DNPL 6

4 GeV ELECTRON SYNCHROTRON

Progress Report for the Period 1st June to 31st December, 1967

Daresbury Nuclear Physics Laboratory
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CONTENTS

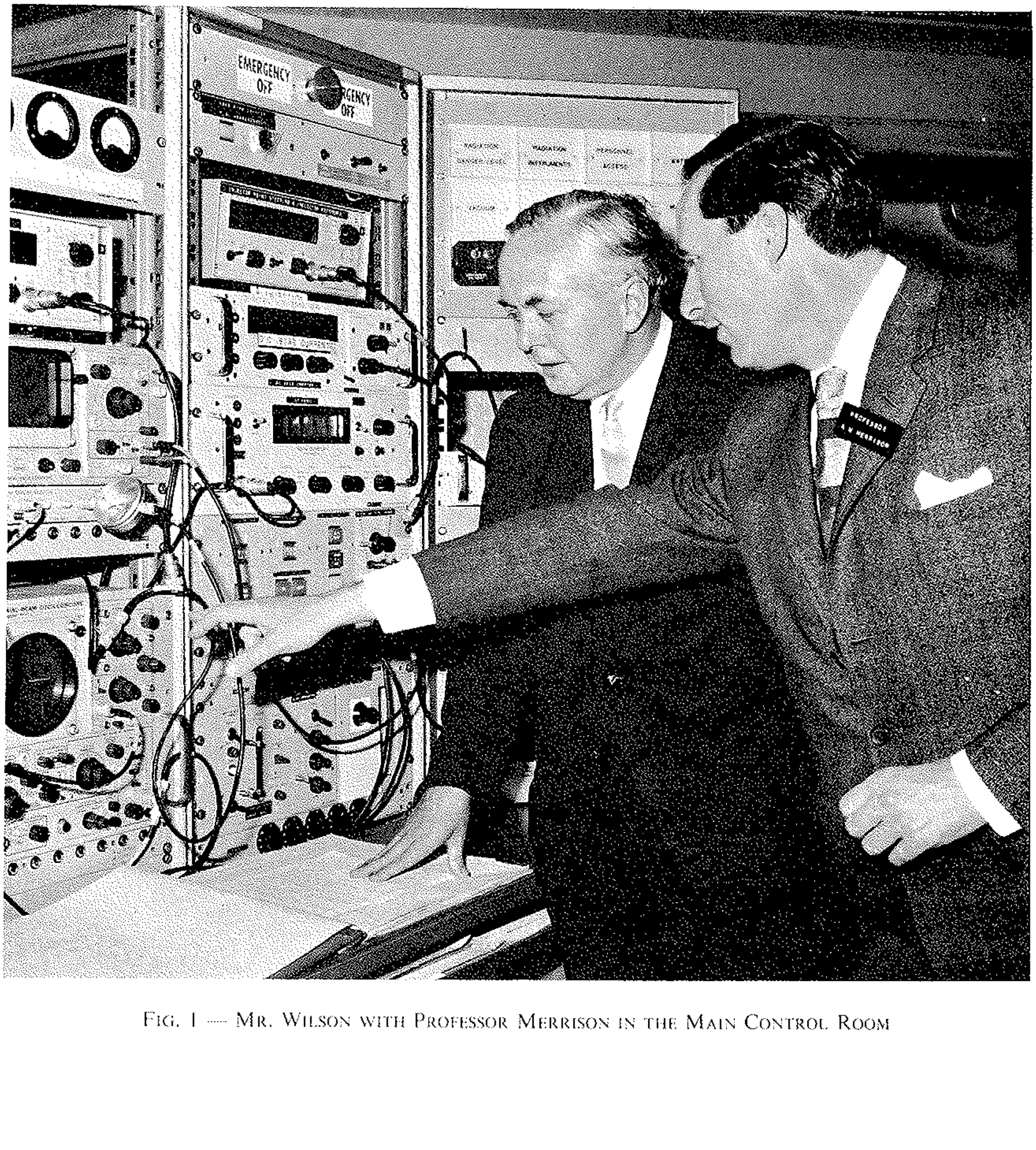

FIG. 1 — MR. WILSON WITH PROFESSOR MERRISON IN THE MAIN CONTROL ROOM

1. INTRODUCTION

The period covered by this report started with the Official Opening of the Laboratory by the Prime Minister, the Rt. Hon. Harold Wilson, O.B.E., M.P., on the 16th June, 1967. This ceremony was performed in the presence of many distinguished people, including guests from all parts of the world. An enormous amount of work went into the preparation for this event and it was generally agreed that the whole ceremony proceeded in an efficient and enjoyable manner.

Following this occasion, the Laboratory settled down to routine operation, running time being divided between the requirements of the various experimental groups to test and set up their equipment and investigations directed towards improvement and understanding of the synchrotron itself. Much of this work is described below.

In November continuous running of the machine on a 3-shift basis was started, and this, by avoiding the delays inherent in daily start-up, increased the available time for experiments. By the end of the year some of the experimental groups were approaching the stage of taking data.

Perhaps the most noteworthy development in experimental physics at the Laboratory in the period covered by this report is the increase in the number of groups planning to conduct experiments at Daresbury. In DNPL 5 six major experiments were listed. Now, in addition to these, further experiments are being proposed by a Strasbourg-Orsay group, and a group composed of physicists from Pisa, Rome and Daresbury. A second Lancaster/Manchester group is making a preliminary study of the problems involved in the photoproduction of many particle final states. In addition, considerable progress has been made in the planning of the magnetic spark chamber work.

2. SYNCHROTRON INVESTIGATIONS

2.1 Introduction

In each cycle of operation a number of shifts have been allotted to machine investigations. Of these, a good proportion have been concerned with problems of electron beam extraction and others with targetting for photon beams.

The remainder have been aimed at improving the performance of the synchrotron itself. An advance has been made in momentum matching at injection and this, in turn, has led to higher beam currents and enabled a start to be made on r.f. capture investigations at high beam intensities. The other major advance which has been made is in the exploration of the effect of high energy beam bump pulses on the subsequent injection conditions, which have led to the complete loss of the next cycle. Various ways of overcoming this problem have been tried, and at the end of the year, it seemed that a satisfactory solution was in sight.

Some of the early findings have been given in a paper* presented at the High Energy Accelerator Conference held at Harvard University in September.

2.2 Field Corrections at Injection

It will be recalled that the pole-face windings on the magnets comprise windings which give a systematic dipole correction between F and D magnets, and dipole windings arranged in triads on F magnets only, which give a local deviation in the closed orbit. Also there are windings on F and D magnets giving quadrupolar and sextupolar fields. In addition, there are Helmholtz coil pairs between magnets giving vertical steering.

Usually, a beam can be transmitted round the ring with the currents in all these windings, with the exception of the systematic dipoles, set to zero. This beam current is very small, however, and it needs a particular distribution of dipole triad currents and Helmholtz coil currents to put the beam on the best orbit at injection. In addition, the quadrupolar correction of the F magnets is usually a critical parameter.

A survey of the magnets in October showed marked departures from the ideal position. In the worst case a magnet was 1 mm out of position at one end. The average error was small, however, and the estimated effect

*Crowley-Milling, M. C.—Proceedings of the 6th International Conference on High Energy Accelerators, 1967, p. 404.

of the overall pattern of displacement was small. This was confirmed by the fact that, when the magnets were repositioned in November, the conditions for optimum beam current remained unchanged. Also one magnet has been replaced, following the failure of a winding, and the change of magnet has also produced no observable effect on parameters.

The pole face winding currents and Helmholtz coil currents have been re-optimised from time to time and always the pattern remains the same, although the amplitudes vary somewhat. The causes of these variations are not understood, nor indeed is it certain what is the cause of the basic pattern of corrections. At one time it was thought that the latter was attributable to the transmission line modes, caused by the magnet power supply pulses. But the progressive damping of this mode has made no difference to the amount of correction needed.

2.3 Missing Cycle Studies

It was described in DNPL 5 how the magnetic flux excursions (or high energy beam bumps) used for targetting and extraction caused residual disturbances at the time of next injection, severe enough in some cases to prevent acceptance of the injected beam on that cycle. Thus it was possible to produce photon beams in straights 6 and 10 (i.e. for the Manchester and Liverpool experiments) only on every other cycle, a severe reduction in the utilisation of the machine. On the other hand the bump employed for targetting on straight 8 for the WAPP experiment appeared to have little or no effect, so that every cycle could be made productive.

At first, the evidence was that the transmission line mode in the magnet power supply network, excited by the bump pulse, was the cause of the disturbance. As explained in the previous report, damping loops were introduced which gave some improvement. It was thought that, by putting in sufficient damping, the effect could be avoided altogether. However, it turned out that further reduction of the decay time of the mode beyond a certain point had no effect on the missing cycle problem.

Accordingly, other explanations were sought, and methods of correcting for the effect were investigated. The evidence suggested that the effect was caused by remanent field effects on the four magnets to which the beam bump pulse was applied. Another winding was introduced around the back legs of one set of magnets and this was fed from a circuit which produced a small current pulse a few milliseconds long which could be timed at about the injection point. The direction of the current was opposite to that employed in the high energy bump pulse. It was hoped to compensate at injection for the remanent field and hence avoid loss of beam on that cycle. This experiment proved unsuccessful until the second bump was moved so as to occur entirely before injection and its amplitude increased substantially. It was thus demonstrated that a pulse in the opposite sense could be made to counteract the beam bump pulse, but it was not clear why a smaller pulse simply giving correction at injection could not be used. Shortly after the period covered by this report it was discovered that only 2 of the 4 magnets involved had remanent field effects and that these two were used in targetting for both Liverpool and Manchester experiments. Thus a simple solution now seems possible although the cause of the remanent field is not understood.

The second method of correction investigated was to alter the pole face winding currents appropriately and this permitted targetting for each experiment on every cycle. The main variations from the standard settings without beam bumps occurred in the region of the bumped magnets as would be expected on the remanent field theory. The modified settings were, however, rather more critical.

2.4 High Beam Studies

As reported in DNPL 5, the circulating current in the synchrotron appeared to be limited to just over 30 mA even if the injected current (within 1% energy spread) was increased to 300 mA. The limitation did not appear to be primarily due to beam loading, nor r.f. capture, but to a limitation in the momentum acceptance of the synchrotron. Accordingly, an experiment was planned to improve the momentum matching, although this was not carried out until December. Theoretically, a single quadrupole magnet is necessary on the injection path (ref. DNPL3) to put off-momentum electrons on to their right orbit in the synchrotron. However, when this was energised at the expected level, little change in beam current was observed. Lower levels of excitation were explored and a significant improvement in acceptance occurred with the magnetic field at rather less than half the expected value. Since using this quadrupole, it has been possible to achieve beam currents of the order of 30 mA with much lower injected currents than previously.

However, it has also been possible to begin to explore methods of counteracting beam loading, since it is now possible to circulate very high currents for the first part of the cycle. The highest recorded has been 90 mA for 200 μsec, before it was lost due to beam loading. The maximum current taken to high energy was 50 mA, using cavity detuning at injection. Further experiments are planned, but there are some vacuum difficulties when high average currents are injected and experiments involving a variable amount of beam loss are undertaken. The planned installation of ceramic vacuum chambers should reduce these difficulties.

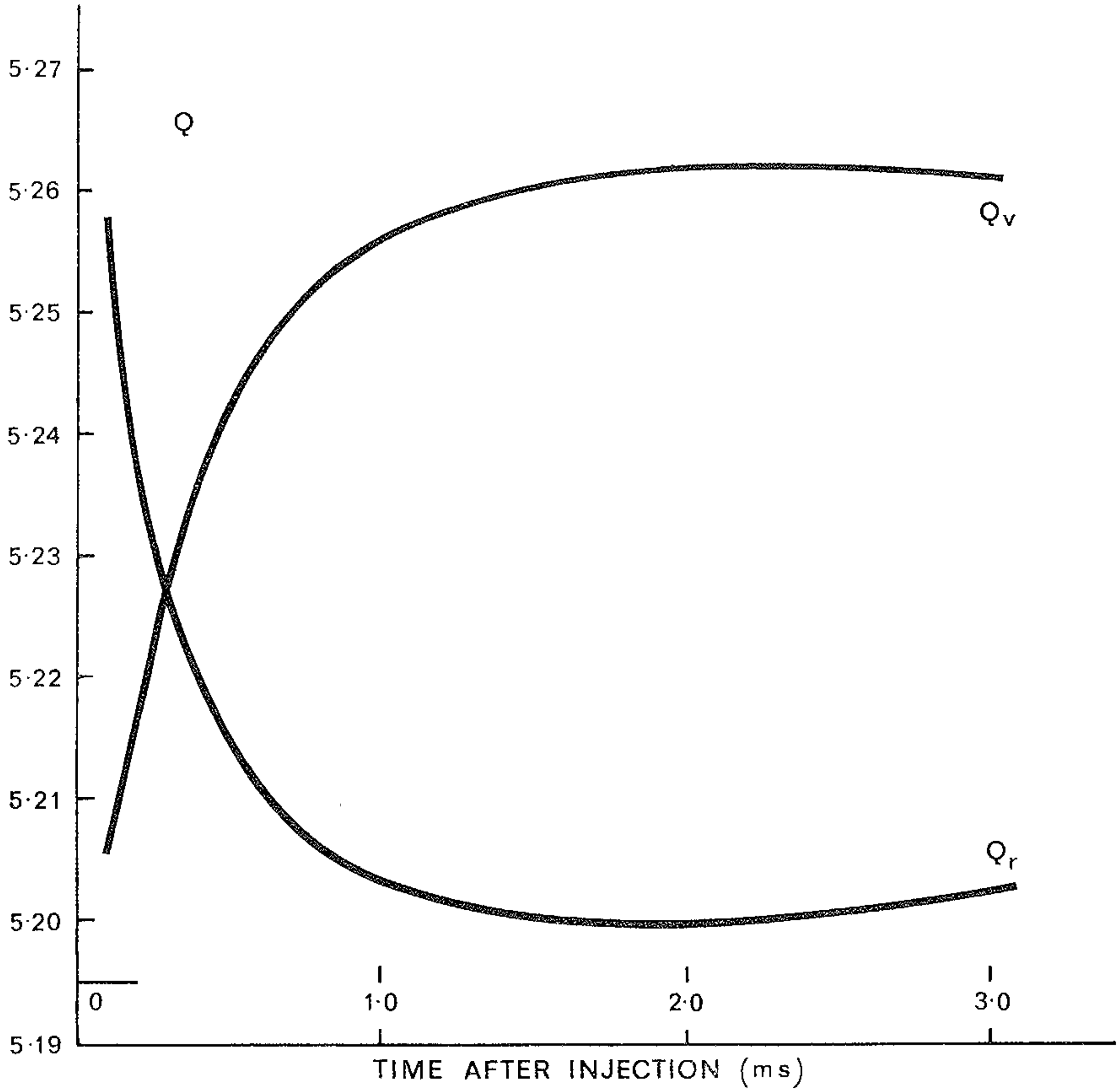

FIG. 2 — UNCORRECTED Q VALUES FOR THE NINA RING

2.5 Q Measurements

A further change resulting from the introduction of the momentum matching quadrupole was that it was now possible to obtain a good beam with zero quadrupole corrections at injection. It has, therefore, been possible to obtain the uncorrected radial and vertical Q values of the synchrotron throughout the cycle and these are given in Fig. 2.

Before the improvement in momentum matching, the highest beams were obtained with a high setting of the F quadrupoles. Sometimes this was so high that the Q value at injection actually exceeded 5.5 and it ran down through the half integral resonance value at 100–200 μsec after injection. Sometimes a sudden loss of a part of the beam occurred at this point, but by critical adjustment of the r.f. level at injection this could be avoided. There is some evidence to suggest that a coupling between synchrotron and radial betatron oscillations can occur near injection.

2.6 Extraction of the Electron Beam

Further experiments have been carried out on the extracted electron beam until the extraction equipment was moved in October to the appropriate section of the ring for providing a beam to the Glasgow target. The performance of the equipment after that date is reported later (Section 3.1).

DNPL 5 reported that beam bump used for experimental extraction was insufficiently compensated and left a residual ripple in the orbit round the ring. This ripple added to the regenerator disturbance to give beam loss at a point downstream from the extraction system. The beam bump winding distribution was modified to give a properly compensated bump and this successfully avoided the unwanted beam loss and a factor of 3 improvement in extraction efficiency was obtained ($\sim 30\%$).

Most of the measurements during this period have been directed towards obtaining a value for the emittance of the extracted beam using 2 quadrupoles and 2 collimator slits in front of a Faraday cup. A difficulty arose in that the kicker magnet was insufficiently strong to bring a 4 GeV beam out along the intended line. The maximum angle which could be used involved a greater path length through the fringing field of the D magnet which followed the extraction system. This fringing field had a big effect on the vertical emittance of the beam.

It was possible, however, to do measurements with the beam brought out along the intended line at an energy of 3 GeV. The results gave an emittance of 1.9 cm-mrad for the horizontal emittance and 1.2 cm-mrad for the vertical emittance. These compare with theoretical values of 1.0 cm-mrad and 0.4 cm-mrad respectively. The high value of vertical emittance was thought to result from coupling between the radial and vertical betatron oscillations in the synchrotron during extraction. The radial Q of the machine is less, at high energy, than the vertical Q, so that, at a point in the extraction process in which the radial Q value is increased to resonance, the two Q values are equal and coupling could occur, although the mechanism has not been ascertained.

It was hoped to overcome the effect of the fringe field by fitting a magnetic shield to the D magnet. This provided a shielded path for the electron beam. However, in the arrangement tried the supports overheated and, since an acceptable electron beam was obtainable without using it, the method was abandoned.

Some Q measurements have been made during extraction in order to improve the understanding of the mechanism of extraction. It was found that the radial Q increased to 5.34 during extraction, the vertical Q being 5.16. The normal values are 5.21 and 5.26 respectively. It seems that the third integral resonance may be the one employed in extracting the beam, but further studies are planned.

3. BEAM LINE INVESTIGATIONS

3.1 Electron Beam Line E1

After initial diagnostic experiments had been carried out with the extraction box in straight 4, the box was transferred to straight 8 in October.

The electron beam line equipment was set up and after several adjustments a satisfactory beam was produced in the Experimental Hall. At first extremely high radiation levels were experienced due to a lack of collimation, but this was soon overcome.

A 10 mm $\times$ 1 mm spot was achieved at the Glasgow primary target by focussing the beam with a quadrupole doublet. Despite the strong focussing the beam entered the beam dump with a small cross-section suitable for measurement by the Faraday Cup.

Measurements of the extraction parameters which produced the highest extraction efficiency, were made at various extraction energies. The best efficiency achieved was 50% and the highest energy extracted was 3.7 GeV. Under these conditions a spill of overall length 500 μsec was obtained. Because of limitations to the existing pulsing units the maximum repetition rate at 3.7 GeV was 1 pulse in 3. New pulsers are being constructed to enable 4 GeV extraction energy to be reached with a 1 in 1 repetition rate.

3.2 Electron Beam Measurements

a) R.F. Cavities

Tests have been made on beam pick-up cavities positioned in the extracted beam line and resonating at the 3rd harmonic of the NINA radio frequency. Using a superheterodyne detection system, it was shown that beam intensities as low as 10^7 electrons per pulse could be monitored satisfactorily. Straightforward amplification and detection of the cavity output signal were used at normal beam intensities (2.10^{10} electrons per pulse) and proved very satisfactory. This system will be used extensively in all future high intensity beam lines.

The cavity used was resonant at 1223.6 MHz, had a loaded Q of 600 and a sensitivity of approximately 0.4 mV per μA of instantaneous beam current.

b) Toroid Monitor

Two systems of toroid monitoring have been investigated:—

i) A high inductance toroid winding giving a direct intensity waveform output, and

ii) A low inductance differentiating toroid requiring electronic integration before an intensity waveform is produced.

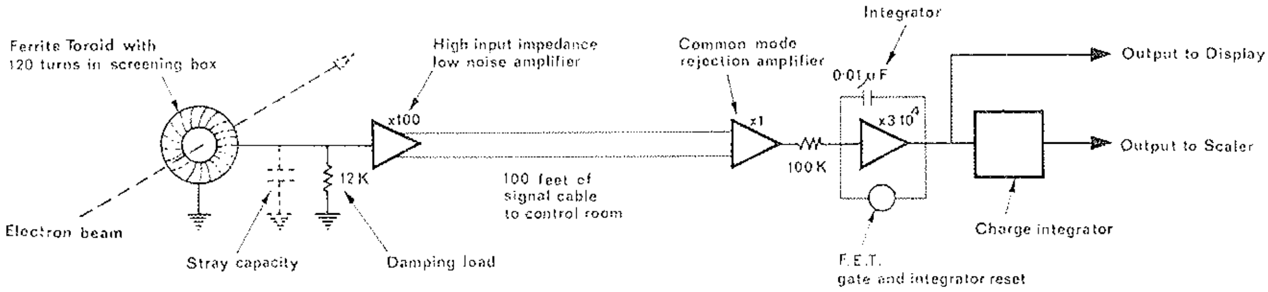

FIG. 3 — THE FERRITE TOROID BEAM MONITOR SYSTEM

System (i) was fairly successful, but to be useful, it needed an increase in beam intensity to make the signal to noise ratio better. This system will be used at a later stage on NINA beams when the intensity is increased.

System (ii) was more successful at the beam intensities presently used (2.10^{10} electrons per pulse). The circuit used is shown schematically in Fig. 3. A gated integrator is used to compensate for the toroid differentiation, the gate being necessary to minimise integration of circuit noise.

With this system the minimum detectable beam current was about 1 μA instantaneous, corresponding to a mean extracted beam current (taking all machine pulses, and 500 μsec long spill) of 0.025 μA.

c) **Secondary Emission Monitor**
This proved a very useful instrument in optimising the extraction system for maximum efficiency. Its output gives a precise indication of the structure of the extracted beam current pulse.

3.3. Targetting
Spill times of the photon beams were lengthened during the period to just over 1 ms, but counteracting the overall improvement in length, modulation is now present at a frequency of approximately 3 kc/s. This was traced to ripples, present in the beam bump, which had sufficient amplitude to cause nearly 100% modulation. In order to improve the waveform of the beam bump pulse to overcome this effect, a pulse shaping circuit, to be added to the present beam bump power supplies, is being constructed.

3.4 Photon Beam Measurements
The gas-filled quantameters have now been working satisfactorily for about one year. Tests made on these quantameters suggest that they are able to operate reliably with the beam intensities and spill times produced at present by NINA.

The prototype secondary emission quantameter is nearing completion. This device should allow accurate monitoring of much more intense photon beams.

3.5 Beam Line Developments

a) **Test Beam Facility**
It is planned to bring a low intensity high energy electron or positron beam out into the experimental hall, by using a doubly converted beam from straight 4 in NINA. This beam will be used in testing development equipment with high energy particles, and will also be suitable for the production of a tagged photon beam of modest intensity.

b) **Electron Beam Line E2**
A second extraction system, now being assembled, will be used in straight 10 to produce a second external electron beam. This will be used by the Manchester/Lancaster Experimental group, directly, and will produce an externally generated photon beam for the Liverpool experiment at a later stage.

While the extraction box is being constructed, Liverpool are using the internally derived photon beam, and the latter will be converted to produce a small electron beam for the Manchester/Lancaster experiment for use in preliminary testing.

c) **Developments on Beam Line E1**
A bending system will redirect the E1 beam into the extension hall for use by the Rome/Pisa/Daresbury collaboration experiment, and, further down the line, this same beam will be used to supply a tagged photon beam to the Track Chamber Experiment.

4. MACHINE OPERATION

4.1 Operational Experience during 1967

1967 saw the commencement of the regular use of NINA. The first half of the year was occupied largely by machine development and the establishment of the required photon beams. However, following the Official Opening Ceremony in June, the machine was scheduled regularly on a 10 days on/4 days off cycle with a 2-shift day and the experiments began to receive the major part of the time available. Operational experience since that time is summarised in Table I. Considerable variations in machine efficiency occurred and still occur, but a sharp rise in useful running time took place following the change from 2-shift to 3-shift operation in November. Table II shows the breakdown of lost time. As can be seen during the first 9 months of 1967 the injector proved the biggest cause of lost time, but since then has improved considerably. The total of good beam time excludes periods of machine development in which little or no beam is required.

TABLE I
NINA Running time from June-December, 1967

Cycle	Schedule Time	Good Beam Time	% Good Beam Scheduled
3	124.5	82.5	66.3
4	124.5	94.5	75.9
5	124.5	59.0	47.4
6	124.5	45.0	36.1
7	124.5	93.0	74.7
8	124.5	94.5	75.9
9	124.5	48.0	38.5
10	124.5	80.5	64.6
11	124.5	55.0	44.2
12	159.0	109.0	68.5
13	159.0	113.0	71.1
14	157.5	127.75	81.0
15	157.5	98.75	62.7
TOTAL	1753.5	1100.5	62.7

TABLE II
Causes of lost time on NINA June-December, 1967

Cycle	Injector	R.F. Supply	Vacuum	Magnet and Power Supply	Targetting and Extraction	Personnel Safety and Timing	Others
3	8.0	13.5	4.0	—	4.5	4.0	8.5
4	2.0	4.0	5.5	4.0	3.0	—	12.0
5	29.0	5.0	10.5	3.5	0.5	3.5	14.0
6	41.5	1.5	22.0	0.5	1.0	3.0	10.0
7	12.5	1.5	3.0	—	—	1.5	12.5
8	16.0	2.0	1.0	—	1.5	—	9.5
9	4.0	1.0	68.0	—	2.0	—	1.5
10	4.0	2.0	20.0	—	2.0	—	17.5
11	12.0	1.0	2.0	49.0	1.0	1.0	3.5
12	2.0	1.5	5.0	27.0	1.0	1.0	10.5
13	18.0	3.0	4.0	6.0	2.0	—	3.0
14	7.5	—	3.0	1.0	6.0	1.0	11.25
15	4.25	15.75	0.25	9.25	3.25	—	26.0
TOTAL	160.75	51.75	148.25	100.25	27.75	15.00	139.75

A major shut-down in October was required for the first major survey of the NINA magnets since the machine was commissioned and for the installation of the first extraction system in straight 8, the correct position for its use by the Glasgow team.

4.2 **Vacuum**

The NINA vacuum system has generally proved satisfactory, although dose rate figures for the epoxy-type vessels show that some are nearing the end of their expected life. The pumps themselves are becoming hard to start and tend to "run away" if called on to pump any quantity of gas. A schedule of performance improvement is being tested and will be carried out at the same time as the ceramic chamber installation. A number of Pfeiffer turbo-molecular pumps have had fractures of the internal toothed belts; this has been proved (and agreed by the manufacturer) to be due to a faulty batch of belts. A number of leak problems have occurred in the flight path due to the beam hitting flanges and causing uneven expansions. Some improvements have been made to the system to avoid this.

The vacuum vessels themselves have given little trouble, but certain areas of the machine are beginning to show signs that radiation damage is occurring. The 'D' chamber in magnet 29 has already developed leaks and has had to be exchanged twice. This chamber is downstream of the inflector and thus catches any beam which is not properly injected or inflected. The leaks have occurred in the same place on each vessel near the first bellows unit and, after an activity decay period, have been patched and repaired. Dosimetry of the remainder of the ring shows that chambers in magnets 6, 8 and 10 which contain internal photon targets are all showing high doses, which will soon be in the region of 10^9 rads, which is the point at which the flexural strength of the resin used is getting low and failures can be expected. However, the beginning of delivery of ceramic chambers should occur soon.

4.3 THE INJECTOR

a) **Introduction**

The acceptance trials of the M.E.L. 40 MeV linear accelerator were described in DNPL 5. The machine was not accepted at that stage because the stability was not considered adequate. A good deal of work was carried out by M.E.L. during the period under consideration and this resulted in the machine being accepted from the 1st December, 1967 following an 8 hour stability trial in November. This work included improvements to the klystron modulators, elimination of instability in the phase servo and replacement of the gun h.t. supply.

b) **The Electron Gun**

Experience with the gun has been satisfactory on the whole, although in August there occurred a breakdown of the bombarder voltage across the ceramic seals through which the filament current is taken and this necessitated some modifications to these seals.

The first cathode lasted over 2,000 hours, but the emission, for a given bombarder power, dropped to 40% over this period. The bombarder power had to be increased to 1850 watts in order to obtain the design current from the linear accelerator. Since the cathode is pure tungsten the reason for this increase was not apparent, until the gun was removed for inspection and it was seen that the cathode had become partially detached from its molybdenum supports and had fallen forward towards the grid. The gun was replaced and the design current was then obtained with only 1150 watts bombarder power.

The 80 kV d.c. supply for the gun modulator, which had repeatedly broken down, was replaced by a conventional rectifier set.

c) **The Klystron Modulators**

It has been explained previously that the linear accelerator output pulse, when momentum analysed, has suffered from a severe variation of output at about 3 c/s, the beat frequency between the synchrotron magnet network and the a.c. supply. In the main this was attributable to a big variation in the phase currents supplying the 12 kV rectifier units for the klystron modulators. The fitting of larger charging chokes to these modulators reduced this variation considerably and the beat, though still apparent, is much less troublesome. In order to eliminate this trouble completely a motor-alternator set has been ordered which will produce an a.c. supply at the magnet frequency and this will be used to feed most of the components of the injector. It is expected in the spring of 1968.

Further work on the flattening of the pulses applied to the klystron resulted in the ripple over the middle portion of the flat top being reduced to 0.3% peak to peak. However, the klystrons have been found to change in perveance, and hence in the impedance they present to the modulator, during their life and this has caused some difficulty in obtaining a flat analysed current pulse for injection into the synchrotron. More will be said about this in the next section.

Apart from difficulties caused by failure of the grid resistors of the switching thyratrons, and the failure of the thyratrons and charging diodes, the modulators have been relatively trouble free.

One of the main pulse transformers failed due to breakdown of an insulator under the oil. This was found to be due to a fault in the manufacture of this particular insulator and it was repaired under warranty.

d) **Klystrons**

An Eimac X3029 drive klystron was replaced at about 1500 hours when its pulse showed a considerable droop with over 10° phase change across the pulse. It was replaced by one of the equivalent tubes supplied by Litton, and this has given a satisfactory performance so far.

The useful lives of the CSF F2049 klystrons have, with one exception, proved disappointingly short. Again, with the one exception, the perveance has changed continuously throughout life, contrary to expectation. Initial perveance is around 1.8×10^{-6} and a tube is no longer considered usable when the perveance has dropped below 1.4×10^{-6}. So far the manufacturer, C.S.F., has recommended a fixed heater power. The Laboratory are seeking from C.S.F. permission to step up the heater power during life to try to maintain a constant perveance. This practice is current in other Laboratories using klystrons, including SLAC. So far two tubes have failed at about 1,000 hours, one developing internal breakdown. One tube, however, has now exceeded 2,000 hours and its perveance remains relatively constant.

4.4 The R.F. System

a) **General Operating Experience**

The r.f. system has worked reasonably reliably during the period. The major addition to the system described in the last report has been the commissioning of the 2054 triode high power amplifier. Otherwise there has been little change and the current accelerated has remained around 1 μA mean. The maximum peak circulating current observed has been about 50 mA. Improvements in the momentum matching at injection, described in Section 2.5 now make it possible to circulate much larger currents for a few turns with the r.f. supply switched on. This implies that it may be worthwhile trying again to capture and accelerate these higher currents and experiments to do this are planned.

With the 2054 in regular use, an energy of 5 GeV has been obtained using a peak r.f. power of about 250 kW. Over 500 kW has been obtained from the 2054 in a test pulse and the waveguide-cavity system has been commissioned to this level. It should, therefore, be possible to achieve the predicted performance of 1 μA at 5 GeV and a small current to 5.3 GeV.

Most of the breakdowns in the r.f. plant during this period have been of a minor nature—occasional trouble with control circuits and so on. Two items have required fairly continuous maintenance though they have not caused significant lost time. These are the cavity tuner motors, which overheat, the cause still not having been established and the master oscillator, which drifts off tune, causing loss of output power and occasionally loss of frequency lock. A transistorised version of the master oscillator is being developed but it will take some time to establish the necessary degree of reliability. The first 2041 failed in December. It had 3,800 hours filament life and had been used for all the development work. The new divider for the programme generator, mentioned in the last report, has been installed, but is still under development.

The cavity voltage feedback arrangement has been shown to work and used from time to time. It requires very careful use at present as it is very easy to overload and trip the amplifier under certain circumstances. Interlock and protective circuits, which should enable the crew to use cavity feedback in a routine manner, have been developed and will be installed and commissioned in February. Some details of this system will be given below.

The frequency control loop works but is only used on any experimental basis at present. The phase jump at injection is being developed but is not yet satisfactory.

b) **The 2054 High Power Amplifier**

During the period, RCA provided the hum-bucking circuit required for the plate modulator, as arranged, but it has not yet been installed.

As mentioned in the last report, the amplifier was shown to work well using a highly non-linear cathode bias resistor. This completely suppressed between-pulse oscillations, and greatly reduced oscillations at low drive levels. As the oscillations at low drive increase with plate voltage, it was agreed to provide a servo system to control the plate voltage in accordance with the peak of the r.f. demand signal, so as to run the amplifier always with the minimum plate voltage and corresponding maximum drive power. This was commissioned in July and works well. For a 3 GeV low current working, when the peak power required is only 50 kW, the plate voltage runs at its minimum setting of 5 kV. As the peak of the programme demand signal increases, a servo causes the plate voltage regulator to move. This operates fairly slowly so that care must be taken not to try to increase r.f. peak power too quickly. If this happens, then the feed-back loop around the amplifier tends to overdrive the 2041 stage. A circuit is, therefore, incorporated to protect the amplifier against this.

Since July the 2054 has been in continuous use without further problems, though the normal working power level is as yet quite low (100 kW peak for 4 GeV, 1 μA current). During August the amplifier was used to test the isolator to full peak and mean forward and reverse power ratings with complete success. The insertion loss was slightly lower than the design figure of 0.6 db, whilst the isolation was 9.8 db.

4.5 Main Control Room

Clearly in a Laboratory of this nature, the arrangement of the Control Room never quite reaches finality, due to the changing nature of the experimental beam lines and to development and rationalisation of the controls for the synchrotron itself.

The following points are singled out for comment:—

a) **Personnel safety**

Component changes have had to be made in the electronic circuits of the personnel safety system owing to unreliability which resulted in spurious trips of the search system.

Extensions have been made to the system to include the experimental areas, which must be searched and locked before the appropriate beam bump can be applied and the beam shutter raised to permit beaming into the area.

b) **IBM 1800 Computer**

The computer has been brought increasingly into use as a data logger and a wide range of machine parameters can be printed out as required. The important parameters in the injector and injection path are being progressively added prior to the planned transfer of control of the injector to the main control room. A warning will be given of variation of these parameters from the correct settings.

c) **Beam Sensing**

Investigation and development of the beam current monitoring system has continued. A good quality display of the integrated and non-integrated signals from the total current monitors is essential at the main control centre and two of the four monitors have been allocated for this purpose. In addition there are requirements for similar displays at the r.f. and injector control racks and for beam envelope displays at the various experimental counting rooms. Suitable fan out circuits are being designed. Also a circuit is being developed to provide digital and analogue read-out of peak and average circulating current.

Work is still proceeding on a system which will display the position of the beam at the 20 beam position monitors around the ring at selected times during the cycle and much of the equipment for this has been ordered.

d) **Timing Pulses**

A comprehensive system for fan out of timing pulses has been installed. However, the circuits designed for providing a peak field marker and for giving pulses at equal increments of magnet phase proved unsatisfactory and some redesign was necessary.

4.6 Health Physics

Radiation surveys have been carried out regularly to determine external radiation arising from the experimental areas, and in some cases this has resulted in modifications to the shielding arrangements. Building work on the extension to the Experimental Hall has led to deliberate restriction of beam intensities made available in some experimental areas during normal working hours, the chief problem being radiation at high levels, i.e. above the height of the normal shielding walls. External radiation from the synchrotron ring and injector is relatively high in three areas, two equipment rooms, above and to one side of the linear accelerator and part of the Inner Hall, near to the inflector. Where practicable, additional shielding is to be provided so that such areas can be made freely accessible to classified workers during normal operational time.

Normally, surveys have been made with the usual portable radiation monitors giving information on X-rays and neutrons over a wide range of energies, but these measurements have been backed up by activation detectors and thermoluminescent dosimeters to provide additional information on the nature and spectrum of the radiations.

Induced activity is an increasing problem and parts of the ring now have sufficient activity to give dose rates at accessible points of tens of rads per hour. The maintenance and modification of equipment in these areas is under strict health physics surveillance. It has been necessary to set up suitable stores where active equipment can cool off before being removed from the ring and additional storage facilities are planned.

Also an active workshop has been established, with a lathe and milling machine, where active material can be worked on under approved conditions.

A code of practice has been written to cover all aspects of radiation work at the Laboratory.

5. MACHINE DEVELOPMENT

5.1 Positron Accelerator

The modulator for the klystron to be used to power the positron accelerator was delivered by M.E.L. in November. The control rack for this klystron is being made by the Laboratory. Besides its projected use for the positron accelerator this third klystron and modulator will be used for klystron testing and modulator development.

The positron accelerator and the 3 kGs focussing coil assembly were due for delivery at the end of November, but owing to difficulties with the coil manufacture, delivery was put back 2 months.

All the design work is complete for the converter target and its associated focussing system and manufacture is well advanced. Installation of the accelerator will present problems, since it is necessary to minimise interruption of machine running cycles. A good deal of preparatory work has been done; for instance, the installation of the 200 kW power supply for the main focussing coils and the laying of cables and pipework.

5.2 Beam By-pass and Debuncher System

Since it is not practicable to coast the electron beam through the positron accelerator, a beam transport system has been designed and installed for taking this beam along a path alongside the positron accelerator at a distance of 1.2 m. This system uses four 45° bending magnets and has a focus in the horizontal plane at its midpoint. A beam position indicator placed here will provide a correcting signal for the energy servo of the electron accelerator.

An adjustable collimator slit, also positioned at the mid-point of the by-pass, will allow the momentum width of the injected beam to be controlled whilst only having a small effect on the emittance. This will be a great asset in diagnostic work on the synchrotron acceptance.

It is now definitely planned to use the debunching effect of the by-pass to reduce the energy spread of the beam injected into NINA. The difference in path length in the by-pass for an electron which is off momentum by 1% compared with an electron of correct momentum is 13.6 mm, which corresponds to 47° phase difference at the linac frequency. It is proposed to insert a short length of corrugated waveguide, suitably powered and phased, into the beam path. The phasing will be chosen to make no difference to the energy of a particle of correct momentum, but to reduce the energy deviation of off-momentum particles by a large factor.

5.3 Proposal to Produce a Flat Top on the Magnetic Field Waveform

The desirability for the magnetic field in NINA to remain constant during electron extraction is self-evident. The extracted electron energy would then be constant within the limits of the synchrotron oscillations. Consideration has, therefore, been made of practical ways of achieving this and some experiments have been carried out on the one-tenth scale model of the magnet network.

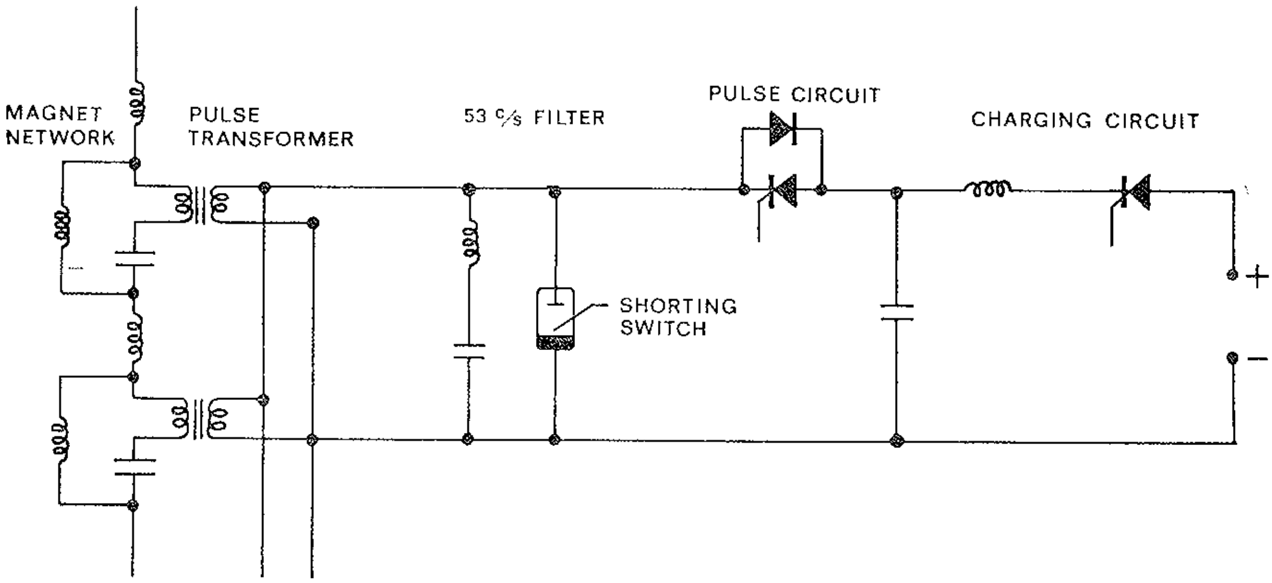

FIG. 4 — SCHEMATIC CIRCUIT FOR PRODUCING A FLAT TOP ON THE MAGNET WAVEFORM

What would appear to be the most straightforward way of creating a flat top is to short-circuit the network capacitor banks at peak field. The field would then remain virtually constant until the short-circuit is broken, after which normal oscillation resumes. However, because of the high rate of rise of voltage in the capacitors when the short-circuit is removed, the de-ionisation time of mercury valves which might be used for switching would not be sufficiently short. Thyristors are ruled out because of the high voltages and currents involved.

A system was, therefore, evolved which avoided this difficulty. It employs a pulse transformer connected in series with each capacitor bank (see Fig. 4) and these are used to introduce a pulse of voltage at a harmonic of the network frequency at the peak of the magnet field. The pulse is produced by discharging a capacitor through a thyristor into the paralleled primaries of the pulse transformers, the inductive load impedance of the magnets resonating with the capacitor at the harmonic frequency. By putting a reverse diode across the thyristor much of the original charge can be recovered so it is only necessary to make up the losses.

It is necessary to put a 53 c/s filter across the primary side of the pulse transformers to allow free passage to the network a.c. and also a high current switch to conduct the energy maintaining pulse.

For design purpose the tenth harmonic was chosen and the specification was for 0.10% peak to peak variation in field over 1 ms with the magnet network set for 5.3 GeV, this giving rather longer flat tops at lower energies. The system was tried on the scale model and operated as expected. A report giving more details is in preparation.

5.4 Ceramic Vacuum Chambers

The contract for the supply of approximately half the full number of ceramic vacuum chambers has been let, and delivery is expected to begin at the end of February. The contract was placed with Feldmuhle A.G. of Plochingen, nr. Stuttgart, W. Germany, who had already made a small number for the German electron synchrotron, DESY, at Hamburg. They will be using a copper-nickel alloy jointing ring brazed in a compression type seal to the end of each ceramic piece of the appropriate cross-section and 12in. long. The metal parts will be joined by argon welding and the chamber will be terminated at each end by a flexible bellows unit similar to the present fibre-glass and epoxy chambers. These bellows units are again being made by Palatine Precision Ltd., of Strood, Kent. The chambers will be metallised internally with a "lossy" resistive coating to avoid charge build-up and this is arranged in two parts, an upper and lower layer, to allow an applied d.c. potential to clear any ions formed during the acceleration period. Experience at Cambridge and DESY showed that only a marginal advantage resulted from making the coating continuous for heating (and outgassing) purposes. It is hoped to start the installation of these chambers at the end of April,1968.

6. EXPERIMENTAL PHYSICS

6.1 Experimental Magnets and Power Supplies

In DNPL 4 mention was made of experimental magnets for use in spectrometers. All types have proved to be very useful, and a further order for four W.17 bending magnets and six HQ29 half quadrupoles has been placed with the Oerlikon Engineering Co. All the yokes have been machined and all the coils wound. Delivery will be spread over the first four months of 1968.

Tenders have been received for the large spark chamber magnet mentioned in DNPL 5. These are being assessed and discussions are taking place with several possible manufacturers. It is hoped to let the contract early in 1968.

The first twenty Brentford power supplies, totalling 4 MW, for supplying magnetic spectrometers have been installed and commissioned. After a good deal of fault-finding, these now all meet the specified stability of 1 part in 10,000, and have been accepted.

A further order for ten 400 kW units and four 200 kW units has been placed with Brentford Electric. Delivery is due to start early in 1968.

6.2 Magnet Measurements

Since the last report on the magnet measurement test area, all the equipment has been installed and brought into satisfactory operation.

A number of Hall probes of the type described have been mounted on various frames that can be attached to the probe arm, for measuring the field intensity in various parts of different types of magnets.

All of these probes have been calibrated against the NMR device in the uniform field of one of the W.17 magnets. The calibrated values have been stored on magnetic tape and suitable computer programmes exist for reading the Hall probe voltages recorded on paper tape, and converting them to field intensity values.

Since the area became available, a total of about twenty magnets has been measured, including one of every type available in the Laboratory. All the experimental groups have completed the measurements they require on their magnets and a pair of Q.16 quadrupoles has been calibrated for use on the extracted electron beam line.

A ray tracing programme has also been developed independently, for determining the effective lengths of magnets from field intensity distribution and field gradient measurements.

Plans are going ahead for the development of a second, larger test area that will incorporate some extra features from experience gained on the present system.

6.3 Bremsstrahlung Spectrum Measurements

A brief description of the experiment was presented in DNPL 4. At the beginning of July 1967 the cabling was complete and the apparatus installed in the experimental area. It was decided, because of saturation effects in the W.17 magnet, to mount the two scintillation counter telescopes at an angle of about 12° to the photon beam line and not at 18° as stated in DNPL 4.

The immediate purpose of the experiment is to measure the spectrum shapes of the photon beams used by the Liverpool University Experiment (photoproduction of π^0) and the Daresbury Laboratory Experiment (wide angle pair production).

The main problem concerned with the measurement has been the high background of electron-positron pairs produced in the air. This has been overcome by using an evacuated flight tube immediately preceding the evacuated W.17 magnet and a system of permanent magnets to clear the background of charged particles.

The experiment is now ready to take data and it is hoped that the necessary measurements will be made before the end of March, 1968.

7. W.A.P.P. EXPERIMENT (DARESBURY)

The construction and calibration of the two identical spectrometer arms for the wide angle pair experiment is almost complete. Preliminary setting up was done using an additional bending magnet placed immediately after the target to deflect the copiously produced ~0° electron pairs into the system. As these pairs are produced at angles very close to 0° all the deflected pairs lie in the median plane of the bending magnet, and do not provide a stringent test for the spectrometer. Thus, final setting up was done using wide angle pion and electron pairs produced in a carbon target without this additional magnet.

The spectrometer design has been changed slightly since the last report in that the vertical aperture defining veto counters (see Fig. 9 in DNPL 5 and Fig. 8 DNPL 4) have been removed. It was found that the singles rates in these counters were so high that the accidental vetoing of genuine events was a problem. The vertical aperture is now defined by a single positive counter at the exit of the W.17. Thus, no scintillation counter in the entire system can now "see" the target directly.

The separation of electrons from the charged particle background, which is made up almost entirely of pions, with protons contributing in the "positive" spectrometer, is achieved by threshold gas Cerenkov and shower counters. The Cerenkov counter is 2 metres long and is filled with Freon. The resolution for relativistic electrons has been measured to be ~65%, with an efficiency for electrons of >99%. An upper limit for the detection efficiency of pions due to knock-on electrons has been measured to be 3×10^{-3}. The shower counters are of the lead/lucite sandwich type and are each 40 cm × 48 cm and 12 radiation lengths thick. Their resolution for electrons has been measured over a range of momenta from 1.0 to 2.0 GeV/c and varies from 35% to 15% at the higher momentum. This resolution assures a 95% rejection of pions for a 95% electron efficiency over the entire range of momenta. Thus, for each spectrometer, the probability of a pion simulating an electron is $<1.5 \times 10^{-4}$.

The data handling system is also operational. It consists of an IBM 7330 tape unit and an SEN interface unit. If the fast logic decides that an event has occurred a master trigger pulse is generated which opens interface gates and interrogates the digitised contents of the momentum, theta and phi hodoscopes in both spectrometers. It also opens fast linear gates to obtain analogue information from the Cerenkov and shower counters which is stretched and digitised and put into a buffer store together with the hodoscope information. The resolving time of the fast logic is ~9 ns, but additional timing information is obtained by using the master trigger pulse to gate a time to amplitude converter, which measures the time difference between the pulses from an aperture defining counter in each spectrometer. The result for electron positron pairs obtained using a bending magnet immediately after the target is shown in Fig. 5. The peak corresponding to genuine electron positron pairs is seen above the accidental background in which the 2.5 ns r.f. bunching is clearly seen. Thus, use of the TAC enables the resolving time to be reduced with no risk of losing good events and also allows a good estimate to be made of the accidental rate within this reduced "gate". After it is digitised the TAC information is also

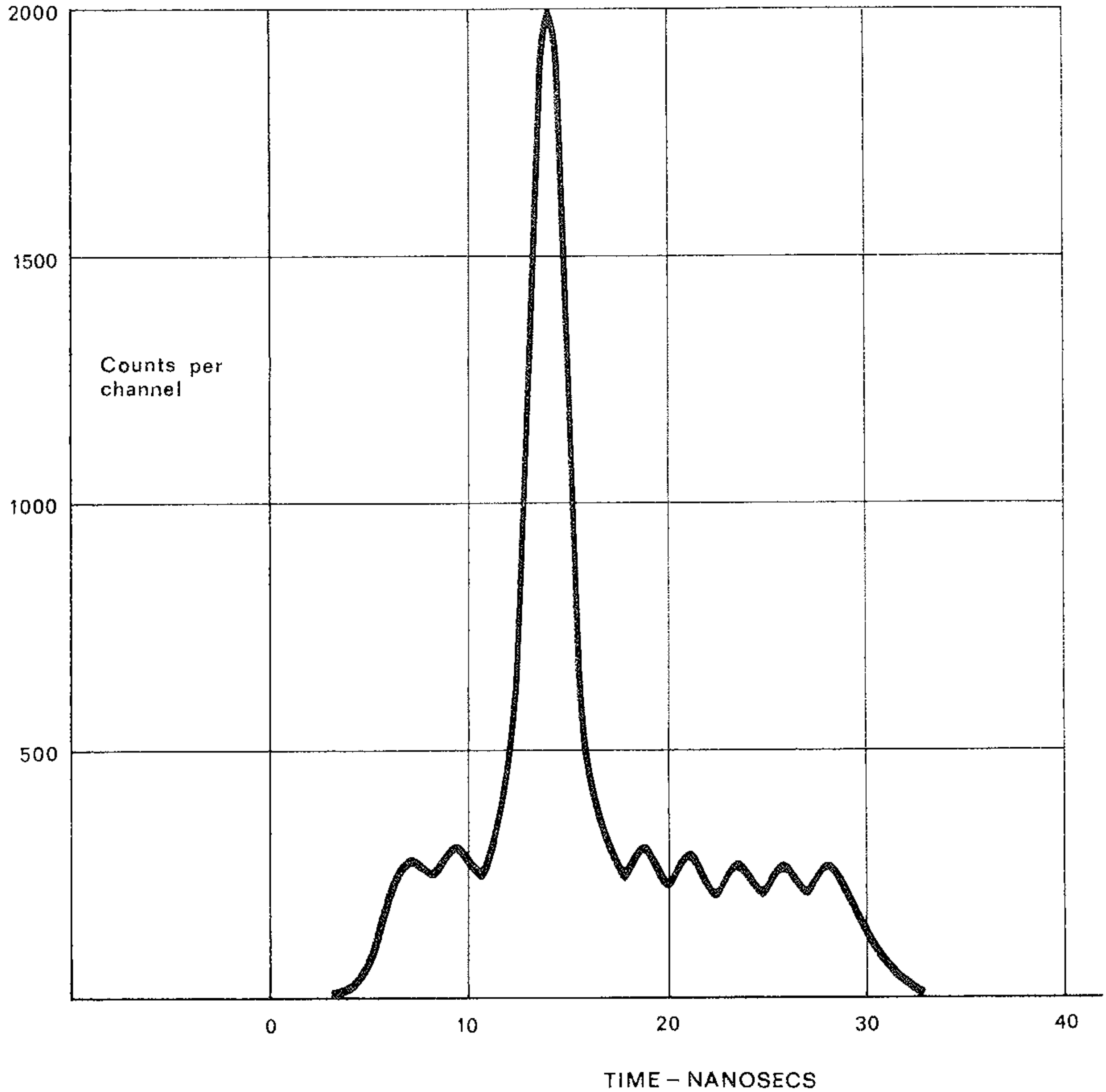

FIG. 5 — T.A.C. SPECTRUM OF ELECTRON POSITRON PAIRS

put into the buffer store. The SEN interface then writes on magnetic tape the contents of the buffer stores together with the contents of a scaler which measures the time relative to the machine cycle at which an event occurs. An event rate of about 30 per second can be handled by this system. To check that the system is working satisfactorily the "signature" of an event is displayed, i.e. the momentum, theta, and phi counters which have been triggered are indicated together with the pulse height produced in the Cerenkov and shower counters. At the end of each run the interface unit writes on the tape the contents of all the visual scalers together with the contents of the twelve multi-parameter units which are manually switched to record the conditions under which the run was taken.

8. K° PHOTOPRODUCTION EXPERIMENT (MANCHESTER)

During this period wire spark chambers were constructed and tested at Daresbury. A triggering system consisting of scintillation counters was set up; a simple coincidence arrangement was found to be adequate to keep the trigger rate down to manageable proportions. A liquid hydrogen target was installed and performed satisfactorily. From November, NINA operated 24 hours per day and the longer continuous periods of running made it possible to test the electronics and computer programmes associated with the spark chambers. A visual display system was installed with the PDP8 computer, allowing continuous checking of the spark chambers. Data was successfully written on to magnetic tape which was analysed in the IBM 360/50 computer. The whole system was shown to detect K° mesons.

The IBM computer was also used to make Monte-Carlo calculations to predict the acceptance of the apparatus. Amongst a variety of electronic developments was a gated integrator, which was designed and constructed for use with the quantameter. The PDP8 computer can now be used to record on magnetic tape the states of the spark chambers, all the counters, the quantameter integrator, the readings of several scalers and the machine energy for each event. It is hoped to complete data-taking on the photoproduction of K°-mesons during the first half of 1968.

9. e-p POLARISATION EXPERIMENT (Fig. 6) (Glasgow-Sheffield Collaboration)

The assembly of apparatus on the proton spectrometer arm, with the exception of the secondary liquid hydrogen target, was completed in September. Prior to this, magnetic measurements were made on the quadrupoles and bending magnets to check their calibration and to determine their magnetic axes relative to their mechanical axes.

As the electron beam was not available at this stage, the photon beam was used to provide a source of particles to test the scintillation counters on the proton arm. It was also found to be possible to make preliminary checks of the spectrometer optics by observing the trajectories of particles in the spark chambers. The energy resolution of the electron shower counter was also checked at this time, using monoenergetic electrons from the DNPL pair spectrometer. The pulse height spectrum had a full width at half maximum of 20% at an electron energy of 2.6 GeV, in good agreement with the expected performance.

The electron beam became available at the end of November, but at this time it was accompanied by a very high level of background radiation. Improvements in focussing, collimation, and steering of the beam and in local shielding were made, and by the end of December conditions were much improved and it was possible to detect electron-proton coincidences between the two spectrometers. The coincidence rate from the CH_2 primary target was found to be within 20% of the calculated rate and the energy spectrum of the protons was also satisfactory. Preliminary tests on the spark chambers showed a reasonably low background with an electron beam of about 1/10 μA incident on a primary target of 2.3 g/cm^2 of CH_2. Work is now proceeding to check the operation of the two spectrometers in more detail.

It is hoped that the secondary liquid hydrogen target will be installed and commissioned by the middle of February, in which case the experiment should be ready to take data by the end of March.

Preparations for analysis of the data are now well advanced and tests have been made on "Cyclops", using single frames. It is hoped that the modifications to enable full lengths of 35 mm film to be scanned will shortly be completed. Satisfactory tests have also been made of the calibration grids, which will be used to correct for optical distortions in the spark chambers. A final survey of the chambers and photographs of the calibration grids will be made after the hydrogen target has been installed.

10. π° PHOTOPRODUCTION EXPERIMENT (LIVERPOOL) (Fig. 7)

The equipment is now functioning well after an extensive series of tests and adjustments. A magnetic tape unit was commissioned in November and is now in use for storage of programmes and data.

The problem of setting up the 49 lead glass Cerenkov counters has been satisfactorily solved by using muons which are produced by stopping the photon beam in a large block of lead. The spray of muons in the forward direction produces pulses of standard size in the glass blocks when the arm carrying this counter is moved into the beam. The rate is about 100 per second in each block.

The various displays provided by the PDP8 computer have been tested with $p\pi^\circ$ events from a polythene target. These show the events rate as a function of (a) proton angle, (b) proton range, (c) the value of incident photon energy calculated from the previous two quantities, (d) the total pulse height from the lead glass counter and (e) flight time of the proton.

The data from the 10 angle counters, the 8 range counters and the 49 lead glass counters, as well as the time of flight is recorded on the magnetic tape for detailed analysis in the 360/50 computer.

The whole system of recording and analysis has been given a preliminary check by using data from targets of polythene and carbon to derive hydrogen differential cross sections by subtraction. The results obtained, in the photon energy region between 800 MeV and 1000 MeV, are in good agreement with previous measurements. The liquid hydrogen target is now in process of installation so that data taking should start soon.

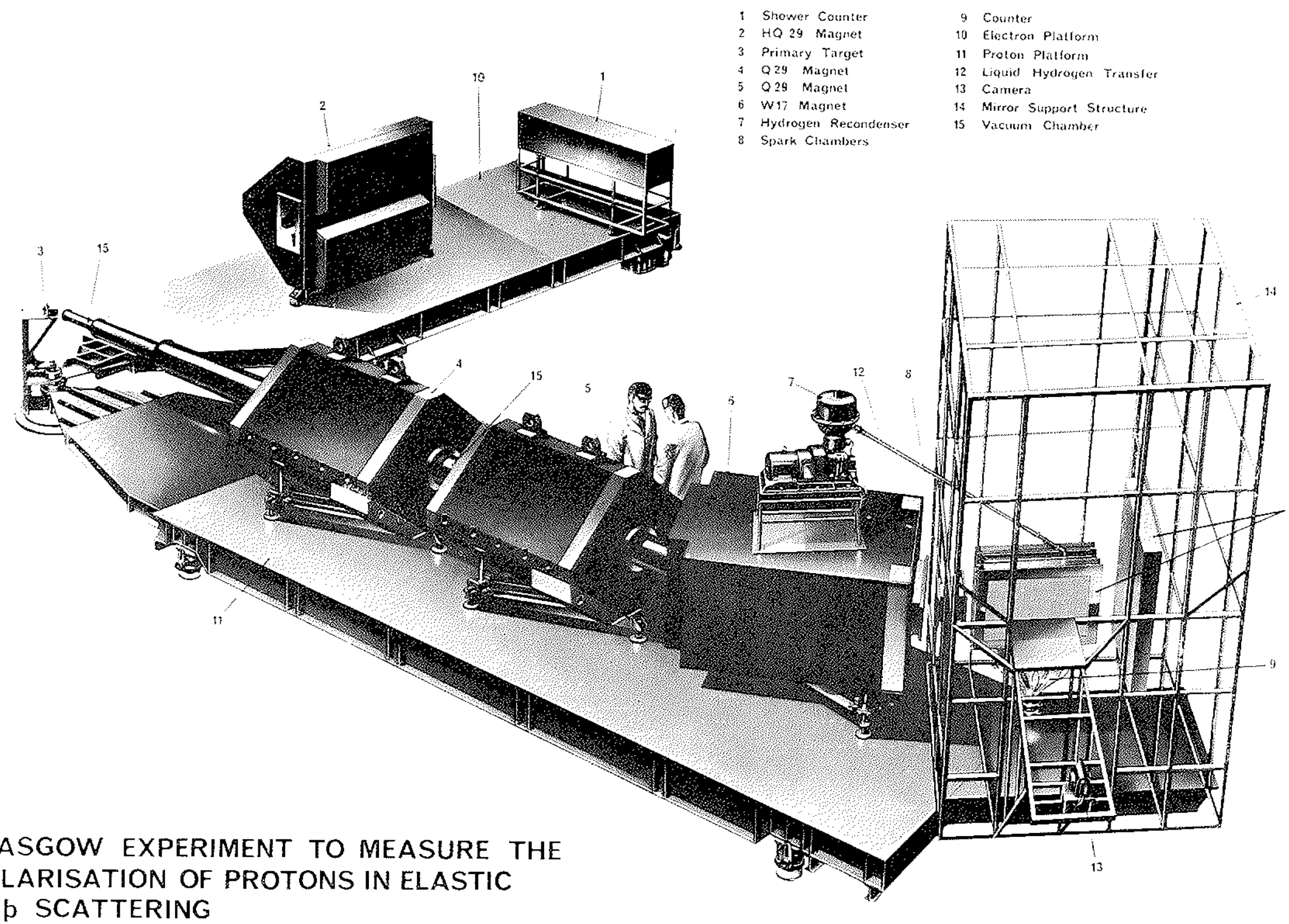

FIG. 6 — ILLUSTRATION OF THE GLASGOW/SHEFFIELD EXPERIMENT

using the Orsay Linear Accelerator. The main object of the experiment is to observe the photoproduction of resonances in the pion-nucleon system, such resonances being copiously produced in pion nucleon scattering. The present experiment is limited by the maximum energy of the Orsay Accelerator to photon energies less than about 1 GeV. By bringing the experiment to NINA, it would be possible to extend the measurements up to photon energies of 4 GeV.

The apparatus (Fig. 8) consists of a 180° magnetic spectrometer capable of measuring pion momenta up to 400 MeV/c. No positive identification of the pion is made since one can show by kinematical reasoning that the proton cannot go in the backward direction, while the number of electrons and other particles at this angle is very small. Monte Carlo calculations are carried out to find the correction for pion decay in the spectrometer. The pions are detected in a scintillation counter telescope and a current mode spark chamber is used to give a momentum resolution of about 0.25%. In order to achieve this momentum resolution it will be necessary to use an extracted electron beam and convert it just before the experimental liquid hydrogen target. The extracted electron beam is swept aside from the target by the spectrometer magnetic field. The mass resolution of the experiment varies between 3 MeV/c^2 and 30 MeV/c^2 for photon energies between 420 MeV and 4 GeV.

An investigation of the feasibility of bringing this equipment to NINA is currently being undertaken by physicists and engineers from Daresbury and Orsay, and it is hoped that this collaboration will lead to successful results in the near future.

13.2 Proposed Collaboration Between DNPL and the Universities of Rome and Pisa

A third group has now been formed at Daresbury and it is proposed that this group collaborates with a group from the Universities of Rome and Pisa to study the electroproduction of pions near threshold by the process $e+p \rightarrow e+n+\pi^+$ with the aim of measuring the pion form factor.

The form of the experiment has not been finally decided but at the moment it is proposed to detect the scattered electron, the pion and the neutron in coincidence and to measure the total cross section for the process at approximately 10 MeV above threshold. The counting rates seem feasible and the pion form factor data extracted for measurements in this energy region should be free from model dependence.

14. PROPOSAL FOR A 15/20 GeV SYNCHROTRON

Consideration of possible developments at Daresbury have led to a serious study being made of a 15/20 GeV synchrotron, which would be injected from NINA. The proposal has been described in a paper* included in the Proceedings of the High Energy Accelerator Conference, held at Harvard in September, 1967.

In NINA a high intensity electron beam of small emittance can be produced, the beam cross-section being smallest at an energy of about 3 GeV (about 1.6 mm vertically × 5 mm radially). At higher energies, quantum radiation effects increase the radial width of the beam. The aperture of a synchrotron injected at 3 GeV could therefore be quite small, say 2.5 cm maximum vertical aperture and 5 cm maximum radial aperture. This, in turn, leads to relatively small magnets, and hence, reasonable cost in spite of the greater number required.

The ring being considered would have a circumference 6 times that of NINA with a magnet bending radius of 120 m, the large radius being needed to keep radiation losses within reasonable bounds. It is proposed to use four 100 m straight sections, two of which would contain 80 m long linear accelerators of the travelling wave type. A third straight would be used for injection and extraction of the electron beam, and, according to the present proposal (Fig. 9), this would intersect NINA and run parallel to the present Experimental Hall so that this could be used also for experiments at the higher energy. This arrangement would cut the cost of the operation considerably, but clearly has some disadvantages in its interaction with the NINA installation.

The r.f. power for acceleration could be either at 816 or 1224 Mc/s, that is, the second or third harmonic of the NINA r.f. Suitable high power amplifiers are available at both frequencies. Preliminary calculations showed that a 15 GeV, 1 μA beam could be obtained with a power of 1.1 MW peak, 300 kW mean, whilst a 20 GeV, 3 μA beam would require 10 MW peak and 1.8 MW mean power.

On the site at Daresbury a large ring could only be constructed by using extensive tunnelling into the sandstone rock of the hillside. Tunnelling costs are not considered excessive, however, and there is the further advantage that the radiation shielding problem would automatically be solved over the major part of the accelerator.

*Crowley-Milling, M. C. and Merrison, A. W.—Proceedings of the 6th International Conference on High Energy Accelerators, 1967, p.A.76.

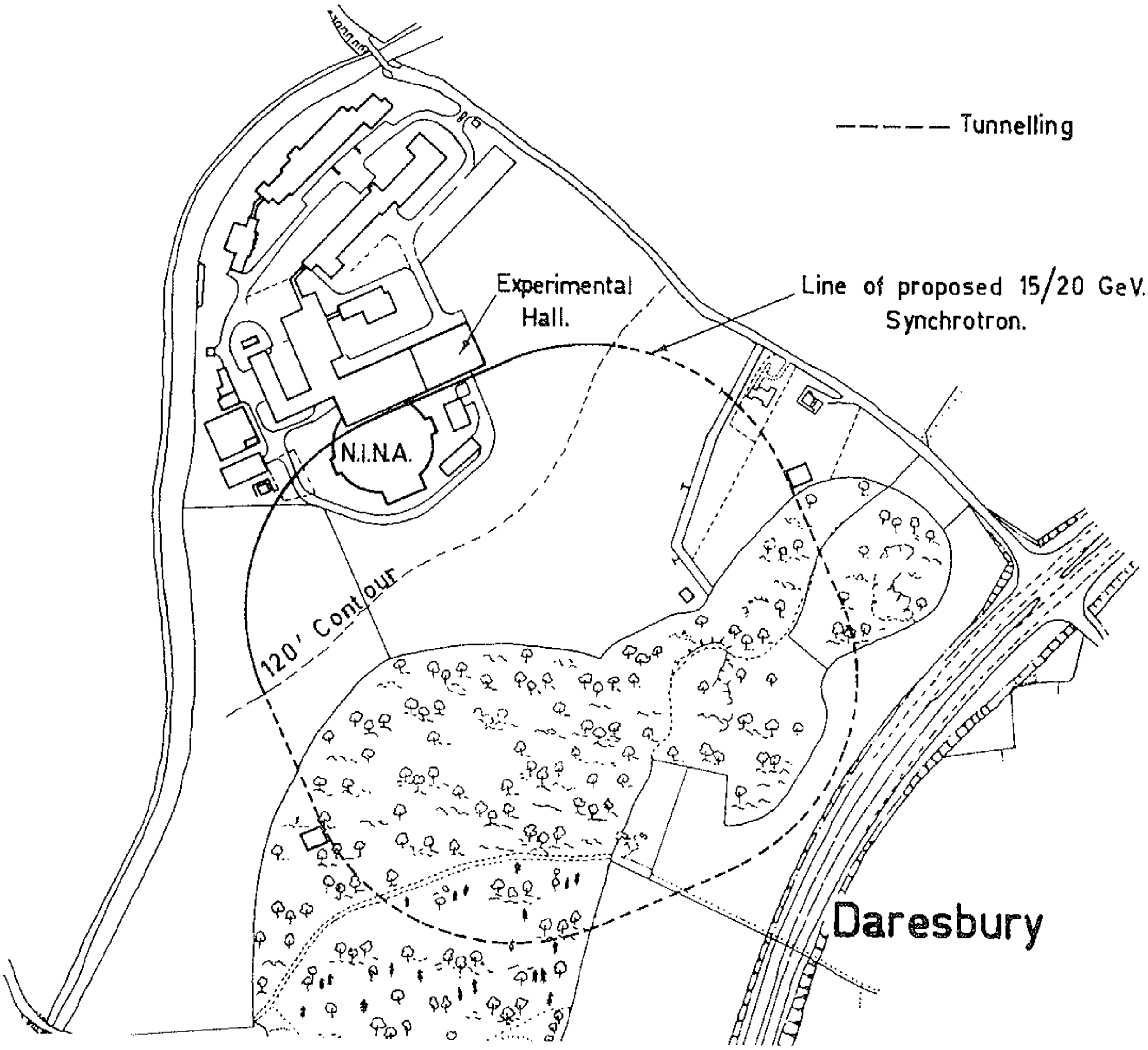

FIG. 9 — PLAN OF SITE SHOWING PROPOSED POSITION OF THE 15/20 GEV SYNCHROTRON

The only justification for considering a large electron synchrotron is, of course, if such a machine would lead to a useful extension in the range of electron and photon physics which could be undertaken. The only machine of comparable energy and intensity is that at SLAC and this has a limitation imposed by an adverse duty cycle. It has been shown that useful fluxes of secondary particles (kaons, pions and anti protons) up to at least 10 GeV/c would be available from even a 15 GeV accelerator. Following a symposium held at the Laboratory in November, physicists are considering the possible range of physics which could be undertaken with such a facility. A preliminary cost estimate for the accelerator, including civil engineering work, yielded a figure of £3.16 millions.

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