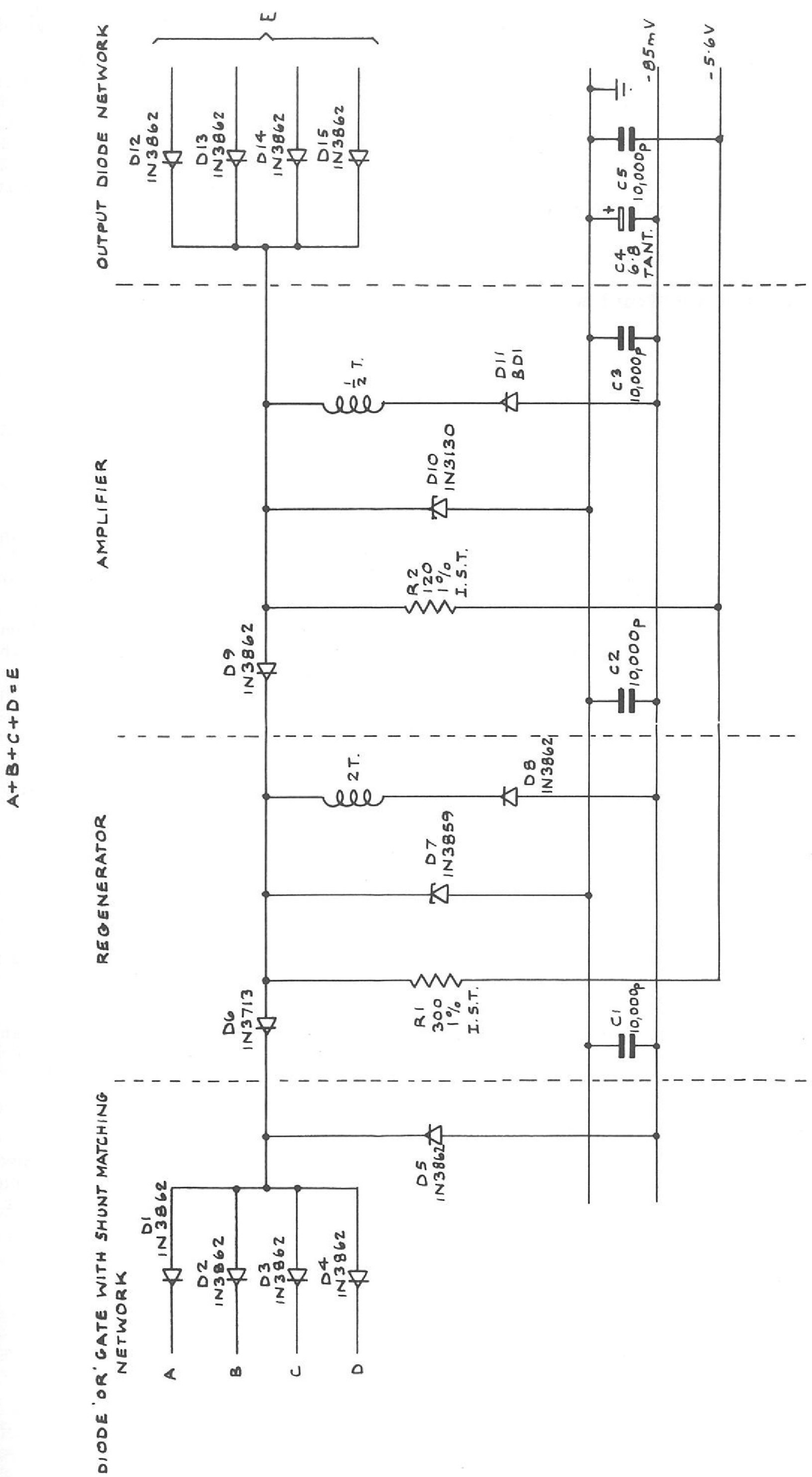

Figure 16(b). Circuit of OR gate card.

The same equipment built from RL series units might occupy 7-10 racks. The book-keeping necessary to keep track of the signal delays over the large distances involved would be large. System modification would be very tedious, so limiting flexibility.

A pulse pair resolution of 10 nanoseconds may be taken as a bench mark in considering the performance of an electronic system. This is a figure achievable by conventional transistor electronics but difficult to reduce. The Tunnel System gives a pair resolution of 5 nanoseconds. To complement this system investigations are underway into an extension to reduce further the size and cost of these complex electronic systems. This may be achieved in cases where a pair resolution of 20 nanoseconds is acceptable. The development will use the hardware and logic concepts of the Tunnel System and provide a useful extension of its present power.

Spark Chamber Electronics

The system used for core read-out from spark chambers which was mentioned in the 1965 Progress Report has been manufactured. Part of it is assembled and operating in experiment No. 11.

Data is being transferred successfully from the spark chambers to a small on-line computer. Samples of the data have been transmitted directly to the IBM 360/75 computer where more extensive analysis can be performed.

Experience with this equipment has suggested modifications which, when coupled with new component development, would significantly improve future systems using this method of read-out.

However, the mechanical problems associated with the transfer of signals from the large number of wires to their respective ferrite cores has proved very cumbersome. One alternative method of read-out uses a magnetostrictive delay line. Electronic systems associated with this type of read-out are being investigated.

As new components become available it is necessary to reassess possible systems. A read-out system used with sonic spark chambers used many individual scalers, one for each datum. These systems were straightforward and reliable though relatively expensive. Wire spark chambers with magnetostrictive read-out are capable of resolving several sparks and so produce more data than those using sonic read-out. The reduction in the price of scalers due to the introduction of integrated circuits has more than compensated for the increased data requirement and one such system is being constructed.

High speed memory elements can be applied to this problem and developments in this field are now being assessed.

Special Developments

The increasing use of small digital computers for data acquisition has resulted in a continuing work load to provide the special electronic equipment required to match the characteristics of the particular computer to those of the experiment.

One such interface has been developed to control the transfer of data between the Tunnel System and a PDP-5 computer for experiment No. 10. A second has been developed to provide a cathode-ray tube display and magnetic tape facility for a PDP-8 computer used in experiment No. 11.

Three other comparable systems are now being designed for experiments which will be mounted during 1967.

The development of integrated circuits for magnetostrictive pulse read-out systems, mentioned above, has obvious applications to general purpose scalers. Though the application of these elements is being considered, the development of devices is so rapid that the field must remain fluid for some considerable time.

High Energy Physics Division - Publications, Reports, Theses

Journal Articles etc.

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A data handling system for wire read-out of spark chambers.
RHEL/M 103

MILBORROW R.S.
Core read-out system for wire spark chambers.
RHEL/M 104

Theses for Higher Degrees awarded to Students using Nimrod

JONES W.G.
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SCOTT D.B.
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The interactions of negative pions with protons at 2 GeV.
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NIMROD DIVISION

During the year the Nimrod programme fully recovered from the effect of the alternator breakdown reported last year. Accelerated protons for high energy physics were available for about 4, 850 hours, this being 82% of the scheduled time. This was by far the longest operating time in any year since Nimrod first worked in 1963.

Four experiments were completed which used, for the first time at Nimrod, 7 GeV protons extracted from the synchrotron. Two of these experiments ran simultaneously using a common secondary particle target in the experimental area on to which the extracted protons were focused.

As experiments were completed during the year, a start was made on a major re-organization of the layout of beams in the main experimental area.

Synchrotron Operation

Overall Performance

The synchrotron was operated using one alternator for the magnet power supply until 11 January, 1966. The second repaired alternator was then installed and the magnet was powered using the full power supply at the end of January. From that date Nimrod was operated on the basis of a 3-week cycle, 404 hours for high energy physics running and 100 hours for accelerator development and maintenance. Of the 100 hours, 12 hours were allocated for routine maintenance. In addition, some machine development time was given towards high energy physics time in order to meet the demands of the programme.

Of the 5, 840 hours scheduled for high energy physics, 4, 850 hours of available good beam time were obtained i.e. beam was available for 82·8% of the scheduled time (figure 18). 1, 564 hours were scheduled for machine development; beam was available for 920 hours or 58·9% of the scheduled time. This lower efficiency is accounted for by the inclusion of start-up times, by special repairs postponed from the HEP time and by the fact that for machine development, extra special equipment is often required.

During the HEP time, the extraction system was scheduled for 2, 588 hours; 1, 942 hours were achieved, an efficiency of 75%. Although this was a lower efficiency than overall, it was not significantly so since the low operational efficiency in the periods 21 February - 14 March and 6 - 27 June were caused by faults unconnected with the extraction system.

There were three shut-downs during the year. From 11 - 31 January the second repaired alternator was recommissioned. From 16 May till 6 June a new extractor magnet was installed. One of the alternator flywheels was inspected for fretting and about one week was used to measure stresses in the new rotor end plates under pulsing and non-pulsing conditions. Nimrod was open to the press and the public from 19 - 21 May. During the 7 days from 11 October the P3 beam line was converted for use as $\pi 4$.

Average beam intensity during the HEP periods varied between $1{\cdot}0$ and $1{\cdot}4 \times 10^{12}$ protons per machine cycle. To obtain this intensity, the injector operated, as before, with a 20mA, 350 μs pulse.

Magnet Power Supply

During the year the power supply produced 8, 439, 000 pulses. Most of these were at currents corresponding to 7 GeV compared with the 4, 500, 000 achieved before the alternator failure in February 1965. Flat top times were about 400 milliseconds until July after which targetting techniques enabled 500 millisecond magnet waveform flat-tops to be used. The corresponding repetition rates were 23·5 and 22 pulses per minute. For the running at the beginning of January one alternator connected with two flywheels was used. The complete rotary plant was used from the end of January. In April the coupling between the two flywheels was undone and since then the machine has been operated with the two motor-alternator-flywheel sets mechanically separate but with the two alternators electrically connected in parallel. In the case of mechanical failure of one set, this mode of operation should minimize the possibility of consequential damage to the other set. The rotor end plates were inspected ultrasonically once every 6 weeks.

On the converter plant the arc back rate has improved from typically 1 arc back in 48 hours to 1 in 97 hours.

Equipment Reliability

The causes of lost beam time are given in the accompanying table.

System	Beam time lost as percentage of total scheduled time.
Extraction system	3·3 (relative to scheduled extracted beam time)
Injector	3·1
Synchrotron radio frequency	2·3
Synchrotron magnet and ancillaries	1·6
Nimrod magnet power supply	1·2 (since 31 August)
Targets and target mechanisms	1·2
Vacuum	1·1
Inflector	0·65
Pole face windings and power supplies	0·5
Coolant systems	0·45

The reliability of the extraction system should be improved by the modifications discussed in the 'Beam Utilization' section. A further 3-4% of scheduled beam time was lost due to routine inspection of the extractor plunging mechanisms when the extracted beam was scheduled.

Very nearly half of the lost time on the injector system was caused by failures of the pre-injector EHT supply unit which occurred in the period before April. All three available supply units developed faults and it was only possible to continue operation by borrowing generators from other Laboratories*. After April the generator behaved well; it was run without pulse stabilisation of the supply at very little loss in performance.

In order to improve the environmental conditions of the equipment on the EHT platform for the ion source, an enlarged platform has been designed and ordered. In addition, an auxiliary platform is being made to support the power generator for the electronics.

The linear accelerator tank has been continuously under vacuum since February 1965 and the ion source has not been changed since August 1964.

The synchrotron radio frequency faults were in the primary frequency generator and programmers for which standby units are now being prepared. Also, there continue to be unexplained transistor faults in the cavity bias supply system. Modified protection circuits should improve this situation. The magnet system faults were mainly the collapse of the graphite 'curtains' protecting the vacuum vessel from injected beam.

Synchrotron Development

Ion Sources and d.c. Accelerators

The single gap accelerator (see 1965 report) has been modified so that it now withstands higher voltages (470 kV d.c. and 540 kV pulsed). It was used in an important experiment on low emittance ion beams. From work at Brookhaven it was known that the low emittance of beams from a PIG ion source was increased by a factor 18 when fitted to a conventional pre-injector. With an identical source fitted to the single gap pre-injector here, the emittance was only slightly increased.

A modified version of the Nimrod r.f. source has been assembled to fit the new lens box of the pre-injector (see Injector and Injection section). A miniature duoplasmatron source is being developed which may have applications for the Nimrod injector.

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*The Rutherford Laboratory gratefully acknowledge the co-operation of CERN and the Culham Laboratory of the UKAEA.

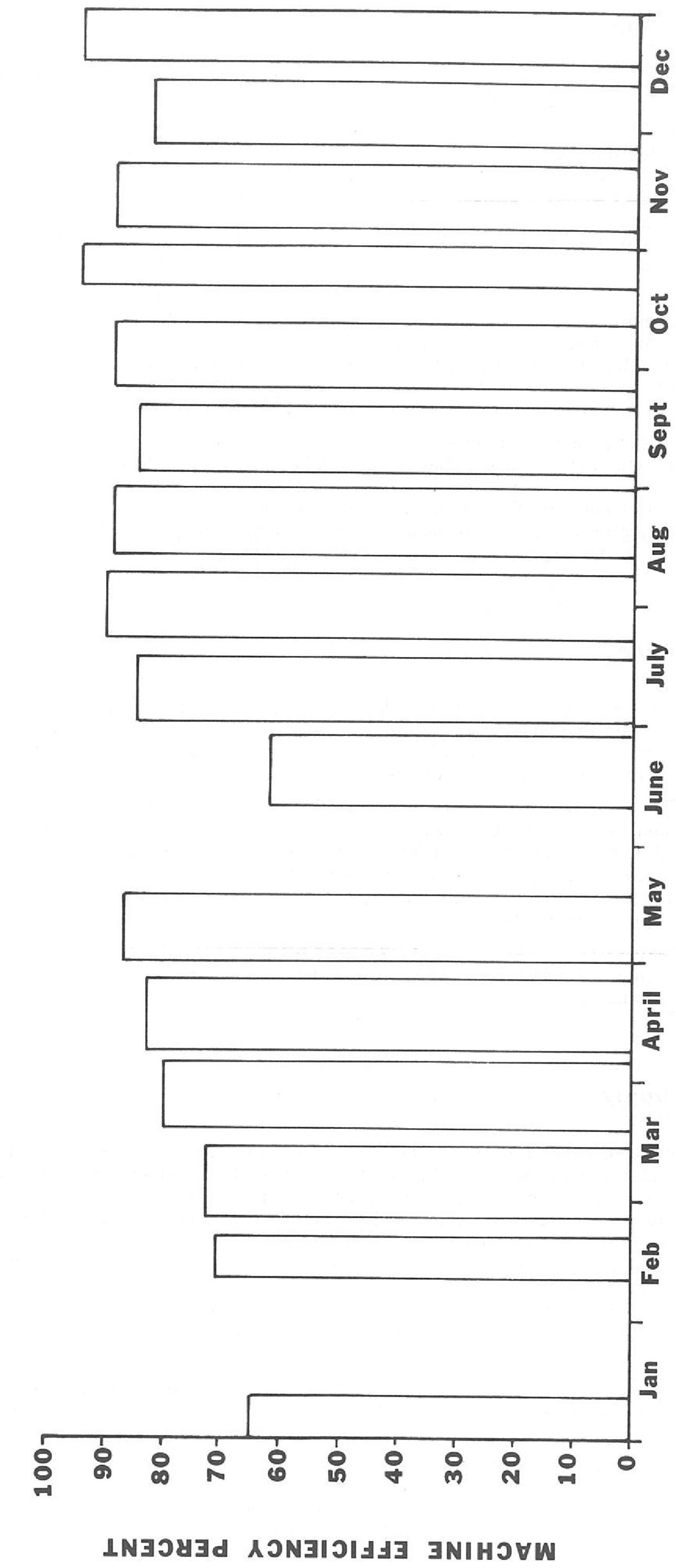


Figure 18. Nimrod effeciency during time scheduled for high energy physics.

Injector and Injection

Two modifications to the injector which are at present under way are intended to forestall possible future trouble and to ease the maintenance problem. Firstly, the design is complete for a major modification to the RS 1041 power amplifier circuit and components are being manufactured. Secondly, the pre-injector lens box has been redesigned (figure 19) and the new lens box will be fitted in January 1967. The linac radio frequency field stabiliser has been redesigned. It now gives a much improved performance which should stabilise against 15 MeV proton currents of at least 30 mA. The r.f. system tuning has been investigated thoroughly with the aim of producing maximum power to overcome beam loading. The retuning has led to more stable operation and less frequent adjustments.

The development of high voltage insulators for use in vacuum has continued. Studies have been made of the effect of contaminants in the vacuum system (such as might be found close to the electrostatic inflector in Nimrod). High alumina ceramic insulators have advantages over other materials such as electrical porcelain. Resistive coatings to provide a voltage gradient on the insulators have been shown to permit working with high average voltage gradients. Experimental work on anodising stress shields has given encouraging results in some cases.

Studies of injection into the synchrotron have continued. A saturation of synchrotron beam intensity with increasing injected current was found (figure 20) and has been shown to be due partly to a space charge limit and partly to an increase in injected beam emittance as injector current is increased. These studies will be continued with the aim of improving the emittance match of the injector beam into the synchrotron. Automatic sensing of proton beam steering into the synchrotron and measurement of emittance is being investigated.

Acceleration Studies

Values of Q_v (the ratio of the vertical betatron oscillation frequency to the rotational frequency of the protons), have been measured during acceleration by exciting the $(m \pm Q_v)$ resonant modes (m is any integer). This work required the development of tuned and untuned amplifiers for energising electrodes in a straight section of the synchrotron.

The coherent vertical instability in Nimrod is pronounced if the protons are steered along the centre of the vacuum vessel and, at present, is overcome by programming the radial position of the beam during acceleration. A system has been built for detecting coherent vertical oscillations of the protons and feeding back radio frequency signals to electrodes to damp out these oscillations. The system works satisfactorily for the $(1 - Q_v)$ mode but further study is required of the $(2 - Q_v)$ mode before final engineering can be completed.

A new radial proton beam position servo system has been made and initial trials completed successfully. This will enable more stable control of the radial position of the beam during acceleration and during targetting gymnastics.

Magnet Power Supply

Dynamic stresses have been measured on the replacements for the rotor end-plates which failed in 1965. Wire, piezo-electric and piezo-resistive strain gauges have been used for this purpose. No appreciable stresses at frequencies greater than the pulsating frequency have been detected. Relative movement between the pole end-plate and its tapered retaining key have been measured to provide further information as to the cause of the end-plate failure. Visual indication of the variation in stress in the end-plate during pulsing has been obtained using photoelastic material on the end-plate. An electronically controlled flash system and an optical system were used to obtain a cine-film of the stress patterns. Full scale end-plate models in a fatigue testing rig have been used to evaluate the relative performance of photo-elastic and ultrasonic techniques for detecting the onset of fatigue failure.

A system for dynamic braking on the drive motors of the power supply has been partially installed and will be ready for commissioning in January 1967. A spare rotor of the solid pole type has been ordered for delivery in Autumn 1967.

In order to provide a more flexible targetting arrangement an intermediate flat top would be useful. This was first produced successfully by the power supply in April 1966 and was followed by further tests during which accelerated protons were retained through the period of the intermediate platform. A considerable amount of investigation work still has to be done to determine the conditions under which the platform may be used.

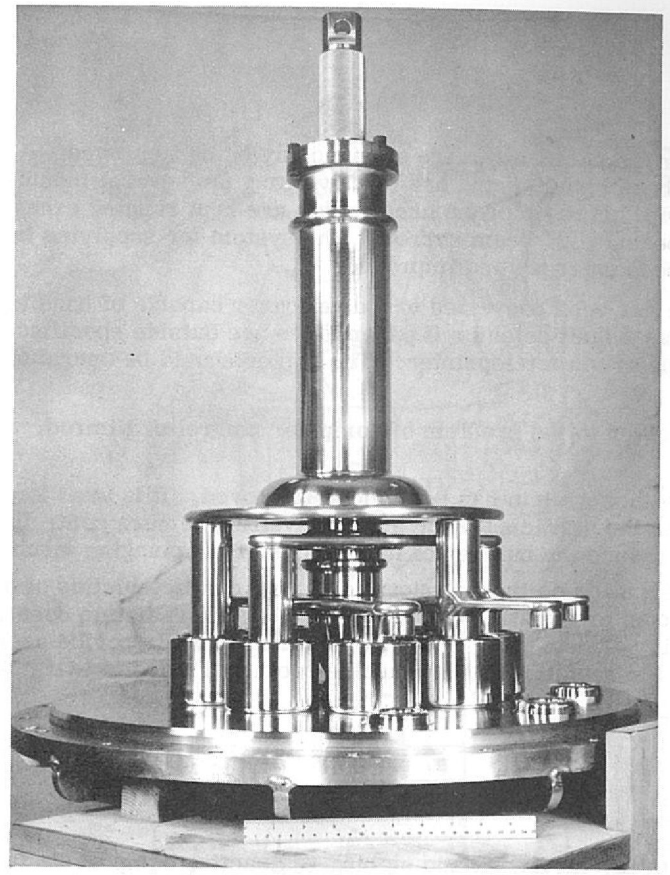


Figure 19. High voltage supports, insulators and electrodes for the pre-injector lens box. As can be seen there are electrodes at four different potentials.

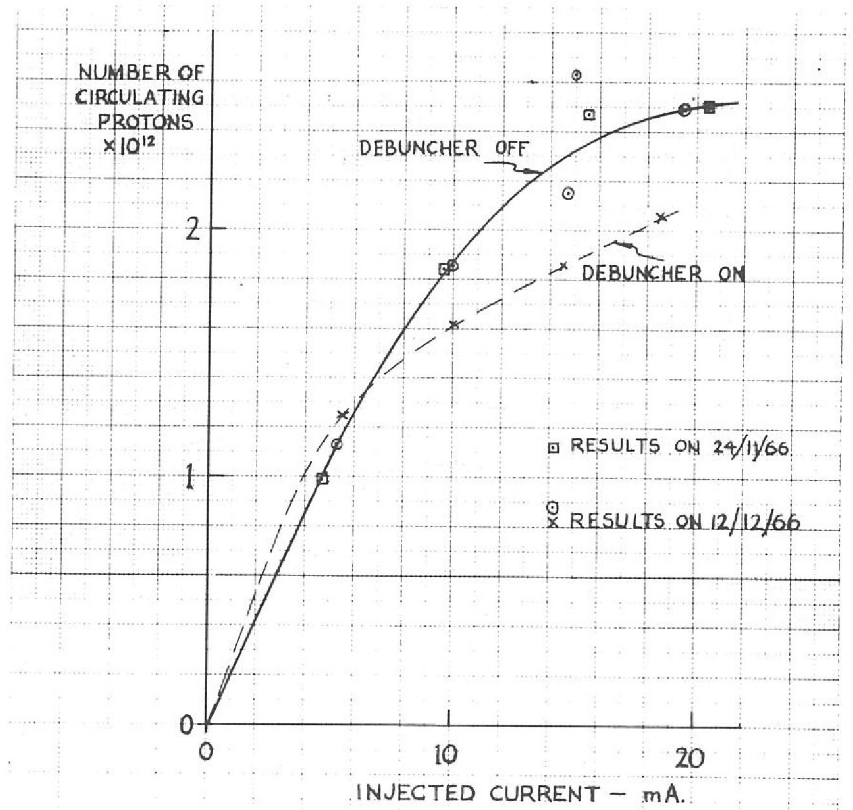


Figure 20. Circulating protons in the synchrotron at a magnet field of 500 gauss as injector current is increased.
Note: the absolute number of circulating protons may be different from scale given by up to 20%.

Controls

The control systems for the accelerator are continuously being improved. A comprehensive signal simulating system has been installed and has been working for several months. In the event of a magnet power supply trip, all parts of the accelerator are kept running except those actually requiring accelerated beam, e.g. beam servos. The system for supplying trigger pulses to high energy physicists has been enlarged and improved.

An available core store has been converted to a data logger capable of handling 400 machine parameters. This will act as a fault detector if parameters are outside specified limits, display being either on an oscilloscope or via a teleprinter. The logger should be operational after the shutdown in February 1967.

Much thought has been given to the problem of computer control of Nimrod. More work will be done in this field.

The closed circuit television system has been much improved. It is used for looking at scintillators in the accelerator and in the extracted beam and a travelling camera controlled from the main control room has been used to reduce the number of inspections of the plunging mechanism.

Measurements have been made on the deterioration of the characteristics of different types of transistors when subjected to radiation close to Nimrod. The radiation dose received was measured using calibrated radiation diodes. The information collected will provide useful design criteria for equipment subjected to radiation in the machine room and close to extracted beams.

Buildings

The problem of maintaining, modifying and storing radioactive components from the synchrotron and beam lines has led to the requirement for an 'active' workshop and store. This has been located adjacent to the North Tunnel Access as shown in figure 21. This workshop will be fully operational in March 1967.

Radiation Dosimetry

The radiation dose received by the inner vacuum vessel is continuously monitored by integrating damage dosimeters distributed throughout the inside lower surface of the vessel. Until recently, rubber dosimeters have been used but these are being replaced progressively by the hydrogen pressure dosimeters developed by the Engineering Division. Immediate readings may now be taken without opening up the vacuum vessel.

The dose pattern radially shows a maximum dose at about 10 cm from the back wall of the vessel. The total dose received by the vessel up to September 1965 and up to October 1966 is shown in figure 22. The accompanying table gives the increase in dose since October 1966 at the positions where the hydrogen pressure dosimeters have been installed.

Radiation dose received by the Inner Vacuum Vessel at 10 cm from the back wall since October 1966

Octant	Average Dose over Octant 10^6 rad.	No. of Protons
1	35·5	
2	14·5	
5	40	24×10^{17}
7	33·5	
8	36	

The total number of protons accelerated to date has been $12{\cdot}7 \times 10^{18}$. The maximum dose received by the vacuum vessel is $11{\cdot}2 \times 10^7$ rad.

The recorded doses indicate that the vacuum vessels should be safe for operation for many years under present operating conditions.

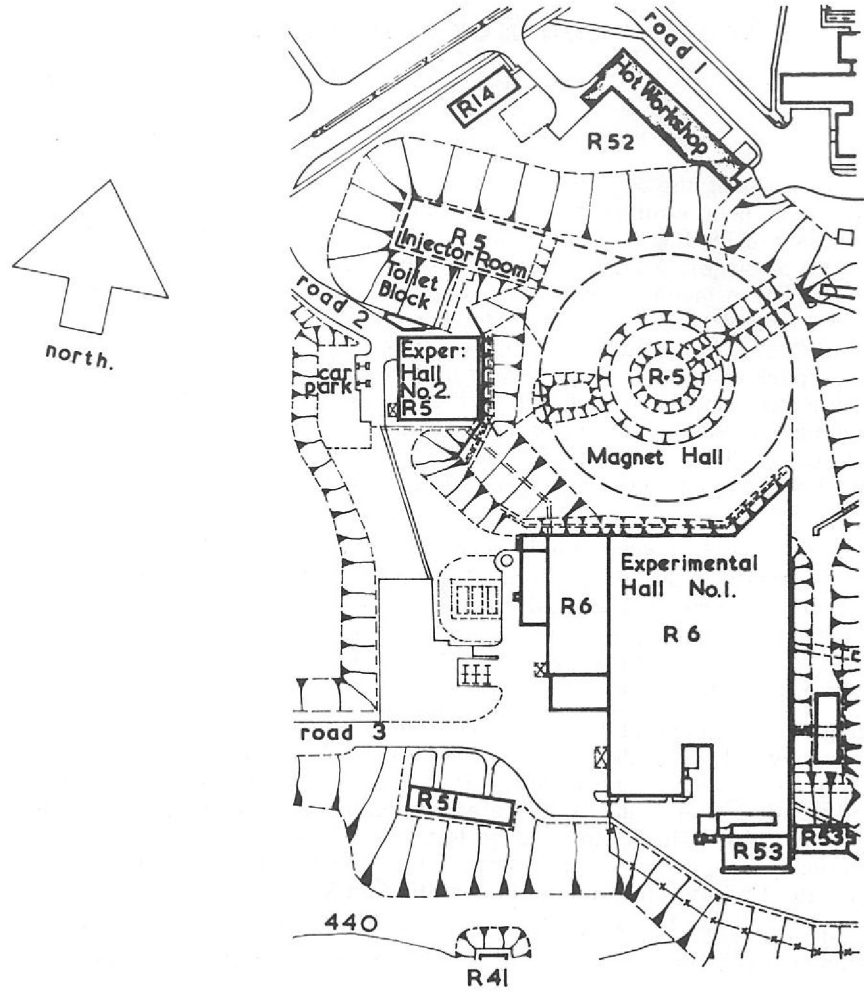


Figure 21. Layout of the 'active' workshop and radioactive component store. Access for personnel and smaller equipment from the machine is through the North Tunnel.

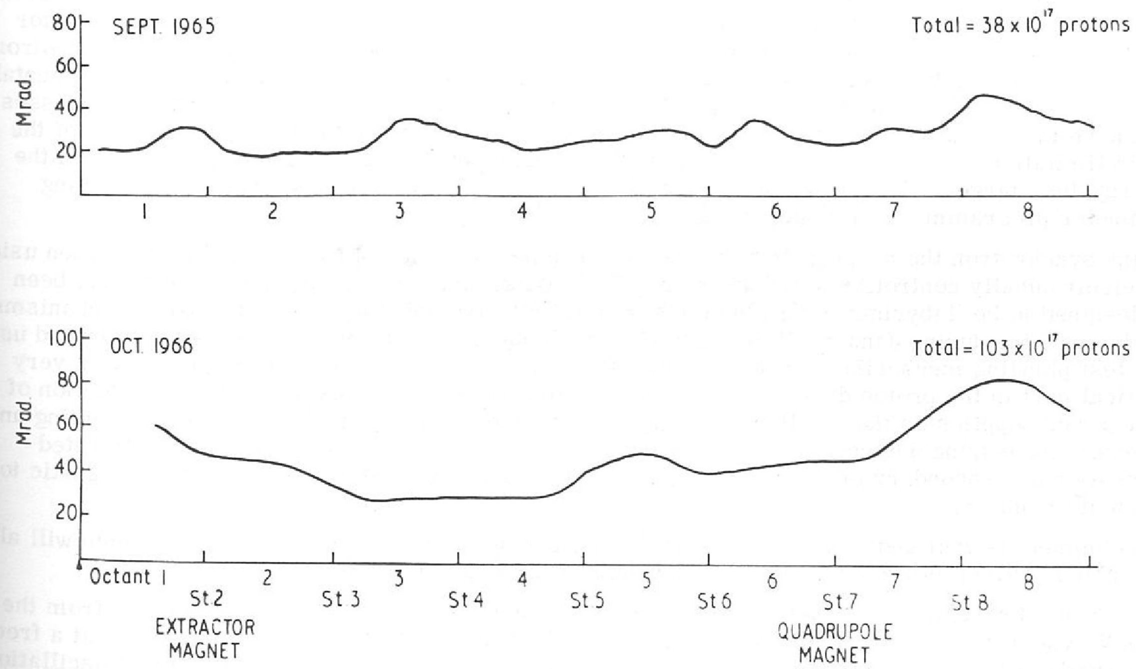


Figure 22. Absorbed radiation dose profiles for Nimrod inner vacuum chamber.

Accelerated Beam Utilization

Targetting

The main methods of controlling the way in which the accelerated protons interact with targets inside the synchrotron have been similar to those described in the 1965 report. There has been development of the method of feeding noise into the r.f. accelerating cavity to produce long spills (several hundred ms) on to targets for particle physics experiments using counter or spark chamber detecting techniques. A servo mechanism ensures that the rate of loss of beam from r.f. trapping is constant; thus for a constant rate of increase of magnetic field during flat top a constant rate of spill of protons on to the target is produced. This technique works very well where the detecting device (for instance a spark chamber) integrates over a time equivalent to several r.f. cycles (a few μs). However, for pure counter experiments, the r.f. structure produced (peak: valley ~ 5:1) is too large. This structure has been reduced by reducing the r.f. cavity volts on flat top from its normal 6 kilovolts to about 600 volts. Adjustments are more critical in this mode; nevertheless effective spill times of 300 ms have been obtained. The techniques described above have been in operation for several months.

Development has started towards a method of producing uniform spills without the requirement to have the r.f. voltage switched on during flat top. The main limitation at the moment is the amount of magnet voltage ripple; this produces a significant a.c. component in the spill rate. In the new technique a feedback system will keep the spill rate as uniform as possible by control of currents in some of the magnet pole face windings. Equipment for this technique has been developed and will be installed ready for commissioning in March 1967.

A method of providing extracted beams for bubble chambers with a fast spill has been developed in the Argonne Laboratory. This method uses a distortion of the orbit of the accelerated protons to deflect them quickly (~ 100 μs) on to a target. At Nimrod it is convenient to produce the fast spill by increasing the radial size of the accelerated proton beam by subjecting the protons to a radiofrequency magnetic field. This field is tuned to the beat frequency between the circulating frequency of the protons and frequency of the radial betatron oscillations caused by the focusing effect of the magnetic field. This equipment will also be installed ready for trials in March.

The redesigned target mechanism heads were fitted at all target stations during the year. Typically these targets withstand over 2, 000, 000 flips; at that level they are normally overhauled.

Extracted Proton Beams

The extracted proton beam line P1 focused accelerated protons on to an external target in Experimental Hall 1. Initial commissioning of this system was carried out last year using 2 GeV protons. This year the system has been developed for 7 GeV protons and was scheduled for operation for 2,588 hours. The extraction efficiency (extracted protons/protons circulating in the synchrotron) of the system was 20%. Extensive studies of the particle optics of the system, both experimentally and using the computer programme NIMDYN, have led to a better understanding of proton losses and have indicated procedures for overcoming some of the losses in future systems. One of the main limitations in the system is the result of scattering and energy spread of protons from the energy-loss target. The properties of the protons leaving this target have been studied using computer programmes LIP 3 and LIMP.

In the synchrotron the quadrupole and extractor magnets (figure 23) are plunged into position using an electronically controlled hydraulic ram. The seal around this rapidly moving shaft has been redesigned to be 'labyrinth' type which has been fully tested and will be fitted to both mechanisms in the machine during January 1967. The electronic control circuitry has also been improved using the test plunging mechanism. The magnetic field gradient on the extractor magnet plays a very critical part in the proton dynamics; this may now be varied more flexibly by the introduction of new power supplies on the auxiliary windings on this magnet. In the P1 line, proton detecting and intensity measuring devices have been developed. There are now fully operational calibrated ionisation and secondary emission chambers and initial trials have been made with a magnetic toroid intensity monitor.

Development is well under way of a switched power supply for the extractor magnet which will allow switching between two extracted beam lines during the same machine pulse.

In 1965 the Frascati Laboratory reported the successful extraction of an electron beam from the 1 GeV synchrotron, using a resonant technique. The beam is made to resonate radially at a frequency two thirds of that of the orbital frequency, resulting in an ever increasing amplitude of oscillation. Once the resonance is well under way, the increase in amplitude every three turns round the machine is sufficient for a large proportion of the particles to jump across the septum of a magnetic channel.

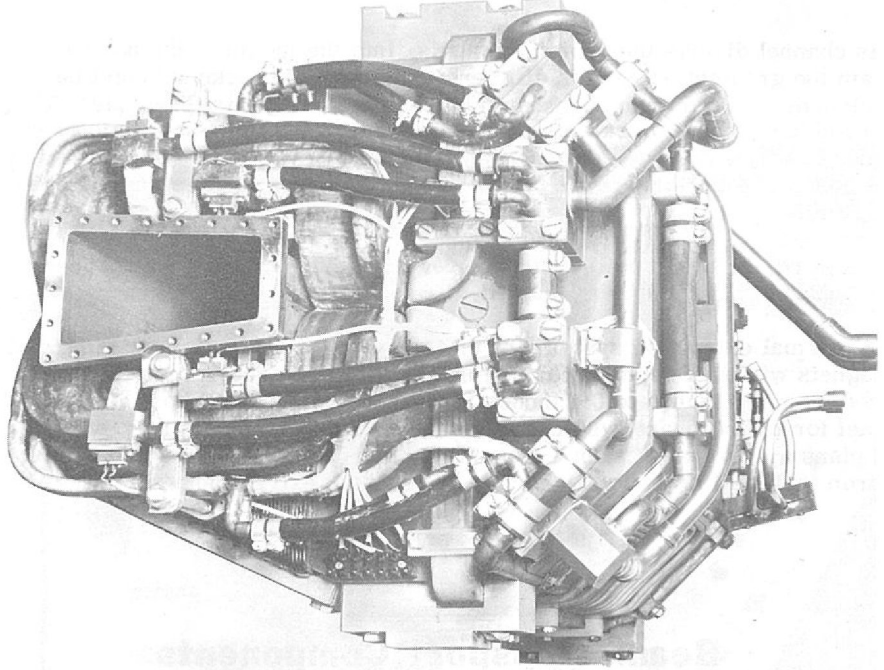


Figure 23. The extractor kicker magnet with its vacuum can removed. Connections for the electrical supplies and water cooling of the main windings and correction windings can be seen.

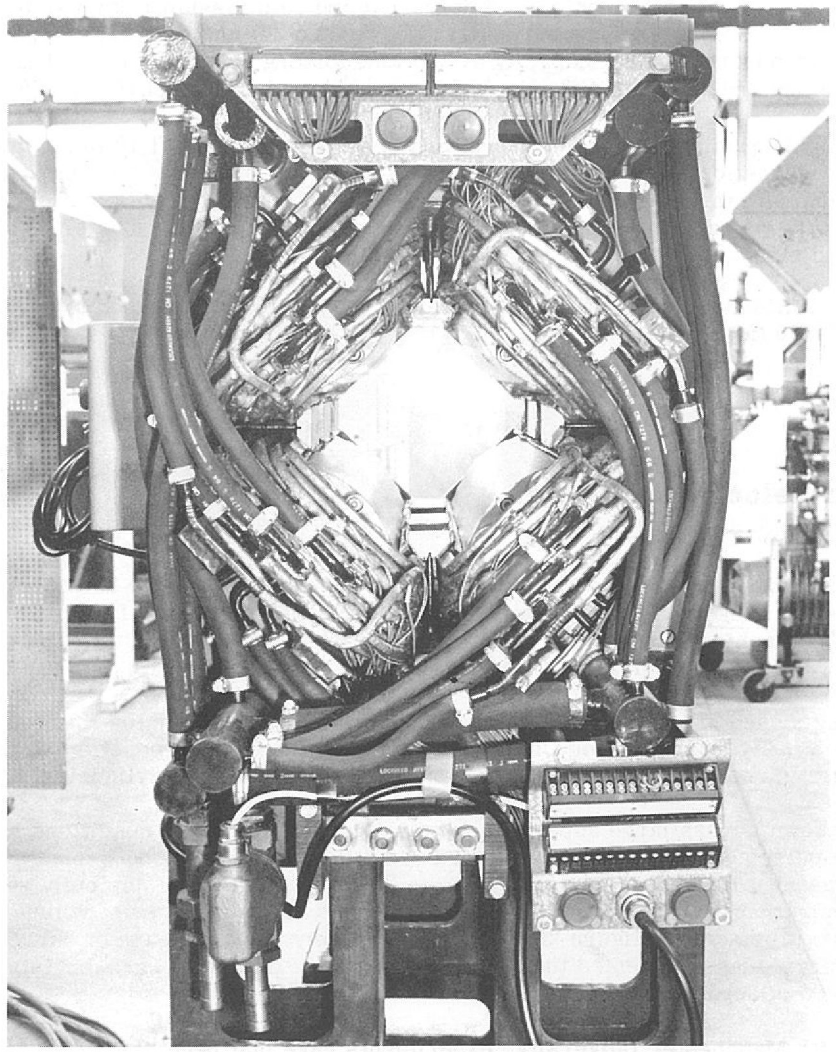


Figure 24. 'Figure-of-eight' quadrupole – a proton's view of the magnet. The cover has been removed to show the connections.

The field in this channel diverts the protons inwards, into the mouth of the normal extractor magnet. In order to obtain the greatest extraction efficiency, the septum thickness must be as small as possible. Efficiencies greater than 50% should be possible using this technique. The pole face windings in Nimrod have been programmed to give the predicted field-shapes to produce the resonance and the resonance has been observed by using a simulated septum in conjunction with a scintillator. Under resonant conditions protons were seen to penetrate across the septum and several centimetres into the scintillator.

Theoretical work is concentrated on the study of beam behaviour during resonance and studies of beam emittance (quality) have just been started.

The work on the normal extraction system and on the resonant extraction system has highlighted the need for magnets with thin septums for use in Nimrod. The septum for the extractor quadrupole has been reduced from 0·6 inches to 0·4 inches in a magnet which is almost complete. Experimental work on a magnet for the resonant system has established that a septum magnet carrying 10, 000 A is feasible and plans are to install such a magnet with its pulsed power supply and plunging device in the synchrotron in June 1967 for initial trials of resonant extraction.

Beam Transport Components

Magnets

During the year, additional components were delivered and commissioned for use in beam lines. These included six 'figure-of-eight' quadrupoles (Q5) (figure 24) and four 50 ton spectrometer magnets (M5). A special transporter with a capacity of 200 tons loading was designed and manufactured for use in the positioning and accurate alignment of the spectrometer magnet (figure 25).

The 'figure-of-eight' quadrupoles are of exceptionally narrow width, 1 ft 10 in., compared with the conventional and magnetically equivalent Q1s which are 4 ft 10 in. wide. These quadrupoles will be used in secondary beam lines close to external targets to enable collection of particles produced at small angles with respect to the incident proton beam. A similar but shorter quadrupole (Q6) has been designed also.

The number of stabilised power supplies for powering magnets has increased to 6-13½ kW sets, 80-50 kW and 30-100 kW sets.

Electrostatic Velocity Separators

The development of d. c. separators has continued and separators can now be designed whose performance is 50% better than previous designs. 80-90 kV/cm fields are now feasible across a 10 cm gap. This has been achieved by the use of electrostatic shields to control the electric field shape and by the use of different materials.

Separators with crossed magnetic and electric fields have been built for the K9 beam line which will serve the 1·5 m Hydrogen Bubble Chamber. These are the first 'production' separators at the Laboratory to use glass electrodes. Development work continued on a cylindrical tank design.

Studies of breakdown across large gaps in vacuum under pulsed voltage conditions have been made using a 1 MV impulse generator. An unexpected result is that the time between application of the voltage and subsequent breakdown is nearly always 25 μs and that two completely separate breakdown mechanisms compete. The first (figure 26a) gives a sharp collapse of voltage and localised filamentary spark; the second (figure 26b) gives a relatively slow increase of current and a diffuse columnar discharge. It is suggested that these correspond exactly to sparks and conditioning currents observed in separators.

In conjunction with Manchester University, experiments have just been completed to photograph the early stages of a vacuum spark. This work confirms recent theoretical work done at the Laboratory.

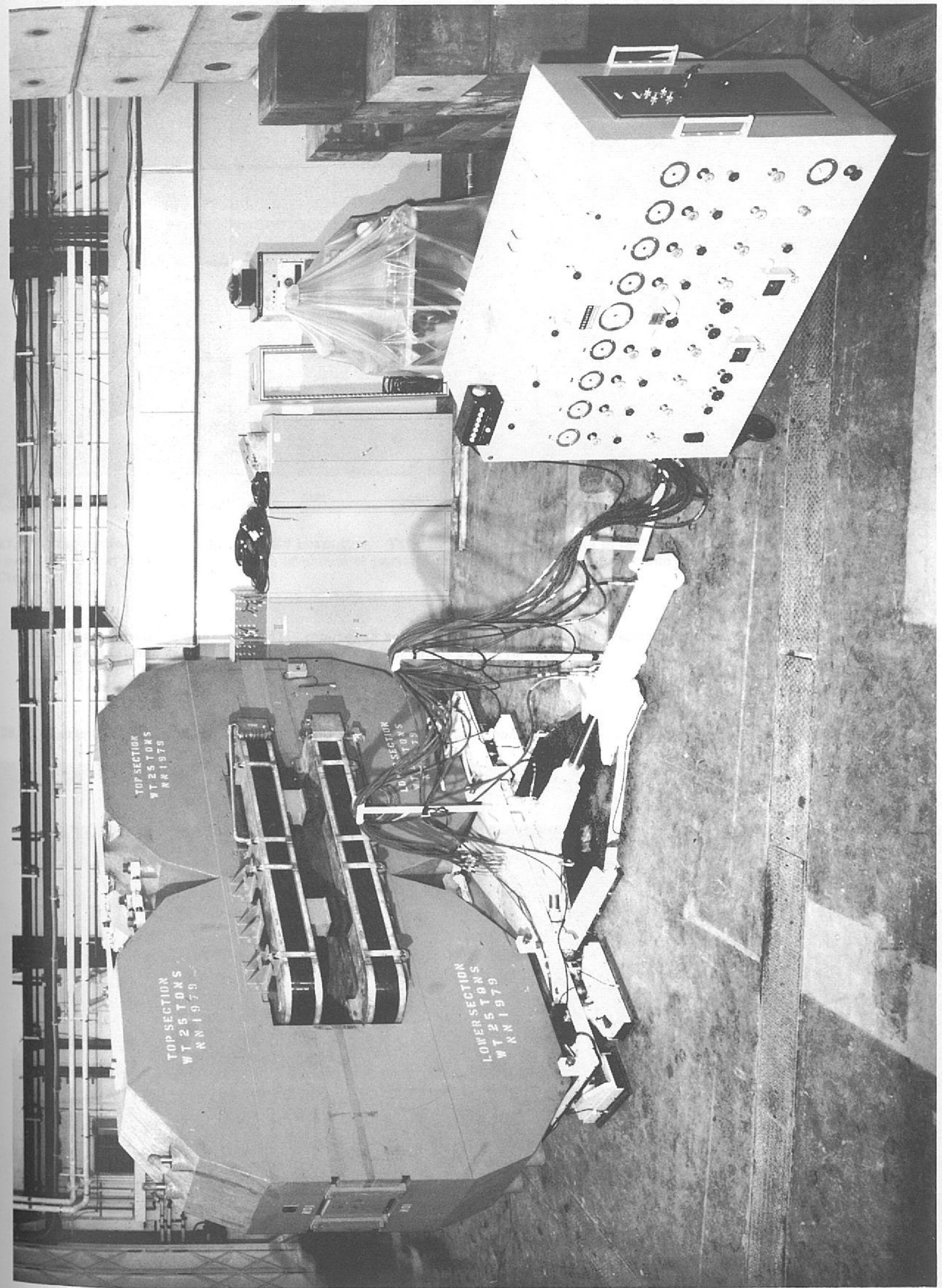


Figure 25. View from a distance of a spectrometer magnet mounted on its transporter with the hydraulic control unit. The magnet may be 'walked' into position. The height of the magnet is 11 feet.

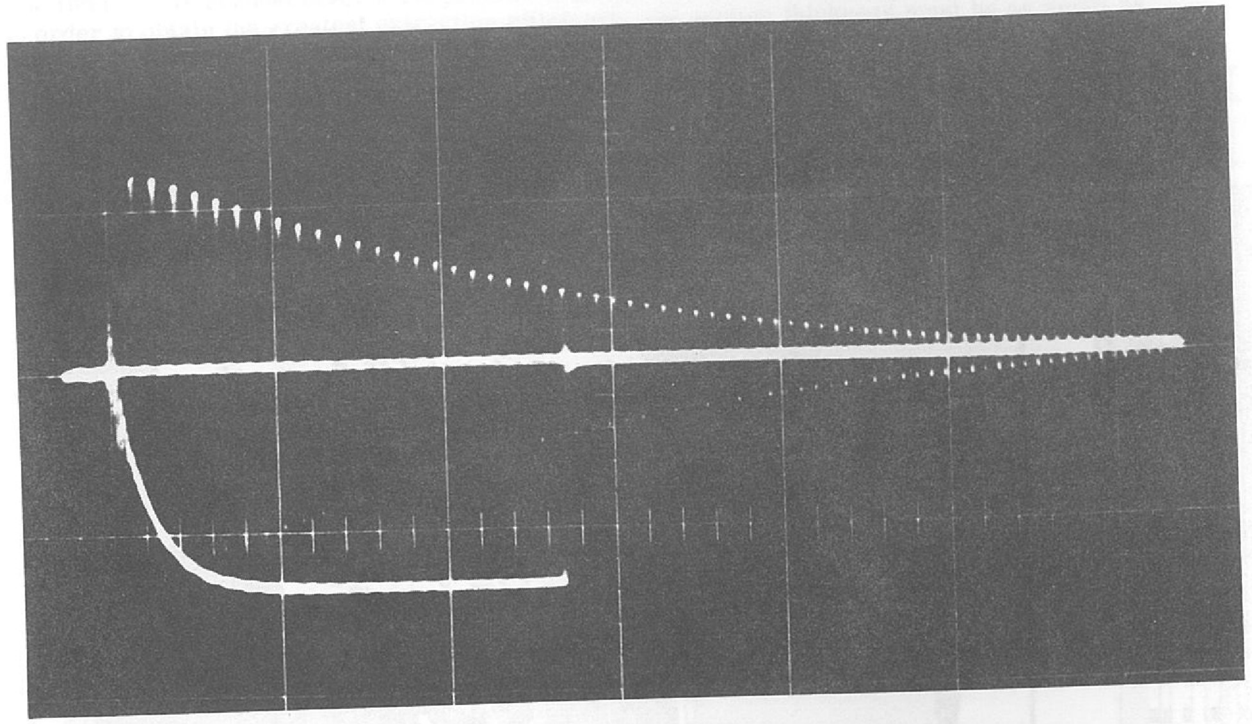
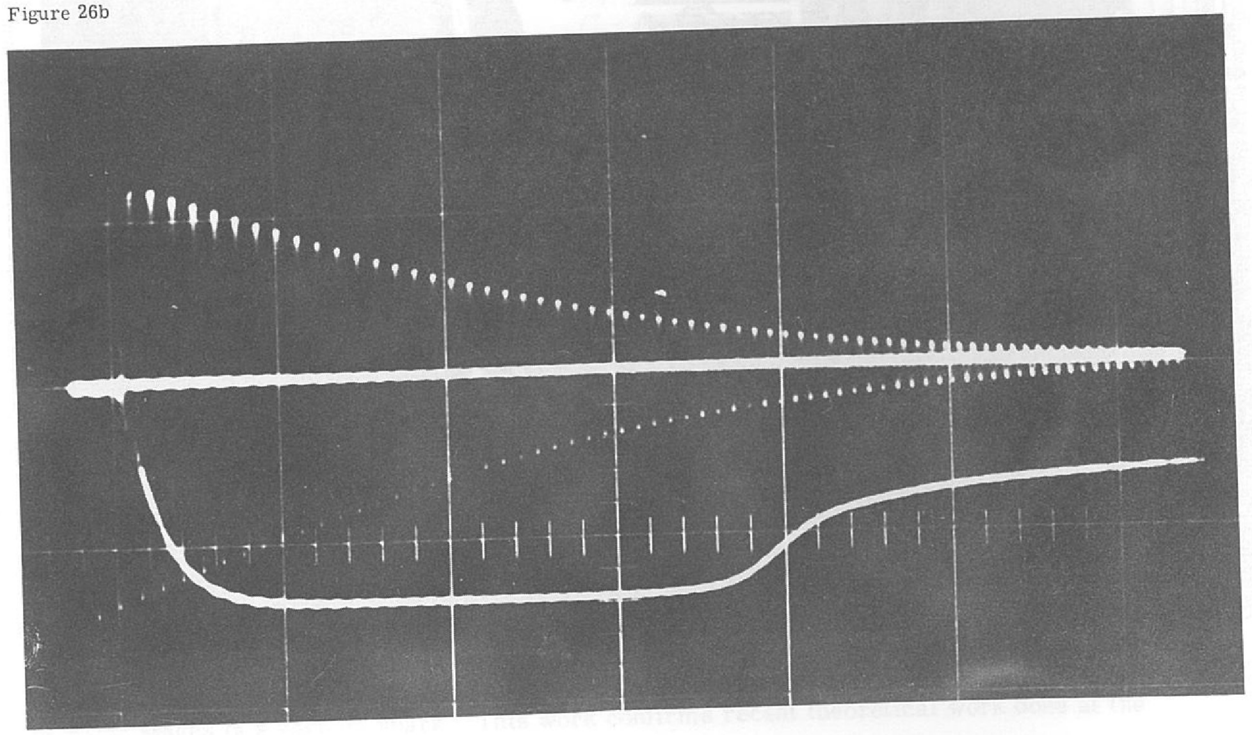


Figure 26a

Oscillograms obtained during the study of voltage breakdown across large gaps in vacuum. The voltage is applied at t = 0 (the oscillatory waveform is for timing at 1 μs intervals). (a) shows the case for a sharp collapse of voltage and (b) the diffuse discharge.

Figure 26b



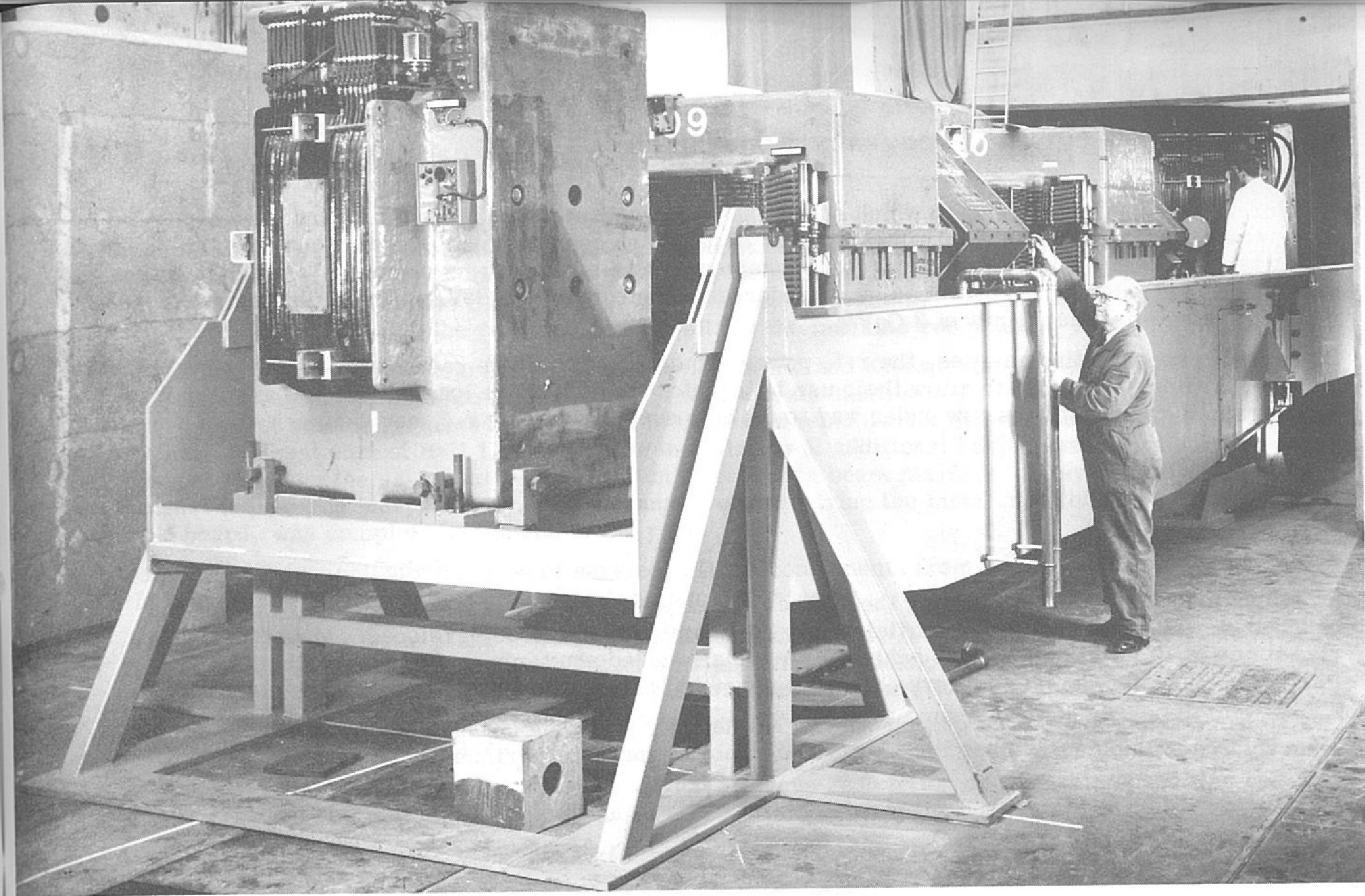
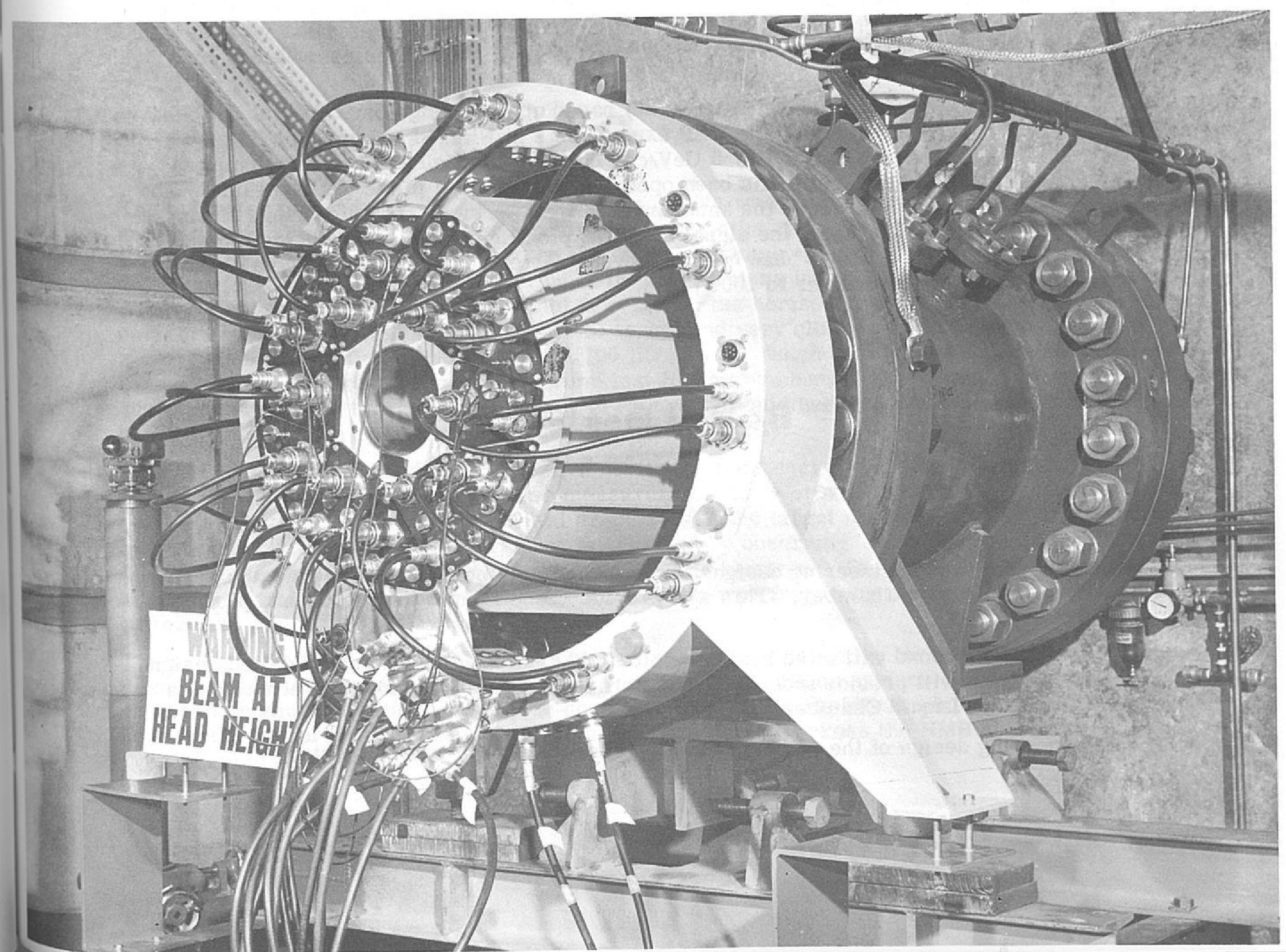


Figure 27. Tilting platform at the end of the K9 beam line. This allows the last magnets in the beam line to be raised and lowered as a unit so that there is a wide range of choice of particle momenta accepted centrally into the 1.5m Hydrogen Bubble Chamber.

Figure 28. Differential gas Cerenkov counter. Alternate pairs of connections go to the kaon or pion detectors respectively.



Superconducting Radio Frequency Separators

A theoretical study was completed which shows that r.f. separators in beams at Nimrod are capable of separating beams of up to eight times the flux of particles compared with conventional electrostatic separators. By using r.f. separators it is possible to extend the momenta up to which negative kaon beams for bubble chambers may be considered. Momenta of 4·5 GeV/c are feasible compared with the present practical limit of 3 GeV/c.

By using superconducting cavities, the r.f. power requirement could be reduced and the duty cycle of the separators increased to allow their use in 'counter' beams where long spill times are required. A programme of research is now under way to develop superconducting r.f. cavities.

Pulsed Magnets

Switching magnets, both for limiting the number of particles reaching a bubble chamber and for the ordered stepping into position of particles into the chamber, have been developed. Magnetic field rise times of 10 μs have now been achieved for the air-cored shutter magnets used in the K1 and P3X beam lines and the ferrite-cored stepping magnets, one of which is now nearly complete.

Design has started on a pulsed magnet with 70 kG field for sweeping charged particles away from the 1·5m Hydrogen Bubble Chamber for a proposed lambda hyperon experiment.

Auxiliary Equipment

An improved and more compact type of beam collimator incorporating an automatic control system was designed, made and delivered initially for use in the K9 beam.

Traversing tables for carrying targets, scintillation counters or other scanning diagnostic equipment have also been modified to use the automatic control system.

An electrically driven tilting platform (figure 27) was designed and made to allow the magnets in the final stage of K9 to be raised or lowered to enable particles with different momenta to enter the hydrogen bubble chamber.

CARP-Counter with Anti Coincidence Rejection of Pions

CARP is a differential gas Cerenkov counter (figure 28) based upon a design developed at Brookhaven National Laboratory. It is intended for use in HEP experiments at Nimrod where identification of kaons is required in the momentum range 1 to 5 GeV/c. The construction and commissioning of this device has now been completed and it has been operated successfully in the K6 beam line. The counter employs reflecting optics to focus the kaon and pion light on inner and outer rings of six photomultipliers respectively. By using the signal from the pion light as a veto, a rejection of unwanted particles of better than 1 in 10^5 has been achieved. A recirculatory ethylene gas handling system is used to pressurize the counter to 1000 p. s. i.

Beam Lines

Beam Line Design

Both the detailed physics and engineering designs have been completed for the K9 separated beam for the 1·5 m Hydrogen Bubble Chamber. This will provide kaons from 2 to 4 GeV/c and pions or protons up to about 7·5 GeV/c.

The overall layout of the second extracted beam complex, X2, has been agreed and detailed design is in hand. This complex will provide from the one external target up to 4 'counter' beams and a beam for the 1.5m Heavy Liquid Chamber.

The detailed engineering design of the π5 beam for Experimental Hall 2 was completed.

Beam Line Installation

The layout of beams at the beginning of 1966 is shown in figure 1. During the year, the P3, P3X and π2 beams were dismantled when the experiments had been completed and the π4 and π6 beams were installed (figure 2). A branch off the Saclay Bubble Chamber beam (K1) was made to provide pions for the Helium Bubble Chamber. A start was made on the installation of the π5 beam (figure 29) by positioning the required components in the machine room during shut-down periods.

In the last quarter of the year at the conclusion of the K4 and K6 experiments, the whole of the extracted beam complex up to the main shield wall was dismantled. This involved moving over 6,000 tons of shielding, much of which had to be stored temporarily outside the experimental area to leave the east part of Hall 1 clear for the installation of additional cables associated with the changeover from the so-called 3-wire system of powering beam magnets to a system in which each magnet is powered independently. This changeover, involving the installation of a new distribution link-board, was complete by the end of the year.

After their long continuous period of service, all the components from P1, K4, K6 and P6 including the magnets were inspected and overhauled when necessary.

Figure 2 shows the state of the experimental halls at the end of 1966. Installed equipment is indicated by full lines. The outlines of K9 and X2 with its associated blockhouse are indicated by dotted lines. A six-week shutdown of Nimrod is planned to start in mid-January 1967 for the dismantling of the east end of the shield wall and for installation of X1 and X2 in the machine room. Installation of K9 should be complete in March 1967 and X2 including the blockhouse in May 1967.

In Hall 2 all magnets are now powered locally; the severe restriction on available space was relieved by the erection of a gallery along the south wall on which most of the d. c. power supplies are mounted.

Targets for High Energy Physics Experiments

Liquid Hydrogen Targets

Six liquid hydrogen targets were successfully designed, constructed, commissioned and used in experiments during the year. Mounted below liquid hydrogen reservoirs, the target capacities ranged from 1 to 10 litres. The K6 target system was the most complex and included three identical vessels containing liquid hydrogen, liquid deuterium and vacuum respectively, mounted as a unit on a remotely controlled rail transport system. In this experiment the vessels were full of liquid hydrogen and deuterium for several months.

Polarized Proton Targets

The polarized target for the K7 experiment (figure 30) was commissioned in the first half of 1966 and was used almost continuously for the last four months of the year on πp and Kp scattering experiments. The target, thought to be the largest (volume, 40 cc) and longest (74 mm) yet built anywhere, gives an average polarization of the free protons in the lanthanum magnesium nitrate (LMN) of about 50%. The magnetic field is vertical; the horizontal cryostat is designed to allow counters to be mounted almost all round the target and very close to it. The cryostat works with a continuous flow of liquid helium from a 100 litre dewar which enables the polarization to be maintained for long periods with much less time lost for dewar changes than with a conventional cryostat. This type of cryostat is more economical in its use of liquid helium; nevertheless, for continuous operation the helium consumption is about 90 litres per day.

Both the magnetic field and the microwave oscillator frequency (~70 GHz) are measured by independent, absolute methods. These measurements have proved to be of the greatest importance, not only in investigating the fundamental properties of the target system, but also in its routine operation. The frequency measurement is achieved by observing 'zero beats' between the oscillator (a carcinotron) and the seventh harmonic of a 10 GHz klystron. The klystron is crystal-stabilized, and its frequency is measured by a standard counter-type frequency meter. An absolute accuracy better than 1 in 10^5 is achieved.

The proton polarization is measured along the length of the target by three independent NMR coils, using both the fast-sweep and the more conventional slow-sweep systems. The fast-sweep system is used in conjunction with an analogue computer to evaluate rapidly the integral $\int[(V_0-V)/V]\,d\nu$, which is directly proportional to the polarization (V is the voltage across the NMR coil and ν is the frequency).

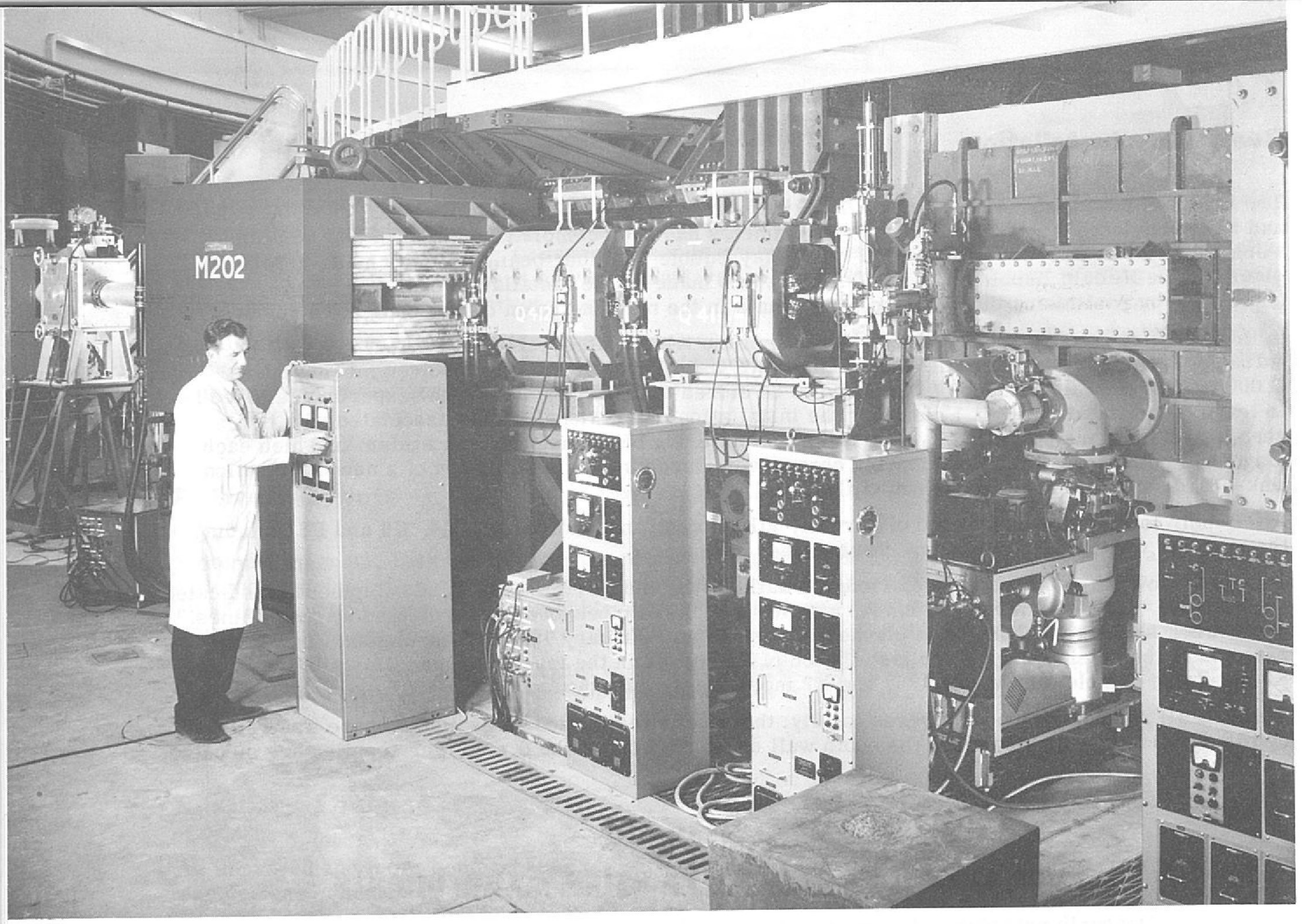


Figure 29. The machine end of the π5 beam line. Pions emerge from the straight section box seen at the right of the photograph, are focused by the two quadrupoles and bent into the parasitic area by the bending magnet through a hole in the steel shielding to Hall 2.

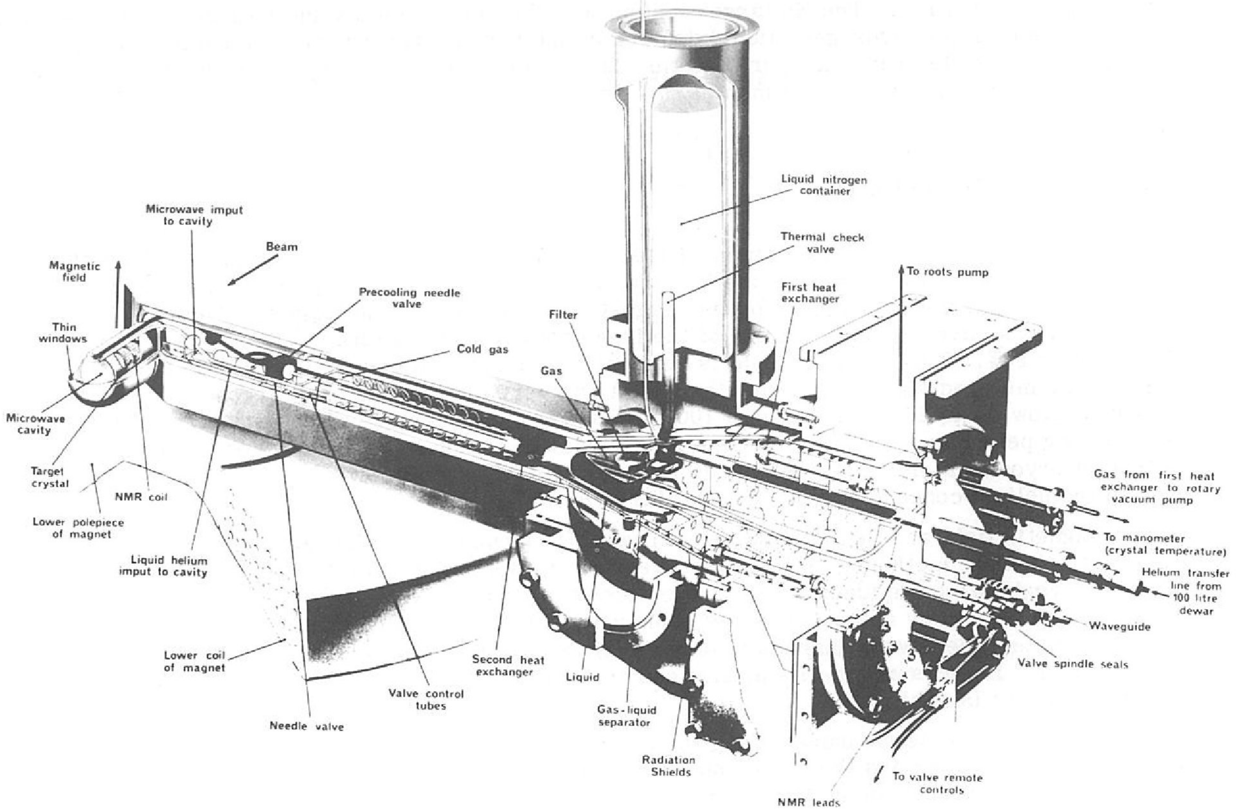


Figure 30. Cut-away view of the cryostat for the latest polarized proton target.

Apart from making targets for scheduled experiments on Nimrod, a basic research programme has recently begun which should provide the information needed to overcome the many severe limitations in all present targets and thus to enable new targets to be made for a much wider range of high energy experiments. The research programme includes basic magnetic resonance studies of new materials, as well as the development of new techniques such as the use of superconducting magnets and cooling by liquid helium-3. For these investigations a superconducting magnet providing a uniform field of 50 kilogauss has been designed and made in the Laboratory (Applied Physics Division), and an electron spin resonance and polarization system using 3 cm microwaves has been built.

As a result of this work it is hoped, inter alia, that it will become practicable to build targets with much higher proportions of free protons (LMN has only 3%), with very good access to particle detection equipment and with low operating costs (both in liquid helium and micro-wave oscillators).

New Experimental Hall

In 1965 the space available in the Nimrod experimental halls was so congested with beams, experimental equipment and the necessary support services that it had become clear more space would be required if the machine was to be fully exploited. The additional space would allow more beams to be installed simultaneously, thus reducing the amount of modification required to meet the needs of new experiments. Where beams do have to be modified it will be possible to do this without disrupting adjacent beams to the same extent as at present.

In January 1966 approval was given for design work to start on a new hall which would more than double the experimental space available. Full approval for construction to proceed was given in December 1966.

An extracted beam from Nimrod will pass through an existing tunnel in the mound into an annexe to the main hall. This annexe will be a single span building 90 ft wide and 70 ft long with a 30 ton overhead crane. The main hall will be a steel framed asbestos clad single span building 300 ft long, 150 ft wide and 65 ft high. A 30 ton overhead crane will be installed and there will be a gallery round three sides of the hall at a height of 25 ft and two longitudinal tunnels 10ft x 10 ft below floor level.

To provide the necessary electrical power for lighting, beams equipment and other apparatus in the hall a 15 MVA sub-station will be built adjacent to the annexe.

The whole scheme includes the provision of equipment to extract the beam from Nimrod and transport it to a target station in the new hall.

The project is scheduled to be complete by the end of 1968.

The Proposed European 300 GeV Proton Synchrotron

A few members of the Laboratory have been directly involved in some aspects of this proposal which is being actively pursued by CERN although no formal request for approval has yet been put to Member States. The United Kingdom has offered a site for the machine at Mundford in Norfolk and we are contributing where appropriate to the work of the UK team responsible for investigating the site in detail and supplying relevant information to CERN. Independently of the site work, we are also participating closely in the work of the European Committee for Future Accelerators (ECFA), a body of European physicists set up initially in 1963 with the task of making recommendations for the further development of high energy physics in Europe, in particular the construction of new accelerators. It reported in 1963 and was reconvened in 1966 to review the evolution of the situation and to bring the 1963 recommendation up to date. ECFA has been studying in some detail the design of the proposed 300 GeV Accelerator and its utilisation, the present situation of high energy physics in Member States of CERN, the present and future forms of collaboration in Europe and the organisational arrangements needed for the proper use by physicists of the various facilities available to them. It will report in June 1967.

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Cine film

A film of the dynamic stresses in an end-plate of one of the Nimrod alternators, made in collaboration with the AERE Photographic Group, was shown at the meeting of the British Association for the Advancement of Science in September 1966.

APPLIED PHYSICS DIVISION

Applied Physics Division is responsible for bubble chamber operation and development, track analysis measuring machines, computer facilities, superconducting magnets, radiation protection, elementary particle theory and the Variable Energy Cyclotron for AERE.

During the period of this report the Variable Energy Cyclotron operated for the first time with both internal and external beams. The machine has successfully reached its design specification and will be formally transferred to AERE at the end of March 1967. Work on heavy ion sources will continue at the Rutherford Laboratory.

The Orion/DDP coupled computer system for on-line experiments ran successfully until mid-September when it was closed down and replaced by an IBM 360/75 computer. The latter is now in operation and will be used for batch data-processing and on-line work.

The CRT flying spot digitiser for spark chamber film successfully measured 30, 000 events for the K_2^0 - $2\pi^0$ experiment. Processing of the data continues.

The HPD flying spot digitiser was brought into operation for the first time shortly before the Orion computer was closed down. During the shut-down the machine was extensively modified and is now being recommissioned for the IBM 360/75.

During this period the Saclay 80 cm Bubble Chamber has been run extensively. 600, 000 pictures were taken on the first experimental run of the Heavy Liquid Bubble Chamber. The 1·5 m Hydrogen Bubble Chamber is again ready and pictures will be taken in mid-1967. The Helium Bubble Chamber is almost ready for its first experimental run. A feasibility study of a high precision bubble chamber using a superconducting magnet is in progress.

Variable Energy Cyclotron

After having obtained the first internal beam in December 1965, the year 1966 was devoted to studying internal beams of various energies, installing and commissioning the extractor and beam handling system and running the first experiments for users.

During January 1966 both proton and α-particle beams were obtained at the maximum design energies of 50 and 80 MeV respectively; as a test of third harmonic operation, in which the particles make one revolution per three r.f. cycles, H_2^+ ions were accelerated to 4.8 MeV. From February to May detailed internal beam studies (such as factors affecting beam quality) were made and several minor improvements to the machine and its diagnostic instrumentation incorporated.

In May a six-week shut-down for the installation and commissioning of the deflector and its power supplies was started. First tests of the deflector were very encouraging and a beam of 25 MeV H_2^+ ions was extracted with about 50% efficiency on 30 June. In July and August extraction was demonstrated for maximum energy protons, α-particles and for ions accelerated on third harmonic. In mid-August the machine was again shut down to make a number of minor adjustments on the deflector, survey the induced activity and install the remaining components of the beam handling systems. By the end of September a beam had been obtained in the scattering chamber of the first experimenter in one of the target rooms.

On 8 November an official inauguration ceremony was held, to which contractors who had contributed to the machine and building were invited, together with Rutherford Laboratory and AERE staff. The official luncheon was attended by some 150 guests; after introductory speeches by Dr. W. Wild, Head of Chemistry Division, AERE, Dr. T.G. Pickavance, Director of the Rutherford Laboratory and Dr. F.A. Vick, President and Vice Chancellor of the Queen's University of Belfast, the cyclotron was declared 'inaugurated' by Dr. J.B. Adams, Member of Research of the UKAEA. After lunch the cyclotron was on view to visitors, who also saw exhibits explaining its construction, operation and the experiments which would be performed with it. The inauguration was followed by a Press visit.

After the inauguration, work was resumed on optimising the extraction and external beam system and setting up the first experiments. By the end of the year an active research programme was beginning to develop.

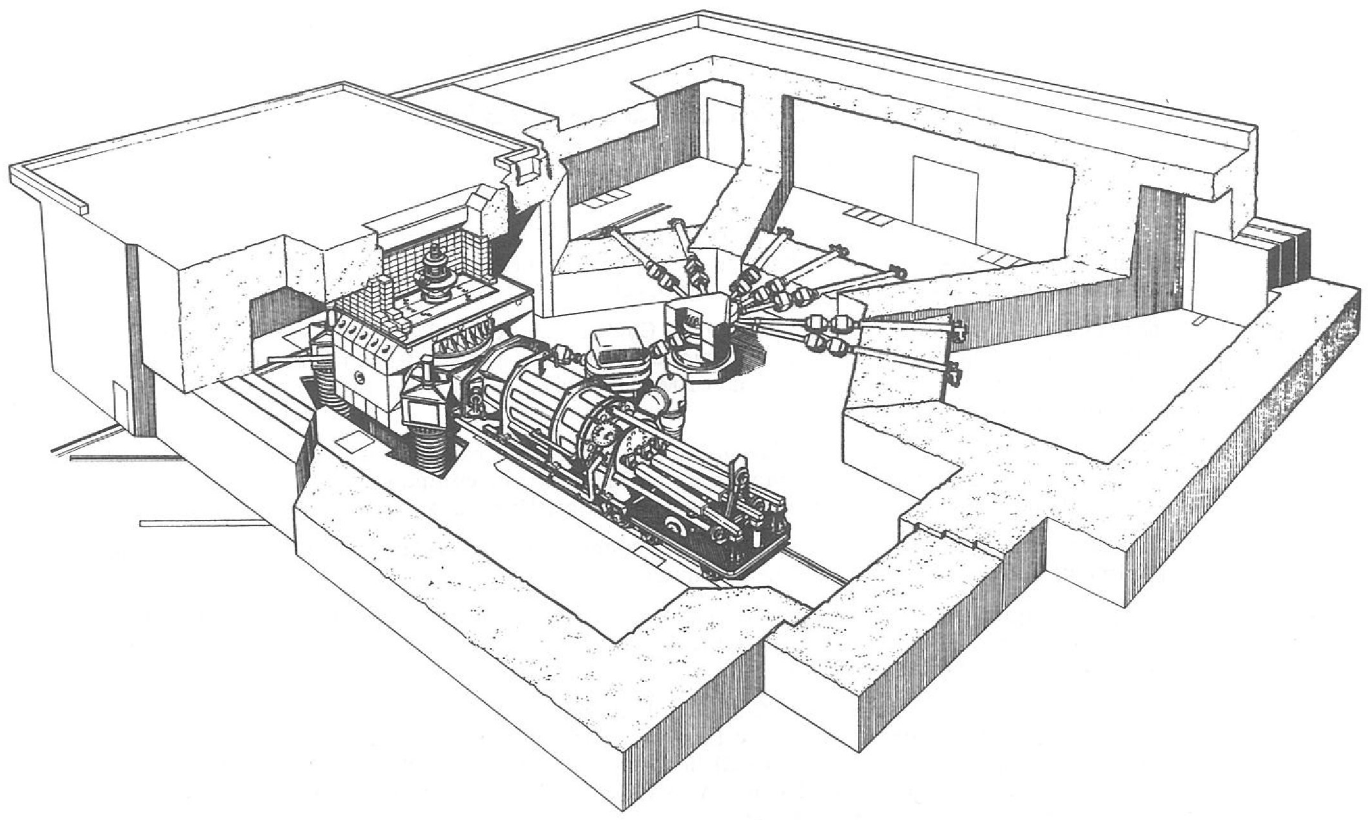
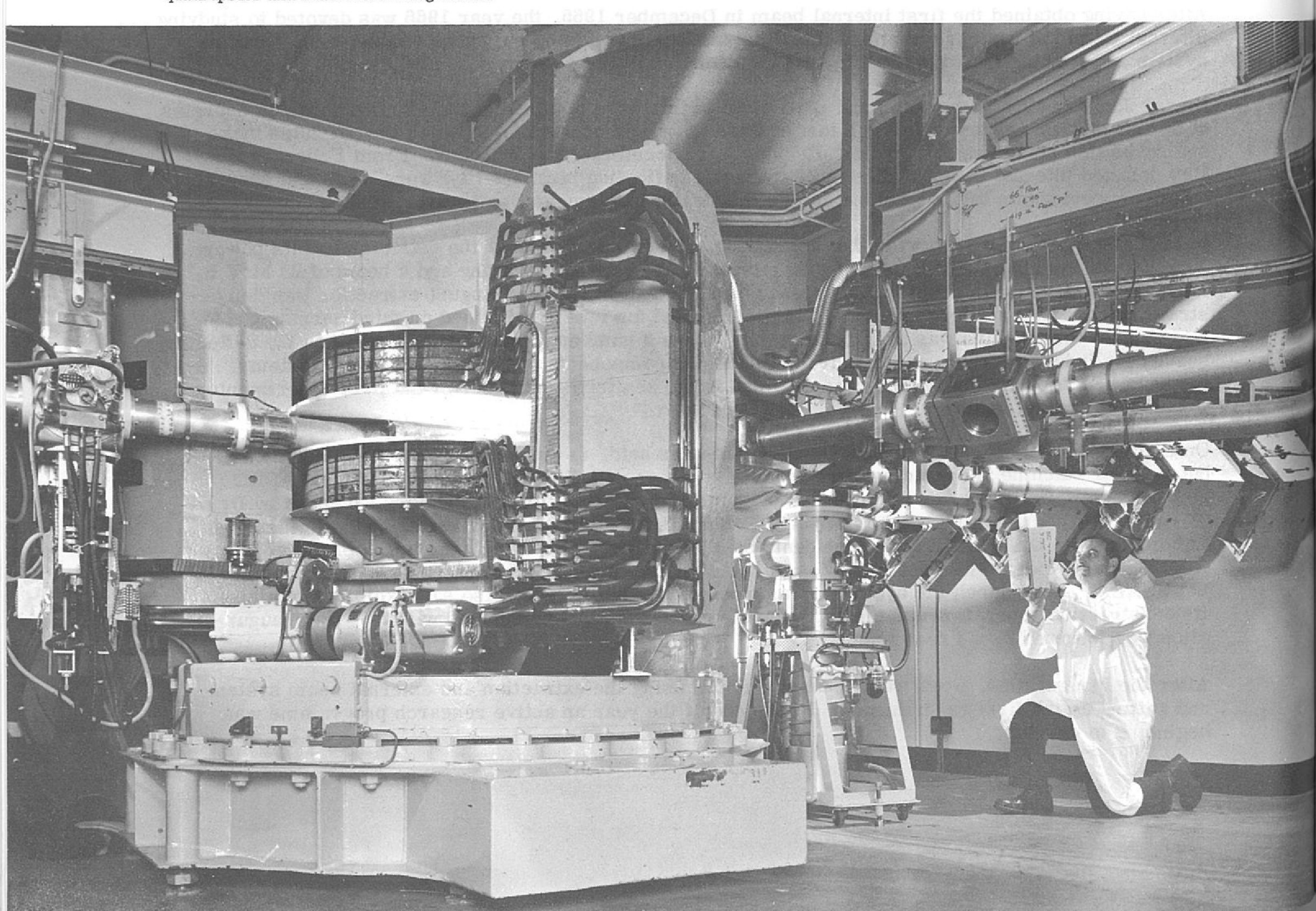


Figure 31. Cut-away view of vault, showing the Harwell Variable Energy Cyclotron and the associated beam transport system.

Figure 32. Part of the beam handling system of the Harwell Variable Energy Cyclotron, showing switching magnet, quadrupoles and beam measuring boxes.



On the whole, progress during the year was encouraging; the machine proved not too difficult to operate and reliability and stability were good. During early 1967 it is planned to develop the extraction of heavy ions and when this has been successfully demonstrated the machine will be formally handed over to AERE who have in fact already effectively accepted responsibility for operations.

A small group at the Rutherford Laboratory will continue the development of heavy ion sources and will ultimately design an axial injection system in which ions can be injected into the VEC from an external source down an axial hole in the magnet. The 4 MeV cyclotron and ion source test rig will be used for experimental studies in this project. Such a system is expected to facilitate more efficient and reliable acceleration of heavy ions.

Computing Activities

During 1966 the Laboratory continued to rely on the Chilton Atlas for the bulk of its off-line computing; some use continued to be made of the Imperial College IBM 7090 and the Glasgow University IBM 7044. Orion was used mainly for the reception (via the DDP-224) of data from on-line experiments and measuring devices. Some experimental groups used small local computers for real-time surveillance of experiments. Orion was dismantled in September and an IBM System/360 Model 75 was installed in December.

The coupled system Orion/DDP continued to be used mainly for controlling the HPD flying-spot digitiser by means of a program in Orion, data being collected by the DDP; during the same time the DDP was being used as a data collector and analyser by the CRT film scanner and a physics experiment (P3 or K6). Several versions were made of the DDP program which managed this multiple activity.

Like Orion, IBM System/360 Model 75 will use the DDP as an on-line data collector and disseminator but the real-time monitoring programs will reside in the System/360, together with one or more non-real-time problem programs. Much of the controlling programs to connect the 75 to the DDP were written during the year; testing began before the end of December.

Much study was given to the supervisory software supplied by IBM with the 75 so that the change-over from Atlas to the Laboratory's own computer during the early months of 1967 should be as painless as possible.

Orion was removed in September so that the computer room and associated areas could be modified for the new computer. Parts of the machine were sent to the Chilton Atlas and parts to the Rothamsted Experimental Station of the Agricultural Research Council so that their Orion could be brought up to the size necessary to exploit the Fortran Operating System developed at the Rutherford Laboratory.

Track Analysis

Conventional Measuring Equipment

The four manual measuring machines are now operating satisfactorily and reliably produce over 500 events each week compared with 300 events before the improvement programme was started. These machines have now been handed over to Central Engineering Group for regular maintenance.

Four scanning tables are now equipped with rough digitisers and are operating satisfactorily. Two further scanning tables are being modified to give larger projected images and will then be fitted with larger rough digitisers. A further machine will be installed shortly.

All the scanning and rough digitising equipment has now been installed in a spacious new scanning laboratory in which special attention has been given to the environmental conditions. The laboratory is equipped with air conditioning and subdued lighting and the overall conditions are much improved. Similar attention is now being given to the environment of the measuring machines.

Plans are being made to attach these machines on-line to a computer.

Computer Systems Engineering

The DDP-224 computer is now maintained by the group and its performance during the past 6 months has been very good.

A complex data link has been designed and constructed to connect the DDP-224 to the IBM 360/75 central computer. This is now fully installed and working.

Hough Powell Device (HPD)

The first half of the year was spent in attempting to operate a production HPD system for measurement of the eta decay experiment. The short-comings of the HPD machine and to a lesser extent difficulties with the Orion computer severely limited the amount of useful work that could be done. Nevertheless, it was possible to gain operational experience with the system and to help train the newly acquired staff. During this period the problems of operations and maintenance became clearer as did the technical limitations of HPD. As the Orion computer was to be replaced by an IBM 360/75 in November a decision was taken to rebuild large sections of the HPD. Operations were therefore terminated in early September 1966.

The second half of the year was spent in rebuilding the HPD mechanics and electronics with a view to increasing the reliability, speed and precision of the machine. Assistance from the Central Engineering Group in the mechanical and general electrical aspects of the machine enabled the HPD group to concentrate on the optical and electronic design. A great deal of work was done over a two-month period and towards the end of the year recommissioning of HPD 1 was started. The latest results from acceptance testing have indicated that the reliability and operation of the machine have been greatly improved.

The latest work on the electronics of the machine has been in the field of high speed memory systems using the latest integrated circuit techniques for speeds up to 30 Mc/s. This equipment has recently been installed on the machine and is undergoing computer tests. This work and the general recommissioning has utilized a DDP-224 computer using programs developed in collaboration with the Theoretical Studies Group. It has also been necessary to become involved in the overall diagnostic programs for the full operating system.

Also during this latter period we have collaborated with the Central Engineering Group and Sogenique, Newport Pagnell, in producing a version of the mechanics known as HPD Mk 2a (our HPD 2). This was delivered to the Group in January 1967.

CRT Film Scanner

The CRT film scanner Cyclops continued to operate during 1966, measuring film from the $K_2^0 - 2\pi^0$ experiment. The scanner and computer system has worked with 80% reliability and a batch of 30, 000 events was measured in a continuous seven-week period. The machine maintained its accuracy of $\pm 3\mu$ over long periods of time and measured events can safely be stored on magnetic tape and processed at a later time on the Atlas computer. Processing on the Atlas computer continued regularly throughout the year.

The scanner control programs in the DDP-224 are being developed to study the possibilities of diagnosing faults in the scanner and data being sent to the computer. A program is also being developed to use a large CRT display and light pen to rescue the events which are rejected by the Atlas programs.

Programs are also being written to control the scanner from the IBM 360/75 and to process the events on the same computer. When the new computer configuration is complete a start will be made to measure two further spark chamber experiments.

Bubble Chambers

1.5 m Hydrogen Bubble Chamber

The chamber was completely assembled and component parts individually tested. All building additions and modifications were finished. Delays occurred on the magnet repair and also on the delivery of a number of items from industry. The first cool-down to liquid nitrogen temperature took place in November and the first operational run with hydrogen is planned for February 1967. Equipment for deuterium operation is nearing completion and first tests with this filling should start in April 1967.

Heavy Liquid Bubble Chamber

During the year 600, 000 pictures were taken in the low momentum pion beam for the η-decay experiment. The chamber was filled with freon and operated at a two-second cycling rate. Preparations for operating the chamber with a propane and methyl iodide or freon mixture were then started.

This involved testing a new glass window designed to a higher stress value. In addition, as the chamber is required to operate at a higher temperature with propane, a preliminary run at high temperature with an inert filling is in course of preparation. The additions and modifications to the building installation needed to satisfy the safety requirements are being planned and the chamber should be ready for initial tests with propane in September 1967.

Helium Bubble Chamber

After completion of the chamber it was successfully cooled down to liquid helium temperature. However, difficulties in completely filling the chamber were then encountered and after warm up the cooling circuits were rearranged to overcome this problem. The complete optical system has now been installed and a second cool-down commences in January 1967. During the 32 days of the first cool-down the refrigerator operated satisfactorily.

Saclay Bubble Chamber

The total number of pictures taken during 1966 amounted to 3·2 million bringing the grand total since the chamber came to the Laboratory to almost 4 million. For most of the pion experiments the chamber was operated at 2 expansions per Nimrod pulse. A high efficiency of operation has been achieved and only one major maintenance of the chamber has been necessary.

High Field Bubble Chamber

A design study of a chamber with diameter 1·5 m and magnetic field of 70 kG has been prepared and is almost ready for circulation. A superconducting magnet is proposed (see section on superconducting magnets) and the optical system will employ small fish-eye windows and wide angle cameras. The total depth of the chamber is 1·8 m and it is expanded using a piston and Omega bellows assembly. A fast cycling rate of 2-5 expansions per second is planned. Arrangements for bringing in particle beams either on the median plane of the magnet or along its axis have been studied. Detailed design work will be carried out during 1967 to enable an accurate assessment of the effort and cost to be prepared.

For the study of bubble chamber optical and dynamical problems a 10 in. hydrogen chamber kindly loaned by Liverpool University has been set up. The first experiments will be on bubble formation.

Superconducting Magnets

This group is studying the problems of using superconducting alloys to produce high magnetic fields. There are many potential applications in high energy physics for magnetic fields higher than those provided by conventional iron-core magnets; these include polarized proton targets, bending magnets, quadrupoles and large volumes of high field for bubble chambers and spark chambers. Longer term possible applications include particle accelerators and storage rings.

Recent developments in the production of superconductors in the form of high current stabilised cables enable large magnets to be designed with reliable and predictable performance; as a result of this, work on superconducting magnets at the Rutherford Laboratory has been expanded and in conjunction with the Engineering Division the group is designing and constructing specific magnets for use in the Laboratory.

During 1966 two corrected solenoids, giving fields of 25 kG and 50 kG, were constructed for research into new polarized target materials in the General Physics Group. Construction also began of a 110 kG, 12 cm bore solenoid for superconducting magnet research. Design studies were made for a 50 kG, 150 cm long bending magnet for use in the extracted proton beams from Nimrod and for a 70 kG split solenoid magnet with a bore of 190 cm. This is the magnet for use with a high precision hydrogen bubble chamber proposed for use on Nimrod (see section on high field bubble chamber).

Equipment was set up to test samples of superconducting cable up to 3, 000 A, and to carry out stress and normal resistivity tests on such samples. Studies were made of the stability of composite superconducting cables and of heat transfer to liquid helium in narrow channels. Other experimental work included optimisation of low temperature current leads, development of superconducting switches and test on superconducting niobium-tin flux concentrators.

Preliminary theoretical studies were made of the possibility of using pulsed superconducting magnets to replace conventional magnets in high energy accelerators. Provided the a.c. heating effect in the superconducting material can be reduced sufficiently considerable reductions can be achieved in the size and cost of future accelerators. Superconducting magnet techniques also offer the possibility of inexpensive conversion of Nimrod to an energy in the region 40 - 50 GeV.

Radiation Protection

Introduction

Despite the increased exploitation of the PLA and Nimrod, radiation exposures have been maintained at moderate levels. No genuine whole-body exposures greater than 1·5 rem occurred in 1966 (to be compared with the upper limit of 5 rem recommended for radiation workers by the Ministry of Labour 'Code of Practice'). The monthly issue of film badges has increased to 1200 β-γ films and 300 neutron track films. 140 radioactive sources are now held in the Source Library for general use within the Laboratory.

Nimrod

Nimrod returned to 7 GeV operation early in the year and substantial use was made of the extracted proton beam. During those periods in which the external proton beam was operating general radiation levels in the main experimental hall exceeded 2·5 mrem/hr and have necessitated a 'Red' radiation classification. With internal target operation radiation levels do not generally exceed 1 mrem/hr. However the whole-body exposure to Nimrod personnel has remained gratifyingly low, no one having exceeded an exposure of 1·5 rem for the year.

The general levels due to induced activity have changed little, the particular short-term changes due to differing modes of operation being much more important than general long-term changes.

During the year existing and new measuring techniques were studied in detail. The standard hand survey equipment is the NIS 295 ratemeter with a LiI scintillator in a 4 in. diameter moderator or in an 8 in. double moderator. The former is a very sensitive flux density meter, the latter a less sensitive dose rate equivalent meter. When possible they are used together to give a simple measure of the 'effective' neutron energy. In addition the charged particle and gamma dose rate is measured with an N 596 portable electrometer with a normal 'air-wall' chamber. The ion chamber readings are multiplied by a pessimistic Quality Factor of 3.

The film badge readings from persons working in areas subject to hand surveys suggest that, at present, our quite simple survey methods and calibrations are reasonable but somewhat pessimistic.

A dose equivalent neutron ion chamber assembly has been tested and will soon become our basic fixed position and semi-portable instrument. It will be of particular value in regions of high dose rate and in the presence of short radiation pulses. A semi-portable version of the LiI scintillator system using the multiple sphere technique is used for accurate surveys.

Proton Linear Accelerator

Extensive modification to the shielding of the experimental areas was undertaken in October in anticipation of future increases in beam intensity. Measurements of the neutron yields from target materials bombarded by 50 MeV protons and the attenuation of these neutrons by iron, concrete and water were made to facilitate a suitable shielding design. In the new design particular emphasis has been placed on accessibility to the experimental floor during machine operation. This has been achieved by dividing the area into well shielded cells each containing an experimental rig. Early in 1967 overhead roof shielding will be provided for some cells to reduce the skyshine contribution to the leakage radiation.

Systematic studies have been made of the activity induced in a wide range of materials by 50 MeV proton bombardment, many of the dominant nuclides produced being identified by gamma spectroscopy. The radiological hazards of these materials was determined making it possible to give sound advice on the relative merits of constructional materials used in the linear accelerator.

Dosimetry

The development of new techniques and the application of old and well understood techniques to new and novel situations has continued throughout the year.

A set of Bonner-Spheres (2 in. -12 in. d.) have been calibrated using neutron sources. Application of the technique to the radiation environment of Nimrod has shown it to be useful for estimates of total flux or neutron dose equivalent but of very limited use for detailed spectroscopy.

Preliminary analysis of the pulse height spectrum from a 4 mm $\times$ 4 mm Li^6I crystal indicates the presence of large pulses ($\sim$ 30 MeV) attributed to spallation reactions in iodine. Observation of these high energy pulses may provide a useful means of estimating high energy neutron fluxes ($E > 50$ MeV). Other means of determining high energy neutron fluxes under examination are the production of Tb^{149} from mercury or gold and the use of counter telescopes.

Neutron track films exposed throughout the Nimrod Experimental Areas have confirmed the dose-equivalent measurements of standard monitoring equipment.

In collaboration with Radiological Safety Division AEE Winfrith, considerable experience has been obtained in the use of LiF thermoluminescent powder. This technique has proved extremely useful both for personal and general dosimetry. On typical maintenance procedures the finger tip doses have been found to be three to four times greater than that measured by wrist films. The surface dose-rates from materials of high specific activity may be under-estimated by as much as a factor 50 by standard beta-gamma instruments. In view of these facts the routine use of TLD personal dosimeters will increase within the Laboratory.

The response of LiF thermoluminescent powder to integrated exposures between 10^{-1} rad and 10^7 rad has been studied using Co^{60} γ-rays for the lower exposures (up to 3 rad) and the 4 MeV electron facility at the Wantage Radiation Laboratory. Above integrated exposures of 10^3 rad the response is a non-linear function of dose and this non-linearity may be correlated with changes in the glow-curves. Similar results are obtained when Li^6F powder is exposed to thermal neutrons.

Li^6F powder has been used to replace the more usual thermal neutron activation detector at the centre of polythene moderators used to measure intermediate and fast neutrons. A series of calibration measurements using moderating polythene spheres of diameters between 5 cm and 30 cm has been undertaken with a variety of neutron sources and monoenergetic neutrons produced by the D-D and D-T reactions. Agreement with theoretical response curves for monoenergetic neutrons was obtained.

Shielding Measurements at Nimrod

In order to obtain reliable data to enable the design of shielding for future external proton beams at Nimrod the radiation environment of the external proton beam P1 was studied in some detail in August. Close to the proton beam the dose equivalent due to low energy protons ($\sim$ 1 MeV) was ten times that due to neutrons. A similar result was obtained later at CERN (see section on future high energy accelerators). This experimental result is of importance in confirming the relevance of the dosimetry techniques used on the Nimrod vacuum vessel.

The transmission of neutrons along the north access tunnel of Nimrod has been measured by activation detectors and the experimental data compared with theoretical predictions. This work has also been extended on the CERN PS.

Future High Energy Accelerators

As part of the programme on radiation problems associated with the next generation of high energy particle accelerators the concentrations of radio-nuclides expected in the ground and ground water systems close to the machine have been investigated. Theoretical estimates, checked by experimental data obtained from water irradiations carried out using Nimrod, show that no hazard to public health would exist. An extensive series of radiation measurements around the CERN PS were made by members of the group collaborating with a team of physicists from CERN and the Lawrence Radiation Laboratory. Beam loss distribution, radiation dose close to the vacuum vessel, dose and particle spectra and dose attenuation were studied. Analysis of the data is not finished.

In addition to the above work, shielding studies for the proposed European 300 GeV proton synchrotron have been made as part of the work of the European Committee for Future Accelerators.

Elementary Particle Theory

Activities of the elementary particle theory group included the continuing analysis of pion-nucleon scattering and examination of resonances uncovered thereby, dynamical studies of such systems especially in terms of the quark model and problems arising out of CP non-conservation particularly in terms of the suggested C non-invariance of electro-magnetic interactions.

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THE PROTON LINEAR ACCELERATOR DIVISION

The year 1966 has seen a steady advance in the work of the PLA. Pressure of demand for machine time has led to a modification of the target room area, whereby the time taken in the setting-up of experimental equipment is appreciably reduced. Machine development has seen substantial improvements in both polarized and unpolarized ion sources and in duty cycle modifications. What follows is a condensed summary of the PLA Progress Report for 1966.

Nuclear Physics on the PLA.

The demand for experimental time on the PLA, continued at a very high level with a total of nine experimental teams using the machine. These teams were composed of physicists from eight British universities, the Atomic Energy Research Establishment and the Rutherford Laboratory. The machine was scheduled for over 6, 300 hours of operation.

In view of the very large demand for experimental time, the major modification to the target rooms carried out during the past year has been a re-arrangement of the radiation shielding so as to allow improved access to experiments whilst the machine is in operation. As a result it is hoped that the amount of time the machine is switched off to allow for setting up of experimental equipment will be considerably reduced. This system of experimental cells came into full use towards the end of 1966.

The demand for experimental time using the polarized proton beam, which is one of the most intense in this energy region, increased and the polarized proton source was used for 45% of the scheduled machine time. The double-focusing spectrometer was again used in a large number of experiments.

The experiments carried out during 1966 can be roughly divided into three broad groups: first, those concerned with the elastic and inelastic scattering of protons from nuclei. The elastic scattering results are usually analysed in terms of the optical model, or in the case of deformed nuclei attempts have been made to describe elastic and inelastic scattering in terms of the strong coupling approximation or coupled channels method. For inelastic scattering when the configurations of the initial and final states are known the distorted wave Born approximation (DWBA) method can be used.

The second group of experiments are those concerned with pick-up reactions. The processes studied are usually (p, d), (p, t) or (p, He^3) and may have the object of either investigating the nuclear reaction mechanisms involved or the structure and properties of the residual nucleus. The results are again frequently analysed using the DWBA method. The values of the distorting potentials used in this method are obtained from the optical model analysis of elastic scattering experiments.

The experiments on charge exchange (p, n) reactions can also be used to study the reaction process or the properties of the residual nucleus. In the study of (p, n) reactions the time-of-flight method is used to measure the neutron energies. The facility for this work on the PLA, is the only one available at these energies and allows measurements to be made in a previously unexplored energy region.

The section of the PLA Progress Report for 1966 concerned with nuclear physics covers 130 pages and the following summary is necessarily condensed, presentation of experimental detail being out of the question. However, before we embark on the summary, to illustrate the general principle, one type of current experiment may be selected. To the nuclear physicist, neutron and proton can be characterized by an isotopic spin quantum number $T = \frac{1}{2}$, the third component of which $T_z = +\frac{1}{2}$ for a neutron and $T_z = -\frac{1}{2}$ for a proton. A nucleus with equal numbers of protons and neutrons, e.g. Mg^{24}, will have $T_z = 0$, while Mg^{25} will have $T_z = +\frac{1}{2}$ and Al^{25} $T_z = -\frac{1}{2}$. There will be excited states in these latter nuclei, however, which tally with corresponding states in Na^{25} and Si^{25}, for which $T_z = +3/2$ and $-3/2$ respectively: these excited states of Mg^{25} and Al^{25} will have $T_z = (\pm)\frac{1}{2}$, $T = 3/2$. The corresponding $T = 3/2$ levels in Na^{25}, Mg^{25}, Al^{25} and Si^{25} are called an isobaric multiplet.

Now, the levels in Mg^{25} and Al^{25} can be conveniently reached by the (p, t) and (p, He^3) reactions from Al^{27}: naturally, the spectrum of particles obtained is quite complex. We can identify the states sought in two main ways. First, one knows the ground state in one of the $T = 3/2$ members, Si^{25}, and the approximate value of the energy can be estimated (the chief factor is the Coulomb term, but there are others). This is only approximate, and identifies a region for search. The second criterion follows from the fact that, because of the close similarity between the states, the angular distributions of tritons and He^3 should be the same: this has been shown to be the case within close limits.

From this experiment can be deduced, among other things, (1) more accurate parameters for the formula giving mass relations between members of an isotopic spin multiplet, and (2) a value for the mass of the ground state of Na^{25}, previously known only very roughly.

Elastic and Inelastic Scattering of Protons

The experiment to measure the differential scattering cross-section for proton-proton scattering to an overall precision of 0.5% has been completed and the results fully analysed. The scattering phase-shifts are now known to greater accuracy at 50 MeV than at any other energy above 10 MeV. The results of this experiment have been particularly valuable in removing several anomalies which existed in previous phase-shift analyses of earlier data.

The work on proton-deuteron elastic scattering has continued. The differential scattering cross-section and polarization have been completely remeasured at 30 and 50 MeV using improved experimental techniques. The results are again in wide disagreement with theoretical calculations. In an effort to understand these problems a phase-shift analysis is to be made of the experimental data. Triple scattering experiments to assist in this analysis are at present being planned.

A phase-shift analysis of p-α scattering data in the energy region from 14 to 48 MeV has been completed. Measurements have also been made of the polarization in p-α scattering over a wide angular range at five closely spaced energies in the region of 27 MeV. This energy corresponds to a resonance in the compound mass 5 system and a phase-shift analysis of this data together with measurements to be made of the differential scattering cross-section should improve our knowledge of the properties of the resonance.

Studies of scattering from compound nucleus resonances have also been made in the scattering of protons from carbon in the energy region between 25 and 30 MeV. This experimental data, which was obtained previously, has now been very fully analysed and can be satisfactorily described in terms of scattering from an optical model potential and from three resonances in the compound N^{13} system. It is hoped to extend this work to other suitable nuclei.

Measurements have been made of the cross-section and polarizations for elastic and inelastic scattering of protons from Li^6 and Li^7. Similar measurements have also been made for Be^9. In this case the motivation is to study the way in which the polarization data are sensitive to the configurations of the initial and final states involved in the transition. These effects are also being studied in the polarization of protons scattered inelastically from Fe^{54}. Preliminary calculations suggest that simple models which were originally thought to apply in this case do not give good fits to the data and more complicated interactions will have to be considered.

The optical model analysis of data for proton scattering from carbon in the energy region between 30 and 50 MeV has continued. Satisfactory fits to the data have been obtained but the parameters do not seem to vary in a systematic fashion. Further analyses using the strong coupling approximation are in progress. Polarization and differential cross-section data have also been measured for several of the even isotopes of zinc. As zinc is a deformed nucleus, these data will also be analysed using the strong coupling approximation and in particular to test the effect on the parameters of variations in neutron number. Further measurements have also been made for Mg^{24} and these results will assist in the analysis of reaction studies on this nucleus discussed in the next section. Measurements are also in progress on the isotopes of tin and again will be used to assist in the analysis of reaction studies and to study the variation of optical model parameters with neutron number.

The measurements at 50 MeV of differential scattering cross-sections of a range of nuclei for optical model studies have been completed and analysis of the data is in progress.

Pick-Up Reactions

Measurements have continued of (p, t) and (p, He^3) reactions on Al^{27}, P^{31}, F^{19} and Mg^{26} leading to analogue states. The motivation for these measurements is to study the validity of various formulae which have been proposed to relate the masses of nuclei within an isotopic spin multiplet. Information on the excitation of other states in the residual nuclei has also been obtained and will be compared with DWBA calculations. The mass of Ca^{38} which was previously unknown has been measured using the Ca^{40}(p, t)Ca^{38} reaction. Information has also been obtained for the first time about the level structure of this nucleus and has been compared with shell model calculations for A = 38 nuclei.

Studies of the (p, He^3) reaction have continued. The angular distribution for the elastic scattering of 30 MeV He^3 particles from B^{10} has recently been measured on the Birmingham radial ridge cyclotron. Optical model parameters obtained from this data will then be used in a DWBA analysis of the C^{12}(p, He^3)B^{10} results.

The detailed work on (p, d) reactions on the even isotopes of tin has continued and confirms the j-dependence of the angular distributions mentioned in the 1965 report.

Studies of the asymmetries produced in (p, d) reactions using polarized protons have continued. Detailed DWBA analyses for C^{12} and O^{16} at 30 MeV only show fair agreement with the experimental results. Measurements have been extended to Si^{28} and Ca^{40} since the DWBA theories are generally considered to be more applicable for heavier nuclei. Analysis of the data is in progress.

In view of the large asymmetries observed in (p, d) reactions, these studies have been extended to (p, t) reactions. Preliminary measurements have been made for the reaction C^{12}(p, t)C^{10} and large asymmetries observed.

The effects of spherical deformation in the optical potentials used in DWBA calculations have been investigated for the nucleus Mg^{24}. Elastic and inelastic polarization and cross-section measurements have been made as discussed previously. Cross-sections for (p, d) reactions have been completed and measurements for the (p, t) reaction are in progress.

Charge-Exchange Reactions

Measurements of the polarization of neutrons from (p, n) reactions with 30 and 50 MeV protons on D^2, Li^6 and Li^7 have been repeated using improved techniques. The asymmetries observed for deuterium at 50 MeV are in satisfactory agreement with impulse approximation calculations. For Li^6 the observed asymmetries are similar to those obtained for deuterium. For Li^7 values close to zero are obtained but, in this case, as neutrons leaving Be^7 in its excited states are not resolved no comparison with theoretical predictions can be made. Finally, it does not seem that any of these reactions is likely to be a useful source of polarized neutrons.

Studies of the excitation of isobaric analogue states in residual nuclei have continued. Measurements of the angular distributions for these states excited in (p, n) reactions on Al^{27}, Fe^{54}, Fe^{56}, Sn^{120}, Pb^{208} have been made at 30 and 50 MeV using the neutron time-of-flight facility. The results have been compared with calculations made using the DWBA method and indicate that the isobaric spin-dependent potential in the optical model is peaked at the nuclear surface. Further measurements are in progress.

Operation

During 1966 the PLA was operated for more hours and the percentage of lost time was less than in any previous year. The running time of the machine over the past seven years is summarized in Table 1. The scheduled time, 6, 303 hours, was 80% of the total year, after subtracting the shut-down period (5 September to 3 October), the Christmas recess and Open Days for visitors.
The time allocated to maintenance and to the setting-up of experiments was, in general, 3 days in each 14 days and the tendency is always towards reducing this time. The frequency of minor faults causing the machine to trip off (lost time about one minute per trip) reached a very satisfactory low value; total time lost in this way is estimated at less than 5% of the total lost time. About 3% of the scheduled time was used for changing over from one experiment to another. The 5, 605 hours (64% of 365 days) was fault-free time during which beam was being accelerated and was available to the experimenters. Table II shows the distribution of hours between the nuclear physics teams using the machine.

During the year approximately 8% of the scheduled time was lost due to machine faults and half of this time was due to minor faults. The time spent on planned maintenance of the machine had to be reduced because of the high demand for running time and priority was given to the maintenance of rotating machinery (pumps and generators) and to ensuring safe working conditions. There was very little lost time due to the vacuum system and the water cooling system of the machine. There was a leak in a hydraulic tuner in tank 3, which caused a significant loss of time. The other major fault was the failure of some of the rectifiers in the 500 kV d. c. Cockcroft-Walton multiplier. The selenium rectifiers had operated for over 25, 000 hours and their forward voltage drop had increased 4 to 10 times, causing serious overheating.

The main r.f. amplifier valves, the grounded grid triodes, continued to operate very well, There were two faults during the year which necessitated the removal of two valves for overhaul, but the average operating time of the valves is now over 10, 000 hours and one valve on the machine has run for over 20, 000 hours. The deuterium thyratron switch tubes, VX3336, in the modulators have been trouble-free during this year; valve lives of over 10, 000 hours each have now been reached.
Two experimental thyratrons, VX3359 and VX3369, have been run very successfully in two of the modulators.

Machine Development

To maintain and improve the reliability of the PLA, machine development was carried out on many items of the whole installation throughout the year. It is worth recording some of the larger projects of this type, namely, (1) the redesign and rebuilding of the water chilling plant for the drift tube quadrupoles, (2) an improved motor drive for the sliding foil on the spectrometer magnet windowless scattering chamber, (3) the installation of a cable dispenser on the spectrometer magnet, (4) stabilization of generator voltages on the injector platform, (5) a beam position stabilizer using a split ion chamber and the tank 3 adjustable quadrupoles and (6) the redesign of the r.f. drive chain to give higher output and longer pulse length. Space does not permit a detailed description of these and the many other projects of this nature.

Machine development aimed at improving the machine had three objectives: (1) more beam current, (2) higher duty cycle and (3) better energy resolution. The unpolarized proton beam current was increased to 5 μA mean by improving the emittance of the ion source; the previous best current was 3 μA but this could not be obtained reliably. Further increases in beam current are expected from higher currents from the source and from the redesign of the low energy drift space; a new buncher has been designed (for installation in February, 1967) and improved focusing and beam control is being studied. The polarized beam was increased by improving the ionizer and the proton mirror; the latest beam intensity was 1.3×10^9 protons/sec at 53% polarization. The factor of merit of the polarized beam (intensity times the square of the polarization) is 60 times greater than its value 5 years ago. The 2% r.f. duty cycle of the machine is limited at present by the mean power output of the modulators, but an increase in the duty cycle of the beam from 1% to 1.5% will be available in March 1967 due to increasing the modulator pulse length from 400 μs to 800 μs and reducing the repetition rate from 50 c/s to 25 c/s. Design and testing work on the r.f. system to produce a 6% r.f. duty cycle has been mainly concerned with the grounded grid triodes; one valve was successfully operated at 750 kW peak in December – sufficient for any of the final amplifiers on the machine. The energy resolution of the beam remained at about 250 keV (FWHH) at 50 MeV; analysed beams of 50 keV width were obtained for the spectrometer magnet with a transmission factor of a few percent. Studies have been made of means of reducing the beam energy spread. These include double-buncher injection, to reduce primary phase spread; phasing and r.f. control in tank 1 to reduce the emergent phase spread; the installation of a debuncher cavity and the design of a new analysing magnet. Apparatus for the measurement of the radial emittance of the output beam was developed and preliminary results obtained.

Shielding of adjacent areas from the radiation, mostly neutron radiation, produced in the experimental areas has become an increasing problem as the mean current of the machine increased. A related problem was that of access to the experimental areas while the machine was operating. Future machine development would have been restricted by the shielding as it existed at the beginning of 1966. During a one-month shut-down in September the shielding was completely rearranged to provide six cells with sufficient shielding between cells to make access possible, under most beam conditions, to the cells not in use (figure 33). The radiation in external areas is much less than previously. One of the cells will have a top shield of two feet of concrete.

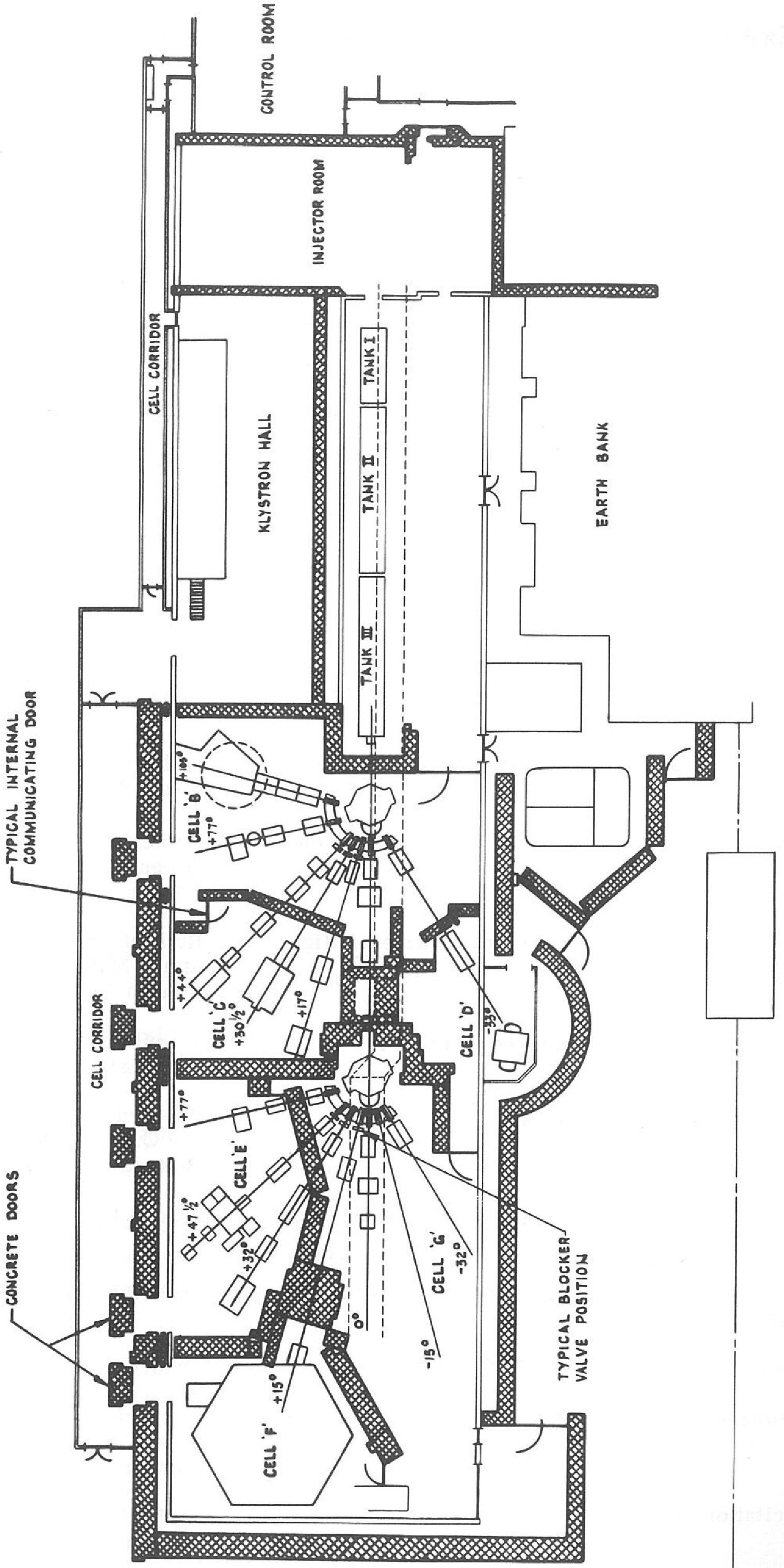

Figure 33. Arrangement of shielding.

Experiments at the Proton Linear Accelerator

Number	Experiment	Group
1	Polarization in proton elastic and inelastic scattering from Fe^{54}	Birmingham University
2	Differential cross-sections for elastic and inelastic scattering of 30·3 MeV protons by Be^{9}	Birmingham University
3	Differential scattering cross-sections and polarizations for p-d elastic scattering	Queen's University, Belfast and Westfield College, London
4	Measurement of the proton-proton differential scattering cross-section at 50 MeV	University College, London and Rutherford Laboratory
5	Elastic and inelastic scattering of 50 MeV protons	King's College, London and Rutherford Laboratory
6	Elastic and inelastic scattering of 50 MeV polarized and unpolarized protons by Lithium isotopes	Manchester University
7	Elastic and inelastic proton scattering cross-sections	Atomic Energy Research Establishment
8	(p, d) and (p, t) reactions on Mg^{24}	Rutherford Laboratory and King's College, London
9	Polarization of neutrons from (p, n) reactions on D^{2}, Li^{6} and Li^{7}	Rutherford Laboratory and Queen Mary College, London
10	Measurement of neutron spectra by time-of-flight methods	Rutherford Laboratory and Queen Mary College, London
11	(p, d) reactions on Tin isotopes at 30 MeV	Atomic Energy Research Establishment
12	Studies of pick-up reactions	Westfield College, London and Queen's University, Belfast
13	Studies of pick-up reactions using polarized protons	Oxford University
14	Studies of analogue levels using (p, t) and (p, He^{3}) reactions	Oxford University
15	Mass and energy levels of Ca^{38}	Oxford University
16	Resonances in p-α scattering	Rutherford Laboratory and Queen Mary College, London
17	Excitation of isomeric states in K^{38}	Rutherford Laboratory (Radiochemistry)

Table I - Running Time 1960-66

	Hours scheduled	Hours available for use	Availability (%)
1960	1, 420	980	69
1961	3, 660	2, 149	59
1962	5, 544	3, 971	72
1963	5, 453	4, 405	81
1964	5, 573	4, 664	84
1965	6, 128	5, 260	86
1966	6, 303	5, 605	89
	34, 081	27, 034	

Table II - Running Time 1966

Experimental Teams	Hours scheduled	Hours available for use
Atomic Energy Research Establishment (Proton Physics)	216	$205\frac{1}{2}$
Birmingham University	720	$594\frac{1}{2}$
King's College, London and Rutherford Laboratory	513	469
Manchester University	600	504
Oxford University (Nuclear Physics)	$900\frac{1}{2}$	835
Queen's University, Belfast and Westfield College, London	$739\frac{1}{2}$	$687\frac{1}{4}$
Rutherford Laboratory (Accelerator Physics)	294	242
Rutherford Laboratory and King's College, London	410	375
Rutherford Laboratory and Queen Mary College, London (I)	818	748
Rutherford Laboratory and Queen Mary College, London (II)	408	$372\frac{3}{4}$
Rutherford Laboratory (Radiochemistry)	96	70
Rutherford Laboratory (Nuclear Physics Tests)	324	$287\frac{1}{4}$
University College London	144	$125\frac{1}{2}$
Others	120	$89\frac{1}{2}$
	6, 303	5, 605

Proton Linear Accelerator - Publications, Reports, Theses

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Ibid.

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Single particle and collective states in the odd isotopes of Tin.
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Design equations in an Alvarez-type Proton Linear Accelerator.
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Italian Physical Society Conference, Trieste, October 1966.

Reports

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PLA Progress Report 1966.
RHEL/R 136

FRIEDMAN E.
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RHEL/R 131

REEVE P. A., SWALES F. J.
Ion-optics of the PLA double focusing spectrometer.
RHEL/R 121

Theses for Higher Degrees awarded to Students using the PLA.

BÜGET N.
Investigations of ratios of isotopes found in nuclear reactions.
University of Birmingham.

CHANT N. S.
A study of nuclear structure with protons of intermediate energy - Studies of (p, d) reactions using polarized and unpolarized protons.
University of Oxford.

EDWARDS V. R. W.
Instrumentation for a magnetic analyser and its use in proton elastic and inelastic scattering measurements at 50 MeV.
University of London (King's College).

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Elastic and inelastic scattering of 50 MeV protons using magnetic analysis.
University of London (King's College).

SCOTT D. K.
The excitation of nuclei with protons of intermediate energy.
University of Oxford.

WATSON D. L.
Polarization studied with 20-30 MeV protons.
University of Birmingham.

ENGINEERING DIVISION

During 1966 the Engineering Division has continued to operate in the manner outlined in the previous report, namely that of managing the technical facilities of a large and vigorous research Laboratory, economically maintaining the building fabric and services and carrying out works of adaption and improvement. The principal services provided from the central organisation to support the Laboratory's scientific work are:

Building and Mechanical and Electrical Services including Design and Installation.

Mechanical Engineering Design and Manufacture.

Electrical and Electronic Design and Manufacture.

Chemical Technology and Special Techniques.

Safety Services.

Typical work undertaken under each heading is as follows:

Building and Mechanical and Electrical Services

The Rutherford Laboratory maintains its own buildings and services and carries out works of improvement and alteration which are within the limit of its resources. Usually projects less in value than £50, 000 can be accommodated by the permanent staff, but for work in excess of this capital value the UKAEA is used as an agent so as to limit the uneconomic retention of a large staff for this work. The following projects each under £50, 000 in value have been completed in the course of the year.

A workshop for the modification of radioactive accelerator parts.

A new stores building of 6, 500 sq. ft.

A plant room, control room and hardstanding for the Hydrogen Bubble Chamber.

Building and ventilation services modifications to accommodate the IBM computer which now replaces Orion.

A plant room and plant and services modifications to accommodate re-arrangement of the track measuring machines.

In the major project section of our work 1966 has been an eventful year in that a design study was completed and approved for a New Experimental Hall for Nimrod. An outline of this project is given in the Nimrod Section of this report. The basic design has been a collaborative venture between staff from the Rutherford Laboratory and the UKAEA Engineering Group; construction will take about two years.

Preliminary considerations are now being given to the building requirements for the High Field Bubble Chamber and its supporting service buildings; for clarity the engineering contribution to this project is described in the Applied Physics Section of this report.

Mechanical Engineering Design and Manufacture

During 1966 the demand for Engineering Design has been increasing. Some of the work has been of a design feasibility character but, in addition to the general engineering work to support the scientific staff, a great deal of effort has been directed to the mechanical engineering problems of superconducting magnets and the associated cryogenic problems. The following extracts indicate the general character of design work in progress during the period of the report:-

Cryogenic Projects

Support continued during 1966 on work for the Polarized Proton Target (figure 30). The cryogenic equipment for the Mk II was commissioned during January. The performance of the target during the year has justified the choice of a continuous flow cryostat; considerable savings of liquid helium result from this system at high microwave power inputs (1 to 3 watts).

An experimental rig has been built and tests performed to determine heat transfer at low pressures (1 torr and below) and liquid helium temperatures. This work is nearing completion and it is anticipated that a report will be issued by April 1967. The information obtained from the tests will be used in the design of liquid helium 3 cooled target.

Engineering design effort has also been applied to the following low temperature projects:

High field solenoids.

A 25 kilogauss superconducting target magnet.

A 50 kilogauss superconducting bending magnet.

A high field bubble chamber superconducting magnet.

A liquid helium supply and gas recovery system.

On more conventional engineering the following are typical examples of work which has been carried out:-

Design of extractor quadrupole magnets.

Redesign of Nimrod Injector high tension platform to overcome vibration problems.

The design of additional cooling services for bubble chamber magnets.

Development of machines for film track measurements.

Recovery and purification plant for deuterium.

Within the Engineering Design Group some engineering research has been completed on the strength of Mylar and Melinex diaphragms, with particular reference to fatigue properties under cyclic pressures. A report will be issued in February 1967. This information will aid the design of Cerenkov Counter Windows, or in any similar application where a low density barrier is necessary to restrain experimental media. Initial work has been done on the preparation of a programme of research in the properties of materials at liquid helium temperatures (4°K).

On the manufacturing side the vast bulk of work is sublet to industry, but the Engineering Division's mechanical workshops produced a wide variety of specialised scientific and engineering equipment. By way of example, it was necessary to develop and manufacture a machine for producing super-conducting alloy strip. This comprised a motor operated rolling mill with profiled upper-roll to produce 20 grooves in long lengths of copper strip 0.8 in. wide and 0.020 in. thick to accommodate the superconducting alloy wire. A complementary machine to the mill was developed to solder the wires into the multiple grooves in the stabilising strip. There has been a continual demand for the support of workshop staff, but recruitment of skilled craftsmen is a continuous problem. Attention has been given to increasing productivity by the application of new methods and machines.

Electrical and Electronic Design and Manufacture

A major activity was the design and construction of magnets together with their highly stabilised d.c. power supplies and associated control circuits. A typical example was an improved design of extractor magnet for Nimrod with increased cooling to allow a higher duty operation for the new Experimental Hall. The plunging mechanism for the extractor magnet has a complex control system using transducers for positional accuracy. Further development has produced a reliable system accurate in end position to 0.01 in. and capable of remote adjustment to this accuracy. A stepping magnet for the control of particle trajectories into the bubble chambers is in the final stages of design and its power supply which discharges a capacitor for each step has been engineered and construction commenced.

Work on the Electrostatic Generator was completed in June after the successful commissioning of that accelerator. Work has commenced and is continuing on the control circuits, power supplies and display console for the HPD 1 which is an automatic track measuring machine programmed into a computer and is an engineered version of the earlier Laboratory machine.

Instrumentation was provided for the Nimrod polarized target to optimise the degree of polarization with the percentage achieved displayed. Work completed during the year included a 150 A, power unit stable to 1 part in 10^4 to energise a superconducting magnet. An "add-on" unit using series transistor control to increase the stability of existing power units by a factor of 10 was developed and the application of this principle to other requirements is being pursued.

A digital computer system has been designed for real-time control of magnet excitation in a multi-magnet beam guidance system.

A preliminary theoretical study has been made of the requirements and performance characteristics of a directly connected "static system" to replace the rotating power supply of the present Nimrod motor-alternator sets and those proposed for the projected 300 GeV accelerator. The technically promising results of the initial study have led to the expansion of the study programme to include

full computer representation of the dynamic response of a distributed public supply system to the pulse load together with behaviour studies of a 100 kVA scale model of the static device itself. This work is now being funded as a co-operative effort by SRC, CEGB and CERN.

The calibration and a standards room is able to undertake high quality electrical measurement and offers this to the whole Laboratory as a service.

There has been appreciable growth in the demand for electronic and instrument repair during this period and even with industry doing the longer term repair work it is a problem to keep the vast range of electronic equipment and instruments, data processing printers and punches etc. in use without embarrassment to current experiments. A separate section was formed to deal with the maintenance and repair of the track analysis machines and bubble chamber data processing plant. This has shown that it is possible to reduce time lost on stoppages and to increase through-put in order to keep pace with the growing demands. A new digitiser has been added to the National Measuring Machine, Image Plane Digitisers added to the film scanning machines and all the units converted to 7 hole paper tape output to feed into the computers.

The electronic equipment from single items to batch production totalling approximately £100,000 in value was produced; the bulk by industry. The average production time was four weeks where all components were available but was a little longer when printed circuits were involved. A small design section was attached to this unit to re-arrange the circuits and draw up the printed masters. Sub-assemblies using integrated circuits and fast logic circuits employing tunnel diodes were not obtainable from industry, so a small production line was set up for this class of work and this necessitated the use of precision parallel gap welders with accurate pulse control. The most precise work concerned a printed spark chamber grid on flexible but thermally stable material. Core matrix and core driver boards also called for high precision.

The operation, maintenance and development of the electrical distribution network in the Laboratory is a growing responsibility. The system has an installed sub-station capacity of 22 MVA with 10 MVA supplied direct at 11 kV. The peak demand was 18 MW and consumption is now at an annual rate of 100 million kWH. There are three major and two minor sub-stations. An additional minor sub-station to feed the Experimental Hall beam line equipment has been planned. Because it has to be linked into the existing system the major sub-station for the new Experimental Hall has been planned by the Engineering Division.

Chemical Technology and Special Techniques

The Chemical Technology Section has been increasingly concerned with radiation dosimetry and an improved method of assessing radiation damage has been successfully developed.

New epoxy resin composites have been evaluated for resistance to radiation damage and some striking improvements over conventional systems have been obtained, which will permit favourable comparison with ceramics in this respect.

Investigation into the production of high modulus high strength laminates using single crystal fibres has been started together with some studies on low density materials. Some attention is now being given to evaluating plastics at low temperatures for application in superconducting magnets.

The chemical analysis service has provided data continuously throughout the year on the performance of cooling water circuits and treatment plants. Full investigational support has been given to many problems of corrosion, trade effluent, safety and other matters requiring immediate chemistry laboratory facilities.

Work on plastic nuclear physics equipment has continued to develop, many hundreds of bonded optical joints between plastic scintillators, light pipes and photomultipliers have been produced. The production of hydrogen targets has continued and experiments to produce these from more stable materials are being considered. Considerable effort has been employed on spark chamber component production, future developments include the study of foam cored panels with aluminium foil and/or melinex facings. The growth of massive single crystals for polarized proton targets has been continued, some improvement in the purity of the starting materials is proposed for future crystals.

Safety Group

The safety policy of the Laboratory emphasises the direct responsibility of the individual through the "chain of command" of the Laboratory organisation. To promote safety consciousness the Laboratory has a Safety Committee with a Special Hazards section, a Fire Committee, a Safety and Productivity Awards Committee, a Site Emergency Working Party and a Safety Group. The latter has a staff of seven and has executive and advisory responsibilities and is represented on these Committees. The Safety Group reports to the Chief Engineer.

The number of items registered with the Safety Group for periodic inspection increased by 7% during 1966 and now total 3, 002. This is made up as follows: Lighting Equipment 2, 156 items, Pressurised Equipment 621 items, Experimental High Voltage Apparatus 120 items, Safety Equipment 74 items and Fire Prevention 31 items. The total number of inspections carried out by Laboratory and Contract staff was 5, 744.

Following a hydrogen bubble chamber explosion in the USA in 1965, considerable emphasis was placed on safety in the use of flammable gases and liquids during the year. Close liaison was established with other organisations having similar problems to obtain and exchange information. Particular attention was paid to safety surveillance in the use of flammable gases and liquids and a Technical Officer joined the Group for this purpose.

During the year a total of 127 injuries involving Rutherford Laboratory staff were reported, 15 of which resulted in lost time. The Accident Frequency Rates for all staff increased slightly, the "all injury" rate from 4. 6 to 4. 88 and the "lost time" rate from 0. 24 to 0. 57. The mean duration of absence from lost time accidents was 14 days. The Lost Time Frequency Rate for industrial staff showed a marked increase from 0. 6 to 1. 74 and it is to this section of staff and its supervision that increased efforts of accident prevention will be made in 1967 by means of safety talks and training. Early in 1966 a "Safety Yearbook" was issued to all staff as an aide-memoire of safety regulations and information. Ten "Safety News" sheets and nine displays in the four Safety Showcases were prepared. Two new Codes of Practice were issued during the year and one existing Code of Practice and one Safety Code was revised.

Engineering Training

The Laboratory encourages its staff to obtain technical qualifications related to the individual's work and ability and day release at local technical colleges is conceded for definite courses leading to such qualifications. This concession was granted to 101 engineering members of the staff throughout the Laboratory both industrial and non-industrial employees.

Additionally 213 attendances were made at short courses ranging from 1 day to 10 days, on such subjects as Low Temperature Technology, Physics for Engineers, Digital Circuit Techniques, Management and Supervision, Vacuum Techniques for Craftsmen, Critical Path Methods, Electrical Safety for Non-Electrical Supervisors and Electronics in Industry. The majority of these courses were organised and held at AERE Education and Training Departments to whom the Laboratory is much indebted for this service.

Both craft and student apprentices continue to be recruited and this year the first ex-NIRNS apprentices completed their apprenticeships; two apprentices were engaged as Laboratory craftsmen; one student apprentice as a Draughtsman and a further student apprentice as an Engineer III.

Engineering Division - Publications and Reports

Journal Articles

CHAPMAN C. E., SHELDON R.
The measurements of radiation absorbed by particle accelerator structural components.
Nuclear Instruments and Methods, 42, 141-153, June 1966.

CHAPMAN C. E.
The effect of radiation on electronic components.
IEE Students Quarterly Review, December 1966.

Unpublished Preprints

EVANS D., MORGAN J. T., SHELDON R., STAPLETON G. B.
Stress relaxation of natural rubber during irradiation.
RPP/E 8

LANGRIDGE J. U. D., SHELDON R., STAPLETON G. B.
Nuclear science and reinforced plastics materials.
RPP/E 6

MORGAN J. T., SHELDON R., STAPLETON G. B.
The effect of radiation on the mechanical properties of aromatic polyimide films.
RPP/E 4

Reports and Memoranda

COLYER B.
Cryogenic properties of Helium 3 and Helium 4.
RHEL/R 138

FOX J. A.
A study on power supplies and controls for ISR magnet systems.
CERN - ISR/ 66 - 25

FOX J. A.
A static power supply for the 300 GeV accelerator magnet system.
RHEL E/PS - DS/300 GeV/JAF - 1

HADLEY H.
Tests on a. c. voltage stabilisers with a cyclic fluctuation due to Nimrod.
RHEL/M 123

MORRIS A., SHELDON R., STAPLETON G. B.
A remote reading integrating radiation dosimeter for the range 10^4 - 10^9 rad.
RHEL/R 132

MORRIS A., SHELDON R., STAPLETON G. B.
Chemical problems associated with the use of Bridgewater Canal water for cooling purposes at the Daresbury Nuclear Physics Laboratory.
RHEL/R 137

MORGAN J. T., SHELDON R., STAPLETON G. B.
Effects of radiation on the mechanical properties of Polyethylene Terephthalate films.
RHEL/R 139

ADMINISTRATION DIVISION

The Administration Division is divided into four groups.

The following statistical information gives an indication of the range of work undertaken. For the General Administration, Personnel and Scientific Administration Groups the information refers to the calendar year 1966 but the financial statistics are given for the financial year 1 April 1966 to 31 March 1967.

General Administration Group

During 1966 the group developed its services to match the increasing scientific and engineering activity at the Laboratory. The following information indicates the scale of operations during the year:-

Stores

A new metal and plastics store was opened in January. A wide range of materials can now be issued promptly to meet the demands of workshops.

Use of care and custody stores has increased significantly. This has freed valuable space in laboratories and experimental halls which had previously been used for storing equipment, not currently in use, but for which there was a likely future need.

Number of items stocked at Rutherford Laboratory	7, 700
Number of issues from Rutherford Laboratory and AERE (each issue covers an average of 2. 5 different items) ..	61, 000
Number of external receipts other than from AERE	15, 500
Value of Rutherford Laboratory stock	£65, 000
Value of Rutherford Laboratory stock turnover	£140, 000

Transport

Transport Section now run a transport service to all the main centres in the area; this is timed to match the non-industrial shift hours which have been co-ordinated throughout the Rutherford and Atlas Laboratories.

Divisional Administration

The appointment of an administration officer for Applied Physics Division has extended the local support. This is designed to help divisions with their internal administration and to make the best use of the central administrative services.

Housing and Hostels

The Cosener's House. A new wing was completed early in the year. There is now accommodation for forty-three visitors, an increase of sixteen.

Rutherford Laboratory houses	160 unfurnished 6 furnished
AEA and Local Authority Houses	116 + 15 all unfurnished

(The extra 15 were to meet the peak caused by 50 staff returning from CERN)

Number of placings during the year:

Lodgings	47
The Cosener's House Hostel	6, 337
AEA Hostels	104
Rutherford Laboratory furnished houses	10
Rutherford Laboratory Flats (Chilton House)	26
AEA furnished houses	-
Privately owned houses or flats	20
Hotels	450

Restaurant

Total number of main meals served	170, 008
Main meals served at weekends and evenings	29, 340

Scientific Administration Group

University Research Agreements

During the year the Laboratory managed research agreements with the Universities of Birmingham; Bristol; Cambridge; Glasgow; London:- Imperial College, King's College, Queen Mary College, University College and Westfield College; Manchester; Oxford; The Queen's University of Belfast; Southampton; Battersea College of Technology (now the University of Surrey).

The following list shows the numbers of agreements in force at the beginning and end of 1966, classified according to type of research.

Classification	1 January 1966	31 December 1966
Experiments with Nimrod	30	24
Experiments with the PLA	9	8
Extra-mural research	3	4
Capital projects	2	-
Major film analysis projects	3	3
Totals	47	39

Visitors

1149 visitors were taken on conducted tours of the Laboratory during the year. On the 19 May, 66 members of press radio and television organisations made a special 'press visit' in order to study selected aspects of the Laboratory's work.

Exhibitions

The Laboratory collaborated with the UKAEA in arranging an exhibit on elementary particles for the Physics Exhibition held at the end of March 1966. During August, again in collaboration with the UKAEA, the Laboratory provided an exhibit on Lord Rutherford for the Westminster Abbey Science Exhibition.

During the year eleven firms held one-day exhibitions of equipment at the Laboratory.

Library

Library loan transactions:	Internal:	Books	2351
		Periodicals	1682
		Reports	1299
			5332
	To external users		785
	Total		6117

Reciprocal arrangements exist with 102 institutions in 22 countries for the exchange of report and preprint literature.

The Library stock at the end of 1966 was:

Books (vols)	5000 approx
Pamphlets	450
Reports & Preprints	8000
Photographs	3000
Slides	900
Press cuttings	800
Periodicals (currently taken)	414

Approximately 500 books and 3000 reports and preprints were added during the year.

Documentation

Number of Rutherford Laboratory Reports issued	21
Number of Rutherford Laboratory Preprints issued	30

Finance and Accounts Group

Rutherford Laboratory expenditure for the financial year 1966/67 in £M

Staff Expenditure		1·87
Divisional Budgets - Nimrod	0·69	
High Energy Physics	0·66	
Applied Physics	0·45	
Proton Linear Accelerator	0·25	
Engineering: see Note 1	0·88	
Administration: see Note 2	0·76	3·69
University Agreements		0·18
Plant Budgets		0·38
Plant Schemes		0·13
Building Works		0·22
Total: see Note 3		6·47
Total recurrent expenditure		5·52
Total capital expenditure		0·95
		6·47

Notes:		
1	Includes Electricity	0·50
	Site Services	0·11
	AEA Inspection etc.	0·03
2	Includes Rates	0·07
	Misc. AEA charges	0·13
	Travel & Subsistence	0·09
	Advertising	0·04
	Telephones etc.	0·04
	Housing, Restaurant etc.	0·08

3 With the exception of 1.88M for staff, this expenditure resulted from 22,500 invoices etc. and during the year 20,000 commitments were recorded.

Personnel Group

The staff in post at the beginning and end of the year and the movement of staff are shown in Table I. The closing strength of Divisions at 31 December, 1966, is shown in Table II.

Table II - Closing Strength at 31 December 1966 by Divisions

	Professional	*Ancillary*	*Industrial*	*Total*
Nimrod	102	139	104	345
High Energy Physics	50	49.5	18.5	118
Applied Physics	80	58	10	148
Proton Linear Accelerator	43	40	27	110
Engineering	50	70	101	221
Administration	6	122	67.5	195.5
Training	3	9		12
Apprentices			37	37
Non Group	3			3
	337	487.5	365	1,189.5

Staff Relations

During the period covered by the report the Rutherford Laboratory Whitley Committee met four times and there were two meetings between representatives of the Trade Unions and Management. A wide range of topics was discussed.

Table I - Details of Staff in Post

	Opening Strength 1966	New Entries	Resignations etc.	Promotions Into Classes	Promotions Out of Classes	Closing Strength 1966	Increase
PROFESSIONAL							
Senior Staff	16	1				17	
Scientific Officer Class	61	4	8	1		58	
Fixed Term	32	17	10			39	
Experimental Officer Class	123	12	12	2	2	123	
Engineers I, II, III	76	5	9	17		89	
Assistant Design Engineers	26				15	11	
Total Professional	334	39	39	20	17	337	1%
ANCILLARY							
Scientific Assistant Class	73	21	15	1	1	79	
Draughtsmen	24	7	2	2		31	
Technical Class	172	27	12	7	4	190	
Non-Technical Class	33	1	1	2		35	
Executive Class	27	1	2	2		28	
Clerical Class	46	14	12	3	2	49	
Secretarial and Typing	28	11	11		1	27	
Photographers	4					4	
Photoprinters	4			1		5	
Machine Operators	3	4	1	1		7	
Asst. Hostel Manageress	1					1	
Scanners	25	16.5	10			31.5	
Total Ancillary	440	102.5	66	19	8	487.5	11%
INDUSTRIAL							
Skilled	155	56	37	3	8	169	
General Workers	135.5	65.5	33		9	159	
Apprentices	32	9	4			37	
Total Industrial	322.5	130.5	74	3	17	365	14%
GRAND TOTALS	1,096.5	272	179	42	42	1,189.5	8.5%