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SECTION 7

EXTRACTION SYSTEMS AND INTERNAL TARGETS

7.1. Slow Extraction System

7.1.1. Principles of Operation

(a) Review

The aim of the proton extraction system is to produce an external beam which contains an appreciable fraction of the accelerated protons and which can be focused with quadrupole lenses to a small image at a target. Small images are particularly necessary when using electrostatic separators in the secondary particle beam.

The basis of the system is that used on the Cosmotron (1,2). A target of a light material is used and the beam is moved towards the target to strike the "lip" (3) - a thin piece of the target standing proud of the main body. This lip reduces the amplitude of the radial betatron oscillations, reduces the energy spread of protons entering the target and also ensures that they traverse the whole target. The energy loss produced by ionization in the target causes the proton to take a new path, oscillating now about a mean orbit which is at a smaller radius than the target. Approximately at the innermost part of their oscillating path, the protons pass through the aperture of a magnet whose field deflects them outwards again. The deflection given is sufficiently large for the protons to travel right across the aperture of the machine and emerge as an extracted beam.

In emerging from the main magnet the protons have to pass through the fringe field which is defocusing in the radial direction and causes the beam to diverge. In the "Cosmotron" this divergence is counteracted by "extraction shims" attached to the outside of the magnet which reshape the fringe field in the region of the beam.

Preliminary calculations revealed that on Nimrod such a system would result in a beam which was too large to be accommodated by standard quadrupoles (mainly because of the larger machine radius) and also that it would be difficult to ensure good enough beam optics in the fringe region (even using special lenses) to allow the beam to be focused to a reasonable spot in the horizontal direction.

The first modification investigated consisted of incorporating a field gradient which was radially focusing in the deflecting magnet. (This was independently suggested by Gan'zhin (4)). This improved the beam considerably but not as much as was desirable. The beam at the magnet M (see Fig. 7.1.1(i) is spread out due to the variation of energy loss in the target (5) and is diverging due to the scattering of the protons in the Coloumb fields of the nuclei in the target (6) (the target is imaged at the extractor magnet). Hence while a focusing magnet can improve the situation with regard to the first effect it is unable to affect the second. A compromise by placing the magnet at a different position is not significantly better than the placing shown in Fig. 7.1.1(i).

(b) The Nimrod System

In the system designed for Nimrod (6) an additional element, a radially focusing quadrupole, is introduced between the target and the magnet and by suitably adjusting its strength the system can be made achromatic, i.e. the effect of differences in energy of the protons after leaving the target is eliminated by the time they reach the magnet (presuming, of course, that the energy losses will allow them to pass through the available apertures of the elements). The target is not now imaged at the magnet, rather the scattered protons are diverging, and the gradient of the magnet is adjusted to produce a focus in the region of the fringe field (Fig. 7.1.1(ii)). Calculations indicate that the beam should have a small diameter in the fringe field, expanding again to a few centimetres outside the machine where it can be refocused by quadrupoles.

As described so far the distances between the target and the quadrupole and between the quadrupole and the magnet would be equal but, because the path from the magnet to the fringe field is in the magnet, further momentum resolution takes place. This can be allowed for by increasing the target-quadrupole distance and by reducing the field in the quadrupole, which leaves the beam not quite corrected at the magnet but achromatic again at the exit.

The vertical motion has so far been ignored. It is not possible to control this independently within the scope of the scheme outlined, but it is found that the motion is contained within reasonable vertical apertures in the magnets and since the fringe field is focusing for vertical motion, the beam is small enough to go into the external quadrupoles. The approximate shape of the vertical profile is indicated in Fig. 7.1.1(ii).

7.1.2. Practical Considerations

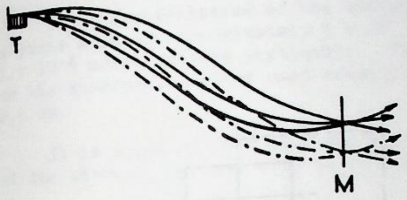
In order that the extraction system should work in the manner described it is necessary that the properties of the machine magnetic field be reasonably uniform in the region where the protons are travelling from target to magnet and this implies that the magnets are within the radial range of what is known as the "good field region", although they are, of course, located in straight sections. At high fields, after acceleration, the circulating beam will have shrunk to a narrow radial width within the "good field region" but the whole of the aperture is used at injection and consequently the extraction system magnets must be "plunged". The magnets are withdrawn at the start of the acceleration cycle and rapidly pushed into position for extraction. The target must also be moved in a similar manner but it is small and is raised up from the bottom of the vacuum vessel.

7.1.3. Apparatus

The target consists of a 3.25 cm long beryllium block which is erected to beam height by one of the Mark 1 target mechanisms described elsewhere in this report. (section 7.4.).

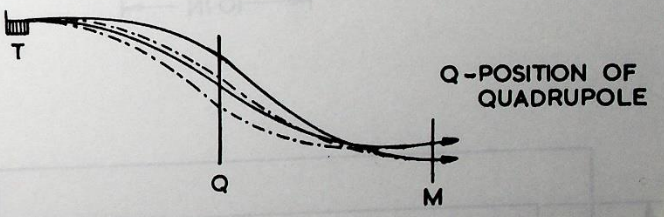
The quadrupole must be placed very near the circulating beam and yet must have a usable aperture only a few centimetres away since on the average the energy loss in the target causes the protons to change their orbit by only a few centimetres. A conventional quadrupole is not satisfactory in this respect and a current sheet quadrupole (7, 8) is used.

The extraction magnet which will be installed initially is of conventional C-shaped design and has a usable radial field of 9 cm. The ratio of the gradient to the magnet strength is fixed by the angle of the pole pieces. It would be

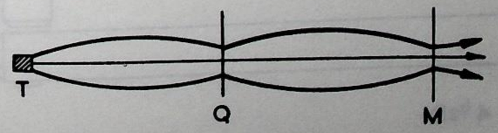


T - Target. M - Position of Magnet
The chain linked lines represent the paths of protons which have lost energy in the target compared with other protons following the solid lines

Fig. 7.1.1 (i) Piccioni System



(a) RADIAL PATHS



(b) VERTICAL PATHS

Fig. 7.1.1 (ii) Paths of Protons, Nimrod extraction system.

7.2. Kicker for Fast Beam Extraction

7.2.1. Principle of Operation

In addition to the slow extraction system described in section 7.1, fast extraction (about 50 μs) is required. A kicker coil is used to distort the closed orbit so that protons hit a target and are moved into the same channel as in the slow extraction case.

The radial motion of the proton beam is given by:-

$$\begin{vmatrix} y \\ \dot{y} \end{vmatrix} = \begin{vmatrix} \cos 0.71\phi & \dfrac{\sin 0.71\phi}{0.71} \\ -0.71 \sin 0.71\phi & \cos 0.71\phi \end{vmatrix} \begin{matrix} y_o \\ \dot{y}_o \end{matrix}$$

where ϕ is the angle of rotation of the protons past the kicker coil and the factor 0.71 is Qr for Nimrod with an n of 0.6.

For a closed orbit: $\phi = 360^\circ$, $y = y_o$ and $\dot{y} = \dot{y}_o - \delta$.
If the change in divergence is δ cm per radian the equation of the perturbed orbit is:-

$$y = \frac{\delta}{1.12} \cos 0.71 \; (\phi - 180^\circ) \text{ cm}$$

The factor 1.12 comes from $\sqrt{\frac{Rm}{Ro}}$ where Ro = radius of curvature of the magnet octants

$$Rm = R_o + \frac{L}{2\pi}$$

L = total length of straight sections.

At the coil ($\phi = 0$) the perturbation is $-0.55\,\delta$ cm, while at the Piccioni target ($\phi = 122^\circ$) it is $0.67\,\delta$ cm (= Y), where:

$$\delta = \frac{\int Bdl \text{ (through coil)}}{Bo \text{ (in machine)}} \text{ cm}$$

For the coil to be effective, the beam must be deflected through at least half its width at the Piccioni target, i.e. $Y = \frac{1}{2}\text{ width} = 0.67 \dfrac{\int Bdl}{B_o}$ cm

$$\therefore \int Bdl = \frac{B_o \times \frac{1}{2} \text{ width}}{0.67} \text{ gauss cm}$$

TABLE 7.2.1(I)

Beam Energy T (GeV)	B_o (gauss)	Beam $\frac{1}{2}$ width (cm)	Required $\int Bdl$ (gauss cm)
8	15,800	7.2	170,000
7	14,000	7.6	158,000
6	12,200	8.0	146,000
5	10,400	8.5	132,000
4	8,600	9.3	119,000
3	6,800	10.2	104,000
2	5,000	11.7	87,300
1	3,000	14.7	65,800

Theoretical values of $\int Bdl$ can be calculated from the field produced by four parallel wires, with a current I flowing through them. The horizontal distance between the wires is 2W and the vertical distance between them 2H.

Then at the centre of the four wire array there is a vertical field only, as the horizontal components of field cancel out.

The field per unit length of the coils is $B = \frac{I}{10} \left(\frac{2}{\sqrt{W^2 + H^2}}\right) \left(\frac{4W}{\sqrt{W^2 + H^2}}\right)$

$$= \frac{4}{5} \cdot I \left(\frac{W}{W^2 + H^2}\right)$$

For coils S cm long:- $\int Bdl = \frac{4}{5}\; SI \left(\frac{W}{W^2 + H^2}\right)$

In practice the coils are two loops of copper-tube, of cross-section $4\frac{1}{2}$ in x $2\frac{1}{4}$ in and of overall length 5 ft 2 in and width 1 ft 7 in. The vertical distance between the centres of the loops is variable between $12\frac{1}{2}$ in and $16\frac{1}{2}$ in (see Fig. 7.2.1(i)). The current I through the coils is produced by discharging a condenser bank through the coils.

Theoretically all the stored energy in the condensers is transferred into magnetic field energy in the inductive coils:-

$$\tfrac{1}{2}CV^2 = \tfrac{1}{2}LI^2.$$

So :-

$$I = V\sqrt{\frac{C}{L}}$$

$$\therefore \int Bdl = \frac{4}{5}\; S. \left(\frac{W}{H^2 + W^2}\right) V\sqrt{\frac{C}{L}}$$

This is a theoretical maximum field which takes no account of ohmic resistance power losses in the coil and leads, and inductive losses in the leads. Also the coils are not parallel wires but rectangular cross-section copper loops.

The coils are placed in straight section 1 of Nimrod and are connected in series electrically, with one coil above the beam and one below it.

Not only can the distance between the coils be varied as described above but the radial position of the coils is also adjustable.

7.2.2. Powering circuits

The coils are powered by discharging a capacity of 500 μF (charged to a voltage which is variable up to 12 kV maximum) through ignitrons in series with them. The oscillation voltage across the coils is clamped by using more ignitrons and damping resistors (see Fig. 7.2.2(i)).

The capacitor bank consists of 50 capacitors each of which is 10 μF; they are rated at 12 kV and 50% voltage reversal is allowed. The capacitors are connected in groups of 5 in parallel and with the low voltage terminals of all the 50 capacitors connected together. Each group of 5 capacitors is discharged by one ignitron (see Fig. 7.2.2(i)) and the cathodes of the ignitrons are all connected in parallel to one end of the kicker coils. The other end of the coils is connected to the common low voltage terminal of the capacitor bank. The damping resistors and ignitrons are connected to the ends of the coil by suitable leads. The 10 damping resistors are each made from a length of resistance wire and are connected together at the low voltage end of the coil leads. The other ends of the resistors are connected separately to the anodes of the damping ignitrons. The cathodes of these ignitrons are also connected in parallel and are connected to the cathodes of the firing ignitrons.

Both sets of 10 ignitrons are fired at the same time causing an almost sinusoidal rise in magnetic field in the coils but the damping ignitrons only start conducting when the voltage across the coils reverses. Hence the magnetic field shape is sinusoidal up to the maximum and then it decays in an almost exponential manner.

The charging unit is arranged to charge a capacity of 500 μF to 12 kV (to an accuracy of 1%) in 2 seconds and to smaller voltages in correspondingly shorter times. The charging of the condensers is initiated by a standard timing pulse at the end of the "flat top" of the Nimrod magnet field. The discharge trigger is a similar pulse at, for example, the beginning of "flat top". This trigger pulse can be delayed by up to 120 ms and after amplification it is used to fire a thyratron which in turn fires two ignitrons. One of these fires the ten main firing ignitrons and the other fires the damping ignitrons. The delay circuit and amplifier are similar monostable multivibrators. The hydrogen thyratron (CV 372) discharges a capacity of 0.5 μF (charged to 3 kV) through two pulse transformers which trigger the two firing ignitrons. Each of these ignitrons discharges a capacity of 10 μF (charged to 6 kV) through the ignitors of 10 of the main ignitrons.

7.2.3. Model Measurements

Some work on a full scale model fast kicker coil has been done using a 250 μF condenser bank. The model coils are now being used as a dummy load for testing the apparatus in the magnet room. On the model the magnetic field was measured for different voltages (up to 12 kV maximum) on the condenser bank. The field in the centre of the coils and also across a horizontal plane through the centre of the coils was measured. A longer search coil than the kicker coil was used so as to measure the integrated field. The field was found to increase according to theory but its decay was not as smooth as the theory indicated. The maximum field for each voltage was not as high as predicted but the theory does not take into account the resistance of the circuit or the inductance of the leads.

According to theory, with a 250 μF capacity charged to 6 kV and a coil and lead inductance of 3.37 μH:-

$$I = V\sqrt{\frac{C}{L}} = 6 \times 10^3 \sqrt{\frac{250}{3.37}} = 5.2 \times 10^4 \text{ A}$$

With W = 9.125 in, H = 7.0 in and S = 60 in:-

$$\int B dl = \frac{4I}{5}\left(\frac{SW}{W^2 + H^2}\right)$$

$$= \frac{4}{5}\left(\frac{5.2 \times 10^4 \times 60 \times 8.125}{7^2 + 8.125^2}\right)$$

$$= 17.5 \times 10^4 \text{ gauss cm}$$

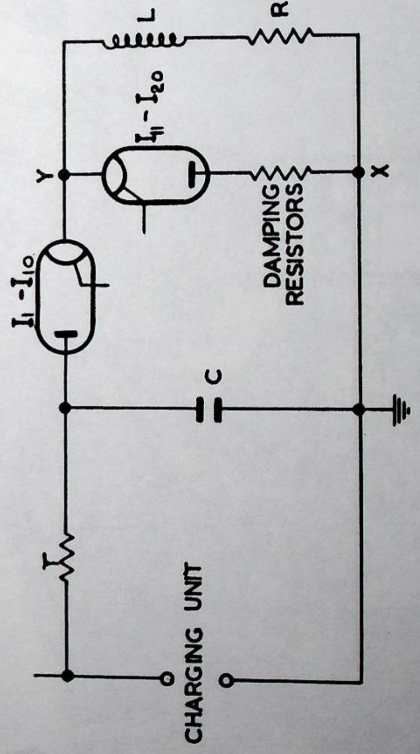


Fig. 7.2.2 (i) Basic Fast Kicker Circuit

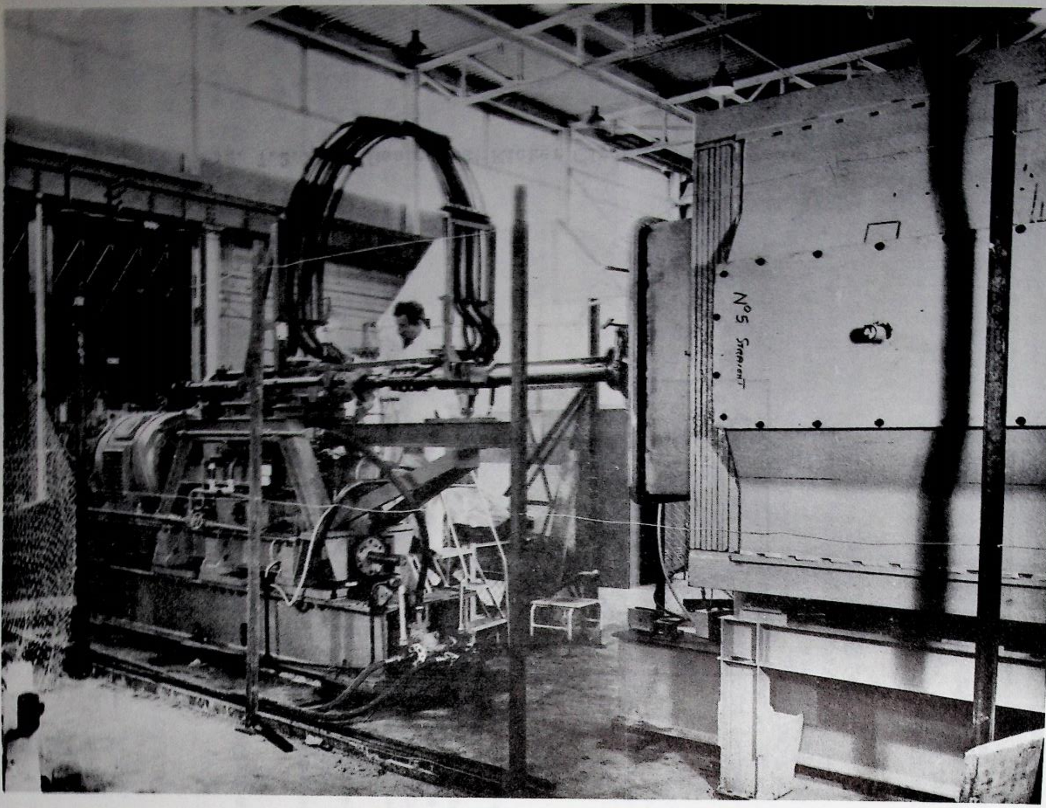


Fig. 7.3 (i) Plunging Mechanism

The measured maximum field under these conditions was 10.5×10^4 gauss cm, so the efficiency of the system is about 60%

7.2.4. Present status

The charging unit, the capacitor bank and the ignitron rack have been installed and preliminary discharge tests have been made.

7.3. Plunging Mechanisms for the Extractor Magnets

7.3.1. Description of System

The plunging mechanisms provide the motive power for moving the extraction and quadrupole focusing magnets into operating position each accelerating cycle of the machine; together with a small target, these form the Piccioni system for extracting the proton beam from Nimrod.

Two separate operations are performed by the plunging mechanism: one is a fixed stroke of 20 in, to a given displacement-time pattern, for plunging the magnet into the beam region and the other provides adjustment for the terminal position of the 20 in stroke.

The plunging action is obtained from a hydraulically operated ram driven by two variable-delivery pumps whose output is controlled by small electro-hydraulic servo-valves. These and all the electric driving motors, auxiliary pumps and hydraulic circuit (including a tank to provide the necessary oil capacity for the hydraulic system) are assembled on a steel structure (see Fig. 7.3(i)); The assembly is held down on to a fixed steel bed with pre-loaded clamps, the fixed bed being bolted down to the main concrete monolith supporting the Nimrod magnet.

The servo-valves are fed by error signals from a digital control system. A position pick-off delivers a pulse signal for every 0.01 in movement of the magnet ram. These pulses are passed to a binary counter which is compared many times during a stroke with a series of numbers carried in a store or programme. This programme consists of a plug-in unit containing a 50 x 56 diode matrix so arranged as to represent the desired magnet displacement-time characteristic in numerical form. Variations in stroke time of about 4:1 can be obtained by adjusting the running speed of a master oscillator which sets the time scale for the counter and programme comparisons.

The error between counter and programme at each sampling point is converted to an analogue signal which is amplified and fed to the servo-valves. Various safety devices and interlocks are built into the control system to cater for such contingencies as excess error, pick-off failure etc.

Adjustment to the terminal position of the 20 in stroke is obtained by unloading the clamps and slowly moving the steel structure along the fixed bed using hydraulically operated rams for both operations. Interlocks ensure that adjustments cannot be made whilst the magnet is being plunged.

The magnet and carriage move on three rails sited in the straight section box; the two outer rails support the weight and the centre rail guides the magnet along its required path. Columns from ground level pass through the base of the straight section box to support the rails, bellows being provided between the columns and the box to ensure vacuum tightness and to prevent any loads and vibration from the moving magnet being transmitted to the box.

A hollow steel shaft connects the magnet to the operating ram of the mechanism. A friction coupling is interposed between the shaft and the ram to permit a small free endwise movement of the shaft relative to the ram in the event of the ram becoming uncontrollable near the end of the stroke. The shaft passes through a self-aligning seal assembly to complete the vacuum tight straight section box. The seals comprise three groups of P T F E chevron rings with two evacuated chambers and one oil filled.

Rigid copper tubes in the bore of the shaft carry the power and water circuits which are routed from the reciprocating shaft to a fixed point on the top of the mechanism by flexible leads attached to a spring steel arch.

TABLE 7.3(I)

Design Data	Extractor Magnet	Quadrupole Magnet
Moving Mass	1 ton	0.2 ton
Minimum time for plunging stroke	200 ms ± 20 ms	
Rest time	50 ms to single shot	
Minimum time for withdrawal stroke	200 ms ± 20 ms	
Minimum cycle time	500 ms	
Stroke length and terminal position tolerance	20 in ± $^1/32$ in	
Datum adjustment per stroke	± 5 in	
Maximum acceleration and deceleration	≃ 5 g	

TABLE 7.3(II)

Mechanism Data	Extractor Magnet	Quadrupole Magnet
Operating pressure	3500 lb/in^2	
Maximum oil throughout	150 gal/min	
Piston Dia.	3½ in	
Maximum piston speed	16 ft/s	
Main electric motor	120 hp	

7.3.2. Present Status

Two mechanisms, with one main pump each, have been delivered to the site and initially these will be capable of plunging the magnets in 0.7 s. One mechanism together with a one ton mass, connecting shaft, straight section box and vacuum seal box for the shaft has been assembled in a test bay.

Short term, manually controlled, tests were followed by sinusoidal cycling of the ram. Response tests for the complete variable delivery pump, ram and servo-control loops are now being carried out.

7.4. Target Mechanisms

The target mechanisms are required to bring a target weighing up to $1\frac{1}{2}$ lb into position beside the circulating beam in about 0.2 s or less.

The Type I mechanisms, which will be in use initially, consist of a frame 1 in high which spans from the inner to outer radius of the vacuum vessel. This carries a shaft which can be rotated through 90° from outside the vacuum vessel by hydraulic apparatus. If the target is short, it is carried on a fixed arm and is raised from the floor of the vessel to median plane height by the rotating shaft. Longer targets are mounted on an arm provided with pulleys and stainless steel belts which keep the target in the same orientation so that it undergoes only a translation on being raised. Vibrations of the target are of the order of 1 thou in significant directions under most operating conditions.

A mechanism providing remote adjustment of target radius and azimuth is nearly designed and should be available for use by the end of 1963.

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