THE EXTERNAL PROTON BEAM AT NIMROD

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1. INTRODUCTION

Nimrod, the 7 GeV proton synchrotron at the Rutherford Laboratory, has been in operation for two years. During this time, development of an achromatic extraction system has been in progress, and beam planning is now closely linked with the fortunes of the extracted of the extracted proton beam.

For the past seven months, EPB studies have been inhibited by restrictions on machine energy and repetition rate, (2GeV and 6 sec, instead of the normal 7 GeV and 2.6 sec respectively), pending repairs to the machine alternators. However, beams have been set up in anticipation of normal running from next November, and include two from an external target in the first extracted beam line, EPB1, (labelled P1 in Fig. 2): they are both high-intensity kaon beams for counter work, K_4 and K_6 in Fig. 2. Diagnostic studies have been carried out in these beams under the 2 GeV regime.

During 1966, EPB1 will be rebuilt to provide a separated beam for the 1.5 m hydrogen chamber, and it is hoped to begin installation of a second external beam channel, (EPB2), as shown in Fig. 4. Experiments using external targets should then provide the major part of the physics program on Nimrod.

Finally, as part of a longer term development program, it is planned to build a third EPB line, to serve a completely new experimental area, inaccessible from internal targets. Possible locations are indicated in Fig. 5.

To provide this beam, a second extraction system will be installed, 90° out of phase with the first one serving EPB1 and 2; the appropriate straight sections are free for extraction components.

2. ACHROMATIC EXTRACTION

2.1 Basic Outline

The principle of the achromatic extraction system developed for Nimrod has been described by Bennett and Burren (1): it is shown schematically in Fig. 1, and the location of the relevant elements around the ring may be seen in Fig. 2; they are:

— An energy-loss target, T, brought up on the inner side of the circulating beam. For long-spill operation, a lip on T serves to reduce radial betatron oscillations (2), and causes the inward-spiralling protons to strike the main target cleanly. It also ensures that the equilibrium radii are close together on entry into the main target.

— An extractor magnet, E, plunged from inside the ring. Protons losing energy in T oscillate about a smaller equilibrium radius, enter E near their inmost swing, and are deflected outwards to leave the synchrotron at a selected point around the next octant. The variable field gradient, n_E, is one of the factors permitting achromatic correction.

— A radially-focusing quadrupole, Q, located about midway between T and E, which is also plunged from inside the ring. The quadrupole gradient, k_Q, is the second variable factor in chromatic correction.

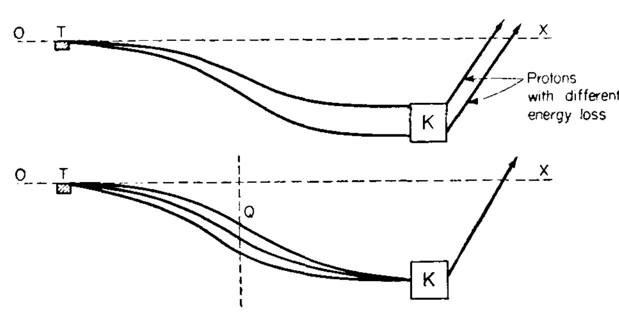

Fig. 1 - Schematic diagrams comparing the normal Piccioni scheme and the achromatic modification.

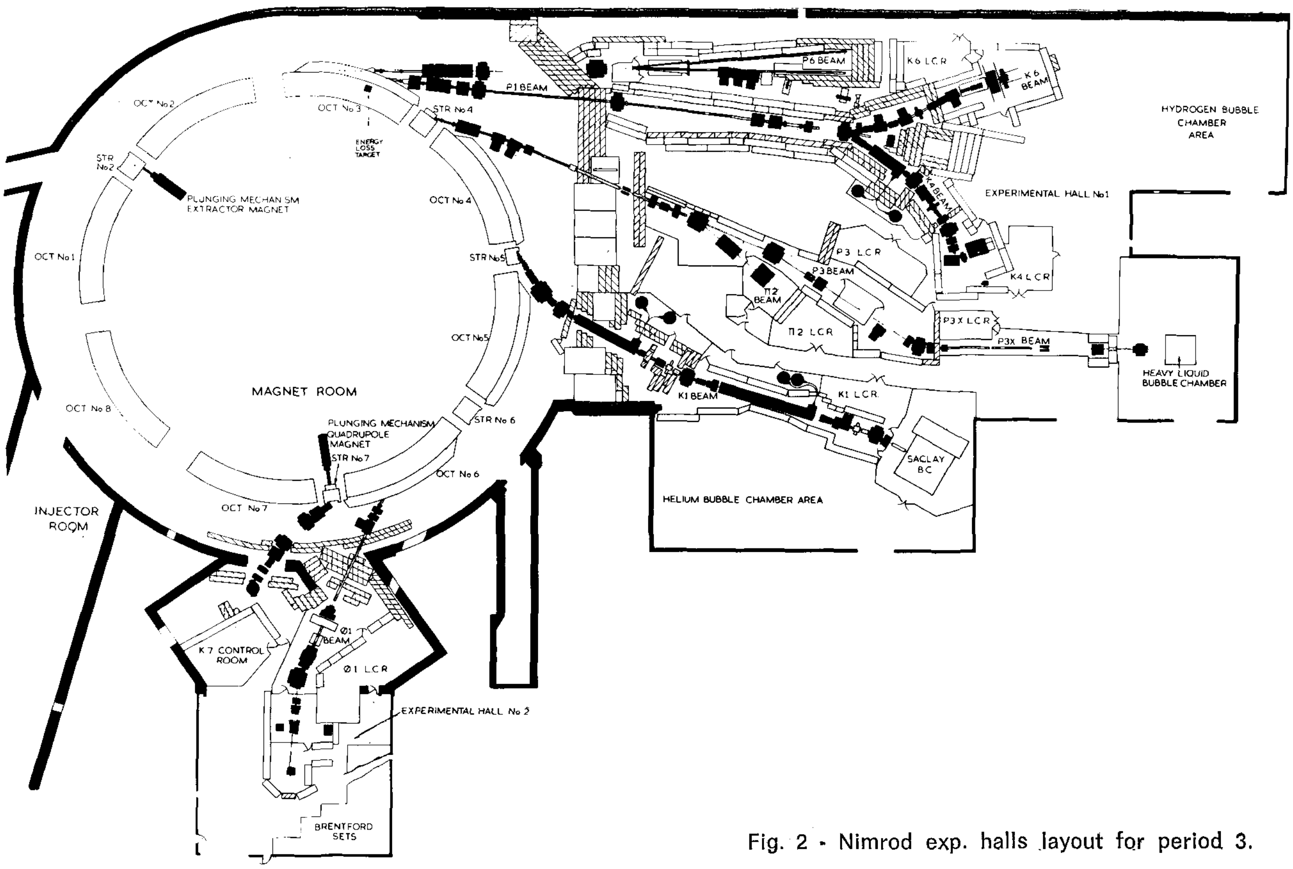

Fig. 2 · Nimrod exp. halls layout for period 3.

The effect is shown by the radial phase plots of Fig. 3: complete achromatism cannot be achieved, but, without correction, the beam would swamp the acceptance of the external transport system. Typical extraction parameters are quoted in Tables I and II for a particular EPB arrangement.

In carrying out the theoretical survey (3) to determine suitable values for k_o and n_E, two different criteria proved useful:

a) The degree of achromatism at exit between central trajectories of different momenta; e. g., phase points such as 1-I, 1-II, etc. in Fig. 3.

b) The divergence contained in the phase space for a single momentum; in general, it is found that minimum divergence implies coincidence of trajectories 2 and 4 in Fig. 3 d.

Contours of equal total divergence for a given range of momenta, plotted on a (k_Q, n_E) chart, also proved helpful, particularly in examining the tolerances on these quantities.

2.2 Extraction System Equipment

Preservation of beam quality requires that the integrated field through E should be known to a precision of 2×10^{-4}, over a range of field levels corresponding to extraction in the range 2 GeV-7.5 GeV. Similarly, the gradient n_E should be known to better than 1%, and should be

TABLE I

Typical parameters at 7 GeV, (14 kG).
Circulating beam and energy-loss target

Circulating Beam:	
Equilibrium Radius, R_0	1878.1 cm
Radial Width	~ 13 cm
Height	~ 6 cm
Radial Betatron Frequency, Q_R	~ 0.67
Vertical Betatron Frequency, Q_v	~ 0.90
Pulse Rate	1 pulse every 2.6 sec
Beryllium Target, T:	
Length × Width × Height	3.25 cm × 3.0 cm × 5.0 cm
Energy Loss	9 MeV $\left(\begin{matrix} +4 \text{ MeV} \\ -5 \text{ MeV} \end{matrix}\right)$
Lip: Length × Width × Height	0.3 cm × 0.5 cm × 6.6 cm
Position: cm from R_0, degrees into Octant 3	(0, 31.63°)
Spill Time	300 — 400 msec

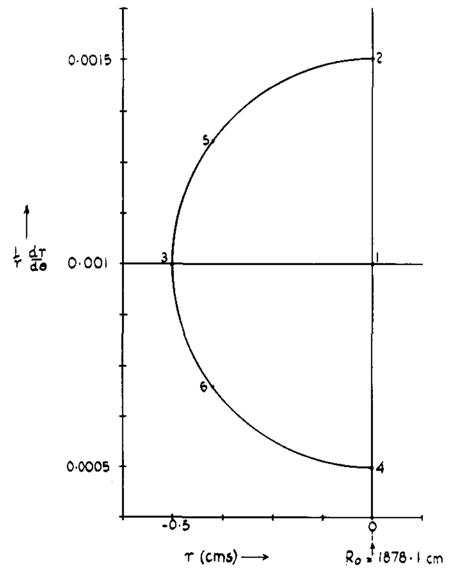

Fig. 3a - Radial phase space at T.

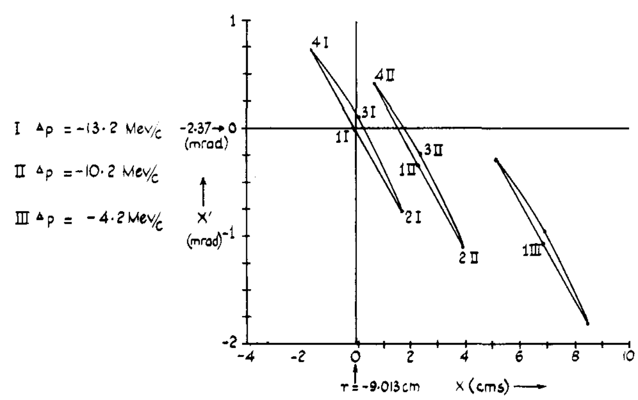

Fig. 3b - Radial phase space after Q.

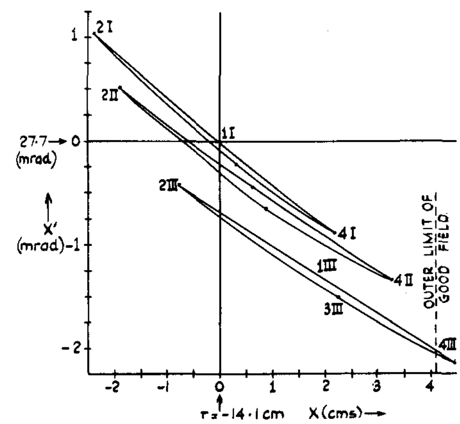

Fig. 3c - Radial phase space after E.

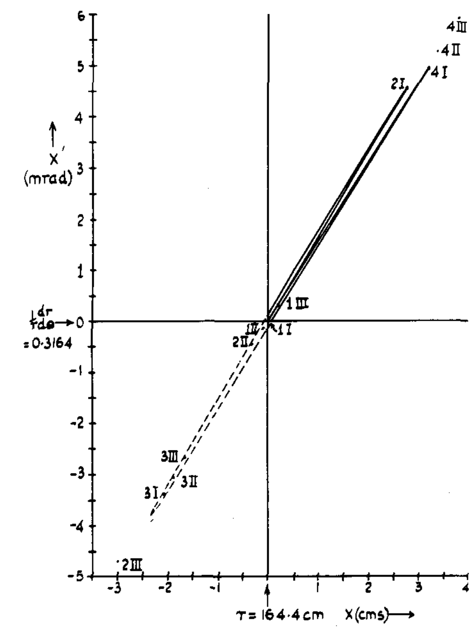

Fig. 3d - Radial phase space at exit of machine.

capable of wide variation. To satisfy these demands, the extractor magnet is fitted with 12 sets of independently-powered pole face windings.

Further, tho prevent closed orbit distortion during the acceleration cycle, the fringe fields of E are minimised by means of an antireluctance winding.

These requirements, together with considerations of radiation damage, vacuum properties, and mechanical stresses due to the plunging duty, place stringent tolerances on the accuracy and quality of manufacture. The coils are insulated by glass cloth, vacuum impregnated with an epoxy resin and hardener choses for their radiation-resistant characteristics, and the whole magnet is contained within a stainless steel casing. Induced activity is likely to be a serious problem, since some 10%-15% of the beam strikes parts of the magnet; levels of up to 5 r/hr have been measured so far, despite the fact that much of the external beam diagnostic work has been carried out at low intensity.

The quadrupole, Q, is a Panofsky-type element of simple construction, but is subject to the same environmental hazards as. E.

The useful radial aperture of Nimrod shrinks from about 91.4 cm at injection to about 30 cm at 7 GeV, so both magnets must be plunged during the acceleration cycle. Weighing 1.0 ton and 0.15 ton respectively, E and Q are each moved through a distance of 51 cm by a hydraulic ram supplied with oil from a variable-delivery pump,

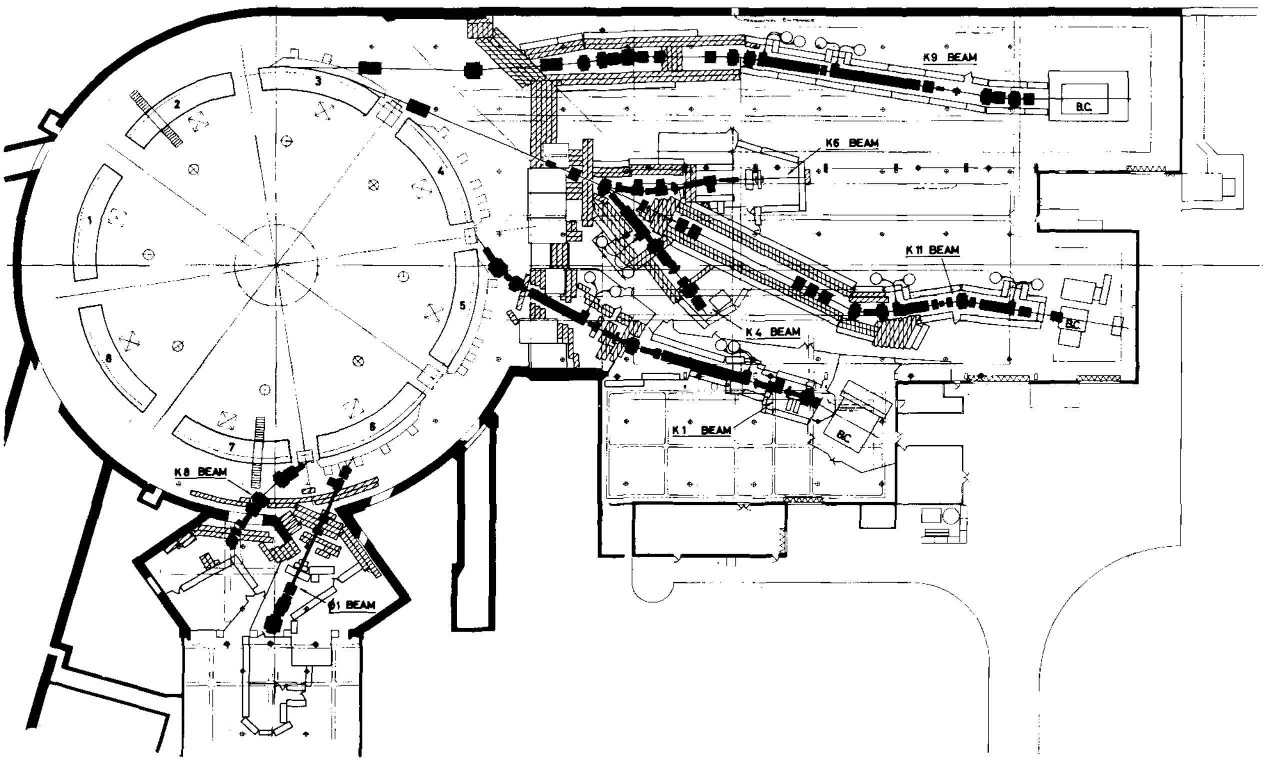

Fig. 4 - Provisional layout for 1966-67.

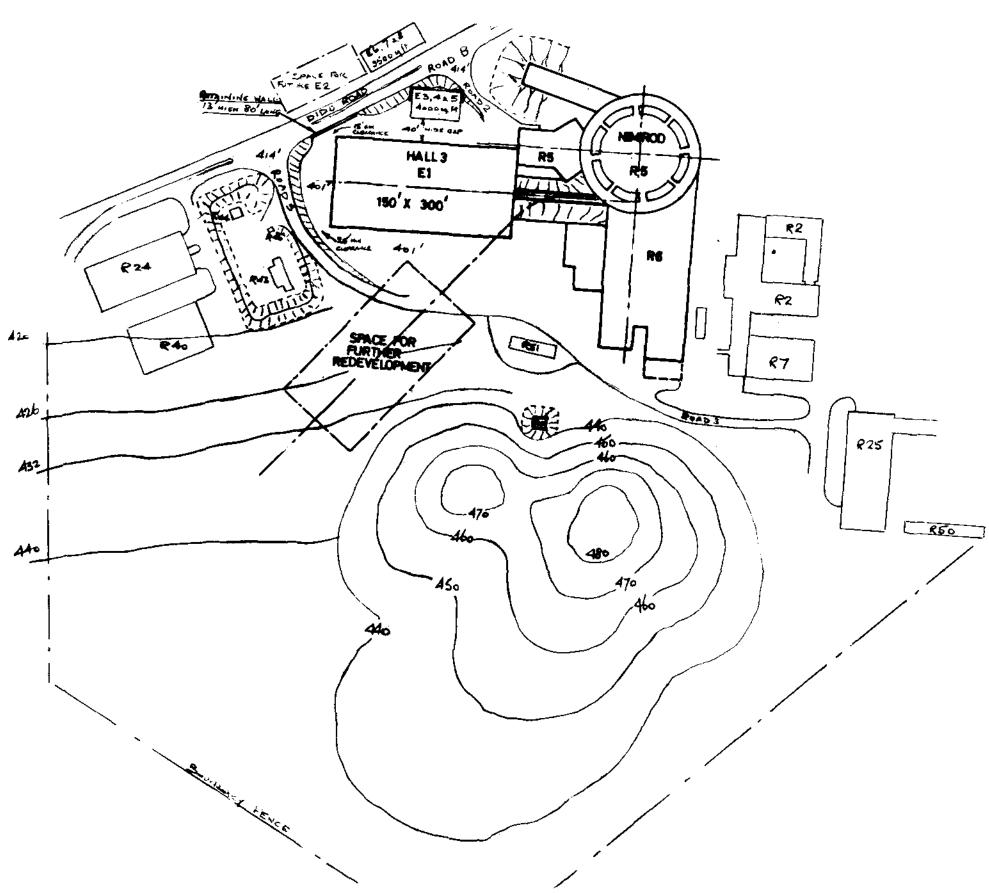

Fig. 5 - Provisional layout of new experimental hall (scale 1/1250).

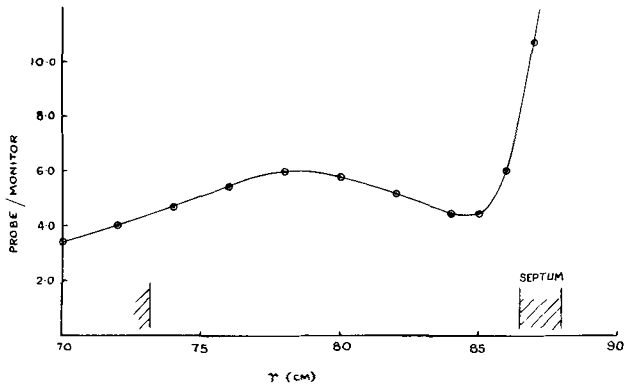

Fig. 6a - Horizontal profile of beam at Q.

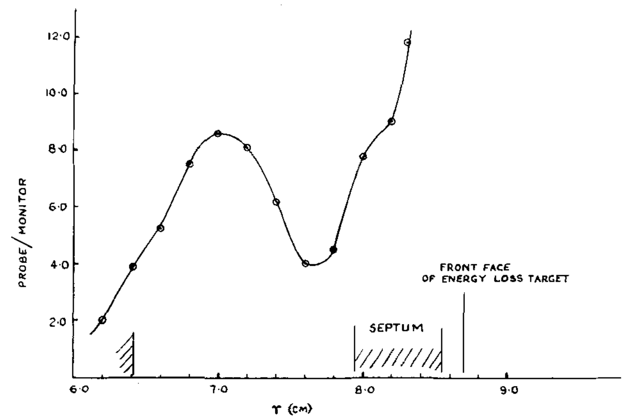

Fig. 6b - Horizontal profile of beam at E.

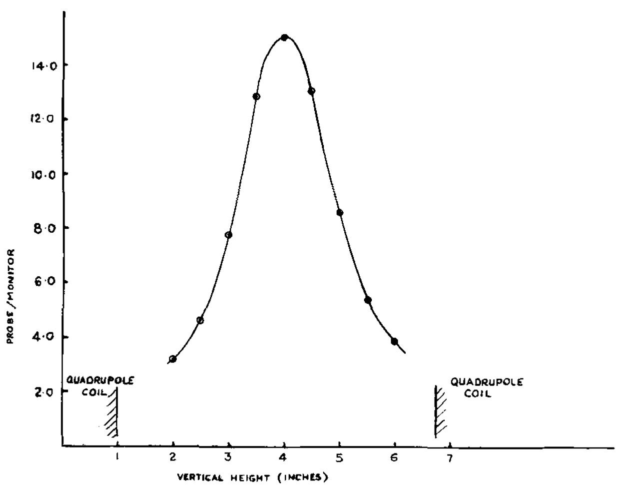

Fig. 6c - Vertical profile of beam at Q.

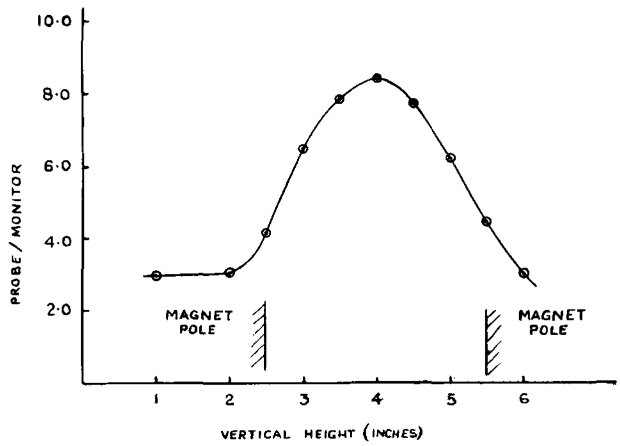

Fig. 6d - Vertical profile of beam at E.

(" swash-plate " pump). The latter is controlled by comparing an error signal from a slide wire, indicating magnet position, with a program signal, and adjusting the swash angle, (and hence the flow of oil to the ram), accordingly (5). Plunging times of 0.5 sec and 0.35 sec have been achieved using one pump and two pumps respectively. The two mechanisms installed in Nimrod have completed over 10^6 cycles during actual operation, and a reserve mechanism has recently achieved the same figure over a three week test period, with 97.5% operating efficiency.

2.3 Targetting

For slow spill operation, (typically 400 msec), the spiral in rate of the beam is only about 2×10^{-5} cm/turn, and the target lip dominates the process: the spread of equilibrium radii for all particles entering the main target is small compared with the effects of Landau spread in energy loss. (Fig. 10 illustrates a typical curve of target penetration during slow spill).

However, for fast spill, (say 200 μsec), the spiral-in per turn becomes comparable with the jump induced by the lip, and the resulting spread of equilibrium-radii at target entry may be as much as the half-width of the circulating beam. This effect is more serious than the Landau spread, and the downstream beam quality degenerates.

A technique of overcoming this effect is currently under investigation. The circulating beam is held on fixed radius by the r.f., just outside the target, so that the distribution of equilibrium radii is determined by the (few MeV) width of the fish. By exciting betatron oscillations, the particles are shaken out and strike a lip-less target, so that subsequent spread in equilibrium radii is due only to the Landau effect. The oscillations are excited by means of a coil comprising the inductance of a tuned circuit, located in a straight section. It is hoped to obtain spill times of less than 500 μsec.

2.4 External Focusing

At exit from Nimrod, EPB1 appears to be diverging from effective sources about 6 m back in both planes. To prevent further blow-up, the beam is turned roughly parallel, as soon as possible, by a quadrupole doublet (4), and in this condition, it may travel some 30 m before further blow-up becomes serious. At a suitable point, a second doublet is used to create a double focus.

In the early studies, these first two doublets were located close together, to create a focus in front of the main shield wall. More recently, the parallel beam has been brought out through the shield wall into the experimental area, to be focused on to the K_4/K_6 target, as shown in Fig. 2.

3. PRACTICAL EXPERIENCE

3.1 Diagnostics in the Extraction System

Several techniques have been used to determine the beam characteristics before it leaves the syncrotron. For example, Fig. 6 shows typical horizontal and vertical profiles measured by deploying scintillating probes in front of Q and E. The measured beam sizes are in reasonable agreement with theory.

TABLE II

Typical parameters at 7 GeV, (14 kG): extraction system elements

Extractor Magnet, E	
Length × Width × Height	85.7 cm × 48.3 cm × 45.7 cm
Magnet Length	75.0 cm
Septum Thickness	5.715 cm
Aperture: Width × Height	15 cm × 7.6 cm
Weight	~ 1 ton
Field × Effective Length	70.96 kG. cm
Field Gradient, N_E	0.217 kG/cm
Distance of Centre from R_0	−14.5 cm
Exit Angle of Beam, w.r.t. St. Section 3	16.05°
Maximum Plunging Capability	50 cm in 0.35 sec
Quadrupole Magnet, Q	
Length × Width × Height	76.2 cm × 32.4 cm × 31.1 cm
Septum Thickness	1 cm
Aperture: Width × Height	13 cm × 13 cm
Weight	~ 0.15 ton
Field Gradient × Effective Length	10.3 (kG/cm) × cm
Distance of Centre from R_0	−9 cm

Attempts to use same techniques close to exit from the machine have not proved satisfactory so far, probably due to background in the long light-guides.

Alignment of the target and plunging magnets was achieved by allowing the circulating beam to spill on to each element in turn, and adjusting each element radially until the times of spill were identical. This procedure accounts for pospossible closed orbit distortions, and gives an estimated alignment accuracy of 5 mm.

Absolute estimates of proton flux have been made with foil activation techniques, both the Al^{27} (p, 3pn) Na^{24} and Au (Tb^{149}) reactions being used. The latter is particularly useful, the threshold energy being 500 MeV. Foil activation has also proved useful in determining target penetration depths, (cf. Fig. 10).

TABLE III

EPB-1 performance at 2 GeV

Extracted Beam Intensity	1.2×10^{11}, per 10^{12} circulating
Protons Entering Energy-Loss Target	6.8×10^{11}, per 10^{12} circulating
Effective Target Efficiency	68%
Effective Extraction Efficiency	18%
Spot Size at K_4/K_6 target	20 mm Vertical × 7.5 mm Horizontal

3.2 Diagnostics in the External Beam

Initial search for the beam at exit from Nimrod was carried out using a hodoscope consisting of ten independent scintillator "fingers", about 1 cm wide. The signal from each finger is integrated and displayed on an oscilloscope with a staggered time base. The device may be set up to give either a vertical or horizontal profile, and has proved valuable in both wide and focused beam situations, depending on the orientation of the elements to the beam axis. Typical results are shown in Fig. 8. Minimum resolution is about 2 mm.

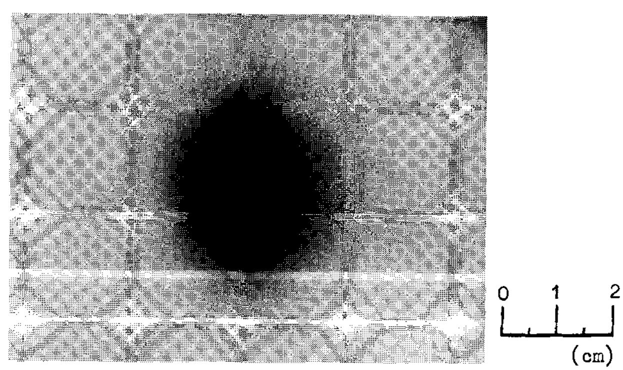

Fig. 7. - X-ray film of focus at K4/K6 target.

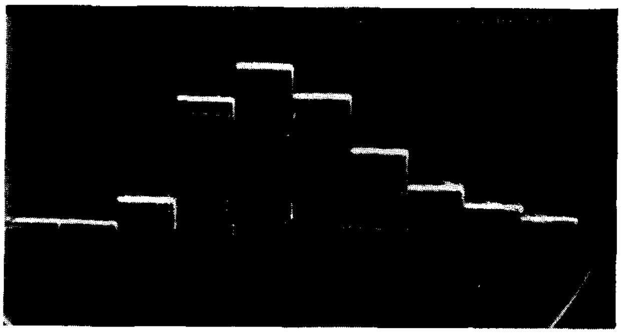

Fig. 8a - Extracted beam at exit of Nimrod displayed on hodoscope.

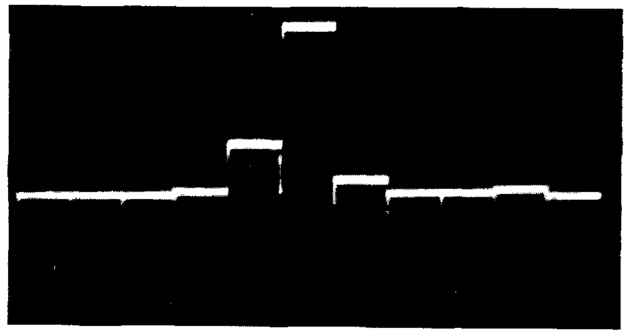

Fig. 8b - Extracted beam at K4/K6 focus. - Hodoscope mounted at 60° to beam direction.

Initial studies at the beam focus were done using a large scintillator viewed by a TV camera, and also using X-ray film (cf. Fig. 7). More accurate analysis involved,

the hodoscope described above, and,

a strip ion chamber operating at atmospheric pressure, with a resolution of 1 mm.

Typical profiles at the K_4/K_6 target focus are shown in Fig. 9. Further development of these techniques is planned for routine beam monitoring.

Relative intensity measurements have been made using ion chambers, variable pressure operation permetting adeguate sensitivity without saturation over a wide range of intensity. Absolute measurements were carried out using aluminium and gold foils. This work has come to fruition since Nimrod was restricted to 2 GeV; at this energy, the following values represent the best conditions achieved so far.

The low target efficiency is not understood at present. The low extraction efficiency of 2 GeV may be explained by multiple scattering effects in the target and by changes in the shape of the Nimrod field; these effects do not scale with energy. It is anticipated that extraction efficiency will improve when the machine reverts to 7 GeV operation.

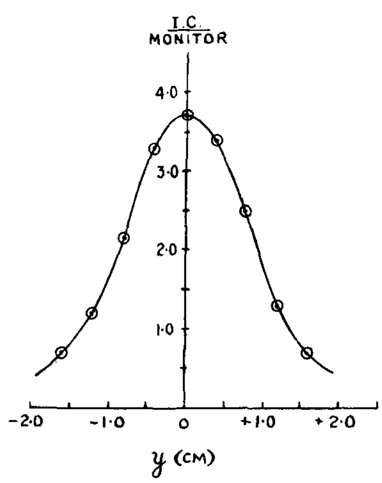

Fig. 9a - Vertical profile of extracted beam at K4/K6 target.

Finally, the spot sizes quoted above are considerably larger than the predicted values, probably due to scattering in air and window material in the EPB line.

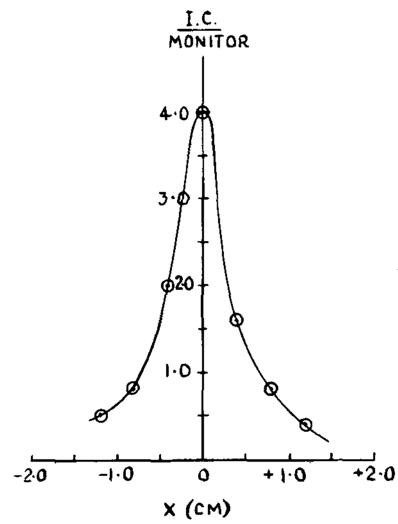

Fig. 9b - Horizontal profile of extracted beam at K4/K6 target.

3.3 Radiation Problems

Radiation poses a serious problem in extracted beams, and the necessarily large quantities of shielding material restrict freedom of secondary beam layout. The shielding parameters for the current arrangement, (cf. Fig. 2), are:

Side Walls	: 4 ft steel + 2.5 ft concrete
Roof	: 2 ft steel + 2.5 ft concrete
Radiation Level on Roof	: ~ 25 mr/hr, per 10^{11} protons on target
Radiation Level on Side Walls	: < 1 mr/hr

This is quite adequate under present conditions, but may not be so satisfactory for operation at 7 GeV with enhanced intensity.

4. SECONDARY BEAM PLANNING

4.1 Advantages of EPB

Internal target operation at Nimrod suffers from disadvantage in two main aspects:

— *Positive beams* may only be provided at production angles of 20° or more; this generally results influx losses of order 10 compared with beams from the forward direction.

— *High Intensity Kaon Beams.* Restrictions of the synchrotron magnet and building geometries lead to diminished acceptance and increased beam length, compared with beams from external targets. This is a particularly serious problem with separated beams for bubble chambers. These considerations provided the initial impetus to EPB development at Nimrod.

Further, and extracted beam offers attractive possibilities in the realm of target sharing, implying more efficient use of the accelerated protons

4.2 Sharing from One External Target

In current practice, sharing from a single external target is restricted to two beams of opposite charge sign, because of layout difficulties with standard beam components. The existing layout is shown in Fig. 2: K_4 is a 0.7 GeV/c separated beam, providing stopping K^+ for studies of rare decay modes; K_6 provides K^- in the range 0.7-2.4 GeV/c to measure K^-p and K^-n total cross-sections. Rates in both beams are expected to be about 1000 kaons/pulse at the experiment.

The K_4/K_6 target is located at the entrance of a bending magnet, to divert the secondaries to either side of the on-going EPB, which may then be re-captured and focused on to a downstream target. Momentum is varied in K_6 (without disturbing K_4) by means of a correcting magnet following immediately after the common magnet. Particles of different momenta are steered along the beam axis, providing that a small variation in production angle is accepted, (less than 10° to cover the 0.7-2,4 GeV/c range).

4.3 Targets in Sequence

At present, the on-going EPB is focused onto a backstop, but future planning involves its deployment on a second, downstream, target. This is the arrangement sketched for EPB2 in Fig. 4. Estimates suggest that only about 10% of the protons survive the first (thick) target in a state to be successfully recaptured. Hence, simultaneous experimentation from both targets may not be generally feasible. However, setting-up may be carried out from the downstream target while the upstream experiments proceed.

Further, the possibility of EPB sharing between the two targets cannot be excluded. This would involve splitting the internal beam spill, synchronised with fast withdrawal of the upstream external target. That is, the sequence during a pulse could be:

— Upstream target in position
— Given fraction of circulating beam spilled slowly
— Circulating beam brought off energy-loss target
— Upstream target withdrawn
— Remainder of beam spilled fast for downstream target.

Similar split spill procedures will be required for the systems described below.

4.4 Beam Switching

In cases where the secondary momenta are so high as to prevent reasonable layout of two beams from a single target, or where the required range of secondary momenta in either beam is too wide, the possibility of using a pulsed "beam-switch magnet" may be considered. This would be cabable of switching the EPB to right or left during a pulse, (in conjunction with split spill from the energy loss target). This situation may arise in EPB1 where the bends in the secondary beam, K9, are necessarily small, (cfr. Fig. 4) K9 is intended to provide P^+ and $\pi^\pm$ over a wide range of momenta up to the maximum possible, (8 GeV/c and, say, 6 GeV/c respectively), as well

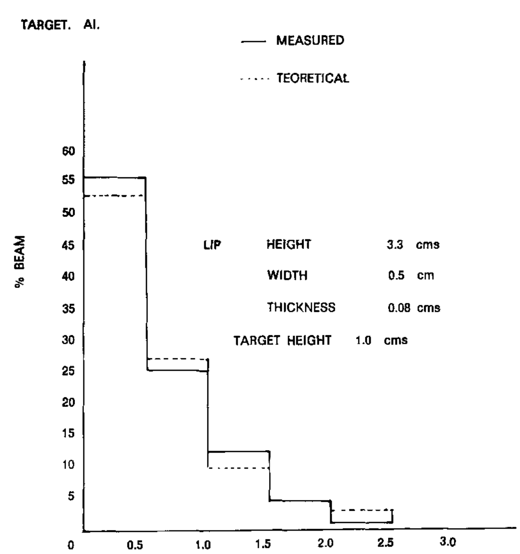

Fig. 10 - Targetting efficiency.

as $K^{\pm}$ in the range 2-3 GeV/c, for the 1.5 m hydrogen chamber. The beam switch would be located at a focus in EPB1 to conserve aperture, and each branch would be re-focused on to its appropriate target.

Switching between two separate EPB channels, such as EPB1 and EPB2, is similar in principle; the switching is accomplished by a change in field of the extractor magnet itself. Tests are under way to determine whether variation of current through the pole face windings of the existing magnet will be sufficient to accomplish the switch.

4.5 Beam Transport Equipment

For all the above techniques, special septum bending magnets and quadrupoles of "figure-of-eight" design would considerably ease the design problems, allowing chosen beam packing, and reducing scattering of the on-going protons. Some elements of these types have been specified, and are about to be ordered.

The authors wish to record their acknowledgements to R. G. T. Bennett and J. W. Burren, who were responsible for the concept of achromatic extraction. Their thanks are also due to M. R. Harold, R. L. Redgrave, R. C. Rowe and M. J. Sheehan, who have assisted with different aspects of the experimental programme.

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THE EXTERNAL ELECTRON BEAM OF THE FRASCATI ELECTRON SYNCHROTRON

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I. THEORETICAL INTRODUCTION

In order to acquire slow extraction of the beam from cyclic Accelerators with high efficiency, low emittance and small momentum spread, the radial betatron oscillations must be brought into resonance (1-6). Long spill out times, otherwise, are achieved by means of nonlinear perturbations.

In the following discussion we will limit ourselves only to Constant Gradient Synchrotrons. As it has been shown by one of us (A. T.) (7), the most convenient resonance to get the above mentioned important features is the $\nu_r = 2/3$ one (consider also references (3-5). The corresponding $\Delta n(x, \Theta)$ perturbation to be introduced must have the following form:

$$\Delta n = \left(\frac{dn}{dx}\right) x^2 \sin 2\theta \quad ; \qquad [1.1]$$

$$\left(\frac{dn}{dx}\right) = \text{constant}, \quad \left|\left(\frac{dn}{dx}\right) x\right| \ll \langle n \rangle$$

If the Synchrotron is a circular one, the resulting equation of the particle motion

$$\frac{d^2x}{d\theta^2} + (1 - \langle n \rangle)\, x = \frac{1}{2}\left(\frac{dn}{dx}\right) x^2 \sin 2\theta$$

$$\langle n \rangle = n_{re} + \delta$$

$$n_{res} = 5/9 \qquad [1.2]$$

$$|\delta| \ll \left|\left(\frac{dn}{dx}\right) x\right|$$

can be integrated by the method of Krilov and Bogoliubov. The first approximation solution is