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DESIGN OF A HIGH CURRENT 200 MeV PROTON LINEAR ACCELERATOR

by

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ABSTRACT

The cost basis in the design of a proton linear accelerator is given, with particular reference to a 200 MeV, 200 Mc/s, Injector Linac for a large A.G.S. Practical details of the r.f. system, and mechanical aspects of the design are considered. Also discussed are tolerances and reliability.

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1. Introduction

The design of a high current high energy proton linear accelerator must take into account several requirements, not least of which is the balance between costs of the linac proper and of the r.f. system. This report describes the process of finding the optimum relation between the two to obtain the overall design; then discusses aspects of the r.f. system (particularly where there is heavy beam loading), tolerances, and mechanical problems.

The particular design described is for the 200 MeV linac pre-injector for the 300 GeV A.G.S. proposed by C.E.R.N. Injection into this machine can be achieved in several ways, of which two have received detailed study (1):

200 MeV pre-injector,	3 GeV linac ,	300 GeV A.G.S.	i)
200 MeV pre-injector,	6 GeV "Booster" A.G.S.,	300 GeV A.G.S.	ii)

The requirements for the 200 MeV pre-injector linac are essentially similar in both cases, though the particular example described in this report applies to the second case. It has the following characteristics (determined mainly by the injection requirements into the 6 GeV "Booster" A.G.S.):

Operating Frequency	200 Mc/s
R.F. pulse length, repetition rate, duty cycle	40 μs, 250/s, 0.2%
Final Energy	200 MeV
Number of Tanks	8
Total r.f. power and beam power per tank (100 mA beam)	5 MW
Mean stable phase angle	26°
Radial Emittance	100×10^{-6} m.rad.
Practical Tolerance on E-field, and phase	0.2%, 0.4°
Momentum Tolerance at 200 MeV	± 0.15%
Momentum jitter	± 0.05%

It goes almost without saying that the major requirement for the linac is reliability in operation: clearly that part of the machine whose cost is only about 2% of the whole must not be the cause of too many breakdowns. Experience gained on the existing 50 MeV P.L.A. at the Rutherford Laboratory suggests that by conservative rating of components (both on the linac itself and on the r.f. system) a high percentage reliability of the order 80-85% can be reasonably expected.

A tentative layout of the linac is shown in figures 1 and 2. Figure 1 shows also the outlines of an experimental area (containing also some beam monitoring apparatus, e.g. time-of-flight), the 6 GeV "Booster" A.G.S., and the main 300 GeV

A.G.S.. Figure 2 shows a possible layout for the linac itself (with its vacuum pumps, focusing equipment, monitoring units) and the r.f. system (power packs, modulators, amplifiers) in separate tunnels. High r.f. power is fed directly through the shielding wall in lines to be kept as short as possible for reasons of good r.f. build-up in the cavities, to be discussed later. The use of separate tunnels, though expensive, is considered worthwhile, since some local control and maintenance of the r.f. system can be done whilst the linac is operating.

2. Cost Optimisation in the Design of the Linac

The costs of a linac installation can be divided into three kinds: fixed costs, such as for buildings, control room, pre-injector, etc., which are essentially independent of the length and power of the linac; capital cost associated directly with the linac itself; and maintenance costs. These last two must be taken into account in a cost optimisation, and can be apportioned thus:

	Capital Costs		Yearly Running Costs
C_P:	Cost per unit of r.f. peak power including valves, modulators, lines, supplies, and controls.	C_P':	Cost per unit of r.f. component replacement, including valves; and electricity supplies.
C_L:	Cost per unit length of structure, including focusing, vacuum, beam lines, and tunnel proper.	C_L'	Cost per unit length for structure maintenance, e.g. pumps.

The C_P, C_P' and C_L, C_L' terms are essentially independent of each other. The C_P terms are dependent on duty cycle, but over reasonable limits, the C_L terms are not. At the chosen duty cycle the total cost for the linac can be written:

$$C_S = (C_P + C_P')P + (C_L + C_L')L \qquad \ldots\ 2i)$$

where P is the total r.f. peak power, and L is the length of the linac. P and L are related by

$$P = V^2/\eta L \qquad \ldots\ 2ii)$$

where V is the proton energy gain, and η is the effective shunt impedance per unit length of the structure (i.e. including longitudinal transit time factor T_0, and stable phase angle ϕ_s). With equation 2ii), equation 2i) can easily be minimised to give (2):

$$L_{opt} = V \left\{ \frac{(C_P + C_P')}{(C_L + C_L')} \right\}^{\frac{1}{2}}$$

$$\text{acceleration rate, } K, = V/L_{opt} \qquad \ldots\ A)$$

$$C_{s,min} = 2v\left(\frac{(C_p + C_p')(C_L + C_L')}{\eta}\right)^{\frac{1}{2}} \qquad A)$$

The equations A) hold providing i) the r.f. frequency can be chosen high enough to avoid voltage breakdown, ii) focusing is practicable at the chosen frequency, iii) r.f. power sources are available. At a specified frequency of operation, as in the case discussed here, the voltage breakdown criterion, and focusing requirement must be included to give an optimised practicable design.

The Alvarez structure is composed of unit cells whose geometry is shown in figure 3. The drift tubes are taken to be of conventional shape, i.e. right cylinders with profiled face as shown (alternative shapes are discussed briefly later).

i) Since the drift tubes must contain quadrupoles, a lower limit must be set to their diameters: at 200 Mc/s this is taken to be $d/\lambda \nless 0.1$. The drift tube bores must allow for beam radial emittance, and misalignments. A bore $d^1/\lambda = 0.026$ (i.e. as on the Rutherford Laboratory P.L.A.) for all tanks except Tank 1 is considered adequate.

ii) To avoid voltage breakdown, the maximum electric field gradient at the surface of the drift tube must not be greater than 14 MV/m at the operating frequency of 200 Mc/s. This condition, known usually as Kilpatrick's Criterion at 200 Mc/s, $E_{max} \ngtr 14.7$ MV/m, is most important in the reliable operation of the linac. By the conservative choice that $E_{max} = 14$ MV/m, rather than 14.7 MV/m given by Kilpatrick's Criterion (which is itself generally regarded as a pessimistic estimate), operation free of voltage breakdown can be expected.

Let E_o be the electric field across the gap, g, and let E_s be the maximum safe electric field that can exist at the surface of the drift tube (the maximum field usually occurs at the junction of the outer profile radius and the drift tube flat). Let

$$E_o/E_s = \alpha \qquad \text{... 2iii)}$$

Some values for α are given by Wilkins (3) for cells of constant profile radii. The acceleration rate for the structure can be written

$$K = (V/L) = (g/L)\, E_o T_o \cos\phi_s = (g/L)\, \alpha\, T_o E_s \cos\phi_s \qquad \text{... 2iv)}$$

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Combining equations 2i), 2ii) and 2iv) gives

$$C_S = (C_P + C_P') \frac{V}{\eta K} + (C_L + C_L') \frac{V}{K}$$

$$= V \left(\frac{(C_P + C_P')(g/L) \alpha T_o E_s \cos \phi_s}{\eta} + \frac{(C_L + C_L')}{(g/L) \alpha T_o E_s \cos \phi_s} \right) \quad \ldots \text{ 2v)}$$

The optimum cost can now be obtained by minimising the expression inside the square bracket, i.e. by finding the optimum relation between K and η through α and T_o, and hence on cell geometry defined by $(D/\lambda,\ d/\lambda)$. Since α and T_o vary with energy (through their dependence on g and L $(= \beta\lambda)$ of the unit cell), optimisation must be carried out at intervals over the energy range.

The optimum parameters having been found, the linac can now be divided into tanks whose lengths can be chosen in several ways: e.g. i) Constant energy gain per tank, ii) Tank length as a specified fraction of one phase oscillation wavelength, iii) Total r.f. power required by tank and beam is equal to that available from a single amplifier. In all cases it is desirable that the tank length be not greater than 20 λ, because of difficulty in tank flattening. (It will be seen later that no tank is greater than 25 metres, a length also recommended in ref. 2)). Method iii) is chosen as the simplest and most economical, and for which the r.f. system is described in detail in section 5. Let the total power available be R MW, and the power lost to the tank be P, then

$$(P + IV) = \frac{V^2}{\eta L} + IV = R$$

$$V = \frac{R}{K/\eta + I} \quad \ldots \text{ 2vi)}$$

$$\text{and} \quad L = V/K$$

where I is the peak beam current, and (K/η) has been optimised. The linac can now be divided into tanks, working from the final energy. Providing the energy intervals are not too great, values for $(D/\lambda,\ d/\lambda)$ to give K, η at the output end cell suffice for the whole tank. This has two advantages: i) for a fixed $(D/\lambda,\ d/\lambda)$ in a tank, g/L is largest at the end cell, and a safe (i.e. free from voltage breakdown) design at the end cell will be safe over the whole tank (this statement is true for all tanks except Tank 1, which is discussed briefly in Appendix A); ii) constant diameters in a tank lead to simplication of design and manufacture. In the particular design discussed in this report the error in the estimate for shunt impedance by taking the end value rather than the mean for the tank results in an error of the order of 4% in the estimate of tank voltage (assuming a 10 mA beam). Since it is not easy to estimate shunt impedance to better than ~ 10%, this error is not serious at this stage.

The constants of proportionality in equation 2i) are based on the Nimrod Injector, the 50 MeV P.L.A. at the Rutherford Laboratory, and on a detailed cost estimate for the R.F. System from a British manufacturer*: C_P = £35,000/MW, and C_L = £6,500/m at 50 MeV. For other energies, C_L can be broken down thus:

£2,500/m	liner and vac. vessel
£1,000/m	vac. pumps and control (i.e. Oil diff. pumps, backing pumps, and safety and control circuitry).
£ 50/m	Tunnel proper[+]
£2,150/m	drift tubes.

The cost £2,150/m for drift tubes is equivalent to £1,000 per drift tube at 50 MeV, where there are 2.16 drift tubes per metre. The cost per drift tubes is roughly constant over the energy range (the major fraction of the cost being the manufacture of the quadrupoles, and assembly, rather than materials), but the number of drift tubes varies inversely as β. Hence the cost per metre of structure can be written C_L = £6500 $(A + B/\beta)$. At 50 MeV, $(A + B/\beta) = 1$, so A = 0.669, B = 0.1035. Hence the capital part of the linac cost can be written

$$C_1 = £6,500\ (5P + (0.669 + 0.1035/\beta)L) \qquad \text{... 2vii)}$$

Other values for the capital cost parameters are available from accelerator laboratories in the U.S.A. (to whom the authors refer, and are grateful for private communication):

Linac	No of Tanks	C_P(£/MW)	C_L(£/m)	Duty factor
Argonne ZGS Inj.	1	16,500	(£2,600 for Cu-steel liner alone)	0.5%
Yale Linac (200 Mc/s, 200 MeV)(2)	6	35,000	6,500	5%
Brookhaven Inj.	1	39,000		0.04%
Mura (200 Mc/s, 200 MeV)(4)	6	29,300		1.5%

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*Marconi W.T. Co., Chelmsford

[+]Based on CERN estimate of 100 Sw.Fr. per cu. metre of linac tunnel.

It is seen there is wide variation in the term C_P, though the second and fourth cost parameters are more akin to the example discussed here since, as will be seen in section 3, control circuity for a many tank system becomes an important item. It is also of interest to note at this stage the similarity of costs of the separate vac. tank and liner system and the Cu-clad liner. The sensitivity of the capital cost to the parameters C_P, C_L can be gauged from the equations 2i) and A): the linac capital cost can be expressed in the form $C = Al + B/l$, where the optimised length is given by $l = \sqrt{B/A}$, and the minimum cost $= 2\sqrt{AB}$. Let l_1 be the optimised length on the basis A_1, B_1. Now let A_2, B_2 be the actual cost parameters, where $A_2 = \gamma A_1$, $B_2 = \delta B_1$. The actual cost is then $C_2 = A_2 l_1 + B_2/l_1$, and the fractional error on the original design optimised cost $C_1 = 2\sqrt{A_1 B_1}$ is

$$\frac{C_2}{C_1} - 1 = \frac{\gamma + \delta}{2} - 1$$

Thus a (say) 10% error in either cost parameter results in a (say) 5% error in the total capital cost. In the practical design discussed, where the optimum is not the design for a simple minimum cost, the error in the total capital cost will be somewhat less than this.

Based on operating experience on the Rutherford Laboratory P.L.A., and on properties of proposed components for the r.f. system, the yearly running costs can be broken down thus:

<u>Maintenance:</u>	Valve		Expected Life, hrs.	Replacement Rate, p.a.
	Final Amplifier	(RCA7835)	10,000	4
	Drive Valve	(RCA2041)	10,000	4
	Switch Valve	(VX 3336)	5,000	8

£3,000/MW Valve Replacement

£1,000/MW R.F. lines, general modulator equipment

£1,300/m Structure costs, pumps, services.

<u>Electricity Cost:</u> (This figure depends particularly in which country such an accelerator would be built, but based on 4,000 hrs. running time for the P.L.A.:)

£3000/MW r.f. power

£100/m linac pumps, etc.

Hence the yearly running costs are:

$$C_2 = £7000\ P + £1400\ L = £1400\ (5P + L) \qquad \text{... 2viii)}$$

If, conveniently, the running cost per metre is assumed to have a variation with β of the same form as in the capital cost (which assumption introduces an error 1% in the total cost), the total cost can be written

$$C_S = £7,900\ (5P + (0.069 + 0.1035/\beta)L) \qquad \ldots\ 2ix)$$

i.e. from 2v)

$$(C_S/V) = £7,900 \left(\frac{5(E/L)_a T_o E_s \cos\phi_s}{\eta} + \frac{(0.069 + 0.1035/\beta)}{(E/L)_a T_o E_s \cos\phi_s} \right) \qquad \ldots\ 2x)$$

It now remains to find the values of $(D/\lambda,\ d/\lambda)$ to minimise the expression 2x) at intervals over the energy range. This has in fact been done for energies up to 250 MeV: by use of data from "Design Notes for Proton Linear Accelerators" by Williams[2] for energies up to about 200 MeV, and above 200 MeV by use of an IBM 7090 program devised by Taylor and Kitching[5]. In doing this the following points should be emphasised:

i) The drift tube apertures, inner and outer profile radii are constant along the linac.

ii) The calculated r.f. power loss to the structure has been increased by 20% to allow for losses on drift tube stems and cavity end walls (this increase is a realistic one, as verified by calculations on the Rutherford Laboratory P.L.A.)

iii) The stable phase angle was taken to be $\phi_s = 26^\circ$. With the maximum E-field value as already given, $\phi_s = 30^\circ$ could also be used.

The curves of optimised D/λ, d/λ over the energy range 30–250 MeV are shown in figure 4 (these curves will cover energies down to $\sim$ 10 MeV). Of particular interest is the increase of d/λ with increasing energy, showing the dominance of the voltage breakdown requirements over shunt impedance at the higher energies. The derivation of $(D/\lambda,\ d/\lambda)$ optimum is shown in figure 5 for the particular energy 170 MeV. In this figure are also shown the effects of a $\pm$ 20% variation in the cost of r.f. power. As discussed earlier, although the minima are sharper with increasing energy, large variations in individual cost parameters result in smaller changes in total cost, or, small variations in geometry. Curves of acceleration rate and practical shunt impedance (i.e. that allowing for the 20% increase in power, as in ii) above) for the optimised geometry are shown in figures 6 and 7 respectively. Again the reduction in acceleration rate is due to the voltage breakdown requirement; and the rapid fall-off of shunt impedance is due, inter alia, to the need to have drift tubes of large diameter in the high energy region.

From these curves figures 4, 6, 7, and equations 2vi) the complete design for the linac can be made. The total r.f. power in each tank is taken to be 5 MW (being tank r.f. loss and 100 mA beam loss), as that available from the proposed final amplifier (RCA Super Power Triode 7835). As stated earlier the tanks are designed from the final energy. Figure 8 gives the parameters of the complete linac: it consists of 8 tanks of which Tanks 2-8 have 5MW total power, and the first tank, 5 MeV long, has only about 1 MW total power. This subdivision resulting in a small Tank 1 is in fact very convenient, since it has been the experience on most present machines that the first few cells of a linac are the ones where most voltage breakdown problems have occurred. Thus, a small first tank built for accessibility could simplify maintenance problems (e.g. polishing drift tube faces). Further, the actual parameters of this small Tank 1 should be chosen not on a cost basis, but on the needs of good particle dynamics over the range 0.5-5 MeV (i.e. practicable quadrupole system with sufficient aperture; lowest possible injection energy, high acceleration rate with perhaps an increasing field along the tank, both to achieve good phase damping). The actual Parameters of the Tank 1 are taken from the redesigned Tank 1 of the Rutherford Laboratory P.L.A. (6), described briefly in Appendix A

The capital cost of the linac can be broken down thus:

Tank	Cost Factor $\left[\int_0^L (A+L/\beta)\,dL\right]$	Structure Cost (£1,000's)	RF Cost (£1,000's)
1			
2	21.08	137.67	165
3	19.95	129.54	"
4	21.37	138.90	"
5	22.14	143.91	"
6	21.60	140.40	"
7	20.75	134.88	"
8	19.90	129.35	"

Total cost of structure, tanks 2-8	£ 954,600
Total cost of r.f. power, tanks 2-8	£1,155,000
Total cost of Tank 1 (based on Rutherford Lab. 'New' Tk.1, and £35,000/MW)	70,000
Additional cost for tunnel to allow intertank beam lines (10m)	10,000
Preinjector (based on Rutherford Lab. 500 KV preinjector	£ 60,000
Total	2,249,600
Contingency (10)	225,000
	2,474,600

These capital cost figures are for the complete linac only. Additional costs are due to control room, and laboratory buildings. Though some measure of (local) control has been included in the C_P, C_L terms, the cost of a control room will depend on, location, complexity and the degree of automation achieved. The number and cost of laboratory buildings would have to be considered along with those of the main accelerator; also laboratory staff and overheads.

The running cost, as defined earlier, would be of the order £220,000 p.a. (though again it should be emphasised that the electricity part of this cost depends on location). To this figure of course must be added the salaries of the operating staff.

3. R.F. System

3 (a) Introduction

It has been seen in section 2 that one of the major cost items is the r.f. system. According to Figure 8 the total peak power required for the accelerating structure alone is 10.0 MW, and 20 MW peak power is required for a 100 mA peak proton beam current. (It is also possible that the peak proton current may be as much as 200 mA, requiring 40 MW peak power for acceleration). It is clear that with the large amounts of power required for the beam, the usual method of allowing the beam to obtain its energy from the stored energy in the cavity after the normal build up period is not satisfactory. This method would result in serious energy modulation of the beam during the 5 μsec beam pulse and, in the case of the 200 MeV linac, loss of beam current. Some method of providing the extra power for the beam is therefore necessary.

One possible method is that proposed for the C.E.R.N. P.S. linac (7) where the extra power will be provided by coupling a second power amplifier to each accelerating cavity and pulsing this amplifier during the beam period. This system requires a long build up period ~ 150-200 μsec in order that the field level in the cavity has settled down to a nearly constant level before the beam is introduced. There are also some complications in the r.f. feed system.

In an alternative method described below, the full power output capability of the r.f. amplifier is utilised to give a fast build up of power in the cavity.

The effects of source impedance on the build up of power in a resonant cavity is investigated, a series tuned circuit with loss being taken to represent the cavity resonator. Resistive and reactive effects of the beam on the cavity are also considered.

3(b) Build up of power in a resonant cavity

Consider the equivalent circuit of Figure 9(a)

where R_s is the source resistance of the amplifier

L, C and R are the cavity series inductance, capacitance and resistance respectively.

The loop is assumed to act as a perfect transformer of ratio n:1

The current I at time t is related to the final current I_o by the relation

$$I = I_o\left(1 - e^{\frac{-\omega t}{2Q_L}}\right) \qquad \text{... 3i)}$$

where $I_o = \dfrac{nE\sin\omega t}{R+n^2R_s}$ is the steady-state current in the resonant circuit and

where Q_L is the loaded Q of the system

i.e.

$$Q_L = \frac{\omega L}{R+n^2R_s} \qquad \text{or } Q_L = \frac{Q_o}{1+\frac{n^2R_s}{R}} \qquad \text{... 3ii)}$$

where Q_o is the unloaded Q of the cavity

In the practical case the value of R_s will depend on the line length between the driving amplifier and the cavity. If the characteristic impedance of the feed line is Z_o, the coupling factor k may be defined by

$$k = \frac{n^2Z_o}{R}$$

so that equation 3ii) becomes

$$Q_L = \frac{Q_o}{1+\frac{R_s}{Z_o}k}$$

If the feed loop is matched to the cavity, k = 1, and the loaded Q becomes

$$Q_L = \frac{Q_o}{1+\frac{R_s}{Z_o}} \qquad \text{... 3iii)}$$

In a linac where only a few mA of beam is accelerated this method of matching to the cavity without beam is acceptable. In the case of heavy beam loading it is beneficial, in terms of build up time, to match the loop to the beam loaded cavity. Let us investigate this case further.

If R' is the total effective series resistance of the beam loaded cavity and Q_B the Q value due to the beam itself, the total Q of the system is given by:

$$\frac{1}{Q_L} = \left(\frac{1}{Q_o} + \frac{1}{Q_B} \right) \left(1 + \frac{n^2 R_s}{R'} \right) \qquad \ldots \text{3iv)}$$

In this case R' is defined by the relation

$$k' = \frac{(n')^2 Z_o}{R'}$$

where n' is the "turns ratio" of the loop feeding the beam loaded cavity

then

$$\frac{1}{Q_L} = \left(\frac{1}{Q_o} + \frac{1}{Q_B} \right) \left(1 + \frac{k' R_s}{Z_o} \right)$$

In the case where the loop is matched to the cavity plus beam, $k' = 1$, so that

$$\frac{1}{Q_L} = \left(\frac{1}{Q_o} + \frac{1}{Q_B} \right) \left(1 + \frac{R_s}{Z_o} \right) \qquad \ldots \text{3v)}$$

It follows that

$$\frac{R}{R'} = \frac{Q_B}{Q_o + Q_B} \qquad \ldots \text{3vi)}$$

Substituting for R' from equation 3vi) gives

$$(n')^2 = \frac{R}{Z_o} \left(\frac{Q_o}{Q_B} + 1 \right) \qquad \ldots \text{3vii)}$$

Equation 3vii) thus defines the "turns ratio" of the coupling loop for the case where the loop is matched to the beam loaded cavity. During the build up period when the beam is not present the loop will be "overcoupled" to the cavity and the loaded Q is given by substituting the value of n' from equation 3vii) into equation 3ii) so that

$$\frac{1}{Q_L} = \frac{1 + \frac{R_s}{Z_o}\left(\frac{Q_o}{Q_B} + 1\right)}{Q_o}$$

... 3viii)

i.e. $$\frac{1}{Q_L} = \frac{1}{Q_o}\left(1 + \frac{R_s}{Z_o}\right) + \frac{R_s}{Z_o}\frac{1}{Q_B}$$

Substitution of this value of Q_L in equation 3i) gives the build up law for this system.

If the line length between source and cavity is such that $R_s = Z_o$

Then $\frac{1}{Q_L} = \frac{2}{Q_o} + \frac{1}{Q_B}$ in the beam loaded case ... 3ix)

or $\frac{1}{Q_L} = \frac{2}{Q_o}$ in the non beam loaded case ... 3x)

In practice the beam loading gives rise to a reactive term which effectively detunes the cavity. Methods of overcoming this effect are discussed below. It is evident from the above relations that the build up time for the case where the loop is matched to the cavity plus beam will be shorter than in the no beam case, even though the beam is not present during the build up period.

3(c) <u>Effects of an active and reactive source impedance</u>

It is probable that the coupled impedance will contain reactive as well as active components. Consider the cases of Figure 9(b) and 9(c) where the effect at the effective loop terminals is capacitive or inductive:

For the capacitive case

$$I = I_o\left\{1 - e^{-\frac{\omega t}{2Q_L}}\left\{\sqrt{\frac{(\omega_c^2-\omega^2)^2+\left\{\frac{\omega_o(\omega_c^2+\omega^2)}{2\omega_c Q_L}\right\}^2}{(\omega_c^2-\omega^2)^2+\left\{\frac{\omega_o\omega}{Q_L}\right\}^2}}\;\frac{\sin(\omega_c t+\beta_c)}{\sin(\omega t+\alpha_c)}\right\}\right\}$$ ... 3xi)

where

$$I_o = \frac{\omega \ldots \sin(\omega_o t + \alpha_c)}{L\sqrt{(\omega_c^2-\omega^2)^2+\left(\frac{\omega_o\omega}{Q_L}\right)^2}};\quad \tan\alpha_c = \left(\frac{\omega_c^2-\omega^2}{\omega_o\,\omega}\right)Q_L;\quad \tan\beta_c = \left(\frac{\omega_c^2-\omega^2}{\omega_c^2+\omega^2}\right)\frac{2\omega_c Q_L}{\omega_o},$$

and $$\omega_c = \omega_o\sqrt{\frac{1+\ldots C}{C_s}}$$ ... 3xi)

and for the inductive case

$$I = I_o\left\{1 - e^{-\frac{\omega_o(\omega/\omega_L)\,t}{2Q_L}}\sqrt{\frac{(\omega_o^2-\omega_L^2)^2+\left(\frac{(\omega^2+\omega_L^2)}{\ldots Q_L}\right)^2}{(\omega_o^2-\omega_L^2)^2+\left(\frac{\omega\,\omega}{Q_L}\right)^2}}\;\frac{\sin\left(\frac{\omega_o\omega t}{\omega_L}+\beta_L\right)}{\sin(\omega t+\alpha_L)}\right\}$$ ... 3xii)

where $$I_0 = \frac{m\omega \sin(\omega t+\alpha_c)}{L\sqrt{(\omega_0^2-\omega_L^2)^2+\left(\frac{\omega}{Q_L}\right)^2}}; \quad \tan\alpha_L = \left(\frac{\omega^2-\omega_L^2}{\omega\omega_0}\right) Q_L;$$

$$\tan\beta_L = \left(\frac{\omega_0^2-\omega_L^2}{\omega_0^2+\omega_L^2}\right)\frac{Q_L\omega_L}{\omega} \text{ and } \omega_L = \omega\sqrt{1+\frac{n^2L_s}{L}}$$

where ω is the driving frequency and ω_0 is the natural resonant frequency of the cavity.

Since $\frac{n^2L_s}{L}$ or $\frac{n^2C}{C_s}$ can be made very much less than unity in the practical case, $1+\frac{L_s n^2}{2L}$ can be written for $\sqrt{1+\frac{n^2L_s}{L}}$, and $1+\frac{n^2C}{2C_s}$ for $\sqrt{1+\frac{n^2C}{C_s}}$. If now the cavity is operated at its natural resonant frequency ω_0 equations 3xi) and 3xii) reduce to

$$I = I_0\left(1 - \frac{\sin\left(\frac{\omega_0 t}{1+\frac{n^2L_s}{2L}}+\alpha_L\right)}{\sin(\omega_0 t+\alpha_L)}\, e^{\frac{-\omega_0 t}{Q_L\left(1+\frac{n^2L_s}{2L}\right)}}\right) \qquad \ldots 3xiii)$$

where $\tan\alpha_L = \tan\beta_L = -\frac{n^2L_s}{L}Q_L$ and $I_0 = \frac{m\sin(\omega_0 t+\alpha_L)}{\omega_0 L\sqrt{\left(\frac{n^2L_s}{L}\right)^2+\left(\frac{1}{Q_L}\right)^2}}$

$$\text{and } I = I_0\left(1 - \frac{\sin\left(\omega_0\left(1+\frac{n^2C}{2C_s}\right)t+\alpha_c\right)}{\sin(\omega_0 t+\alpha_c)}\, e^{\frac{-\omega_0 t}{Q_L}}\right) \qquad \ldots 3xiv)$$

where $\tan\alpha_c = \tan\beta_c = \frac{n^2CQ_L}{C_s}$ and $I_0 = \frac{m\sin(\omega_0 t+\alpha_c)}{\omega_0 L\sqrt{\left(\frac{n^2C}{C_s}\right)^2+\left(\frac{1}{Q_L}\right)^2}}$

It can be seen that the primary effect is a detuning of the cavity by the transformed source reactance. It should always be possible to adjust the length of feed line between source and cavity so that the reactive effect of the source on the cavity is negligible, if not zero.

Reactive effects of the beam on the cavities

Since the beam does not pass through the gap at the peak of the r.f. accelerating field there is a reactive load on the cavity. The "steady state" detuning effect is calculated by use of the relation (9)

$$\frac{\Delta\omega}{\omega_o} = \frac{1}{2Q_o}\,\frac{\eta}{1-\eta}\tan\phi_s \qquad \ldots 5xv)$$

where $\eta = \dfrac{W_b}{W_b + W_C}$, W_b being power in beam, W_C the power in the cavity and ϕ_s the stable phase angle.

The total detuning during the beam pulse will be less than the "steady state" value, given in table (1).

The above expression can be reduced to the form

$$\tan\psi = \frac{Q_L}{Q_b}\tan\phi_s \qquad \ldots 5xvi)$$

where ψ is the maximum phase detuning and Q_L refers to the total loaded Q value, including the beam.

It may be possible to counteract the reactive part of beam loading by an equal and opposite effect due to the coupled source. However there is a practical difficulty, since experience on the CERN linac(6) and the Rutherford Laboratory P.L.A. has shown that breakdown in the output cavity of the final amplifier or the feed line restricts the range of possible line lengths between the amplifier and the accelerating cavity.

5(a) Practical considerations

R.F. Layout and Feed System

From the point of view of economy it is desirable to use the biggest available r.f. power units to drive the accelerating cavities. The choice of power source is linked closely to the operating frequency and control problems. It is evident from section 4 that precise control of amplitude and phase are necessary if the desired output beam is to be achieved. The poor EHT-phase change characteristics of klystrons compared with triodes tend to rule out their use as final power amplifiers. (The phase change for a given change in anode voltage is of the order 5 times that of the triode.) Assuming that a triode is used for the final amplifier, there is available a range of R.C.A. super power triodes which give a peak power output of the order of 10 MW at 200 Mc/s at the required duty cycle. The power gain of such a valve is of the order 15-20 db so that a driver valve capable of giving up to 400 kW peak power is needed for each stage. It has been shown in section 2 that the 5 MW r.f. output power unit is a useful criterion in deciding tank length, assuming that one power amplifier is used to feed each cavity.

(The available R.C.A. super triodes are capable of giving 10 kW peak r.f. power output at the required duty cycle and, since the injected beam current is likely to exceed the design figure of 100 mA, the r.f. system has been designed to give 10 kW useful output r.f. power. All of this power is used to give a fast build up of power in the accelerating cavities). It is desirable from the point of view of reliability that the feed line between valve and cavity be as short and simple as possible. The line length considerations discussed in section 3(c) suggest that a line lengthener between the amplifier and the cavity is desirable.

There is one factor which may complicate the feeding of power to a cavity and which requires further investigation. For the Alvarez waveguide calculations[3] show that the group velocity may be of the order 2×10^6 m per sec. Thus in a practical centre fed cavity the energy takes up to 5 μsec to travel to the ends of the cavity. This time is clearly an appreciable fraction of the beam pulse length. With a 100 mA beam this effect may result in a 10% tilt of the cavity field with resultant loss of beam quality. Dispersion in the guide will distort the axial field further. Several feed points may be necessary in a long cavity to partly alleviate this problem. The r.f. system (figure 10) shows one feed only to the cavity for simplicity.

Drive power for each power amplifier is provided by means of an adjustable directional coupler to a drive line common to all the accelerating cavities.

The loop coupling to each cavity will be matched for the loss corresponding to cavity loss plus maximum beam power loss. This gives the fastest build up condition.

<u>Modulators and Power Supplies</u>

A 20 kW peak power modulator is required for each final power amplifier and about 600 KW peak power for the driver stage. A 12 KV D.C. power pack and voltage regulator is necessary to provide the power for the main modulator.

In addition, modulation is required for the control and screen grids of each driver amplifier and the control grid of each final amplifier.

It may be necessary to provide special stabilizers for the main supply to the modulators in order to achieve the required stability of r.f. level in the accelerating cavities.

Controls and monitoring facilities

The radio frequency power pulse fed to the cavity is shown in Figure 11. This may be divided into three periods as follows:-

(i) Build up period

During this period of up to 20 μsec the full 10 kW power output capability of the amplifier is used to achieve the fast build up in the cavity. A gated signal from a forward reflectometer in the feed line may be used to operate a slow servo to maintain the mean r.f. output power (averaged over 5 to 10 pulses) constant during this period.

(ii) Guard period

As soon as the cavity has reached the correct level for acceleration a gated signal from a biassed detector in the accelerating cavity is used to adjust the grid and anode voltages of the drive and final amplifier at the valve which will maintain a constant level in the cavity. This period may be servo controlled as in the above build up period. This guard period allows time for the field level along the cavity to settle down to a steady value. It also allows some variation in the start time of the build-up period.

(iii) Beam period

This is fixed in length and starting time by the beam characteristics. A gated signal derived from a transparent beam monitor prior to each accelerating cavity may be used to determine both the time and the level at which the amplifier must be adjusted to give the extra power required for acceleration of the beam. A "Slow" servo may also be used to control the power level during this period. It may be necessary to use a fast control of r.f. level during this period if an average error of $\sim 0.1\%$ is to be maintained.

In addition to the level control it is necessary to maintain the correct phase relation between the cavities, particularly during the beam period. A slow phase control is adequate for the build up and guard periods. As the beam enters each cavity there is a "beam filling time" varying from about 150 nS to 400 nS depending on the cavity. It is necessary to change the phase of the input power by the amount given in table (1) during this period. (The rate at which the cavity phase changes is determined by the decay constant as it is for the decay of field amplitude, the beam loaded Q value being applicable). Thus a fast phase changing system is required.

One method of achieving fast phase shifts may be the use of P.I.N. switches to switch appropriate delays into the system.

The main phase control works outside the fast phasing system, and depends on a comparison between signals derived from an accurate reference line and the cavity itself. This phase reference line may be evacuated and temperature compensated to eliminate the possibility of phase errors.

Forward and reverse reflectometers will be used to record the input and output power levels at each stage of amplification. Inter-tank phase monitoring may also be provided.

The r.f. field level in each cavity may be monitored by use of a biassed diode detector utilising a measurement of the D.C. voltage.

Further r.f. parameters are given in table I. The system is designed for a 100 mA beam current, but is capable of accelerating a peak beam in excess of 200 mA, if required.

TABLE (I) RADIO FREQUENCY PARAMETERS

Energy Range (MeV	5-37	37-67	67-96	96-124	124-151	151-176	176-200
Cavity Power Loss (kW)	1.6	2.0	2.1	2.2	2.3	2.5	2.6
Stored Energy (Joules)	87.3	87.5	86.9	89.3	91.5	97.5	99.3
Maximum available Stored Energy (Joules)*	485.0	437.5	414	406	398	390	3[illegible]2
Unloaded Q Value	61,000	55,000	52,000	51,000	50,000	49,000	4[illegible],000
Loaded Q Value†	16,160	15,720	15,400	15,600	15,750	16,350	16,400
Beam Power Loss (kW)‡	3.2	3.0	2.9	2.8	2.7	2.5	2.4
Rise Time to Beam Level (usec)	14.16	14.85	15.02	15.76	16.40	18.08	1[illegible]
Maximum Phase Detuning (Deg.)‡	8.9°	8.3°	8.1°	7.8°	7.5°	7.0°	6.7°

*Calculated for max. 10 kW available peak power to the cavity.

†Assuming that the loop is matched to the cavity plus 100 mA beam and that the source impedance is equal to the characteristic impedance of the feed line.

‡Calculated for 100 mA beam current.

3(e) Calibration

One of the major difficulties in setting up a long proton linear accelerator is the determination of the actual field level and phase in a given accelerating cavity. It is shown in section 4 that a field level tolerance of ± 0.2% and a phase tolerance of ± 0.4° are necessary if the output spectrum is to be within the required figure of $\frac{\Delta p}{p} = \pm 0.1\%$.

and the momentum jitter within ± 0.05%. It should be possible to maintain the cavities within these limits, once they have been set up, by the methods described above. However a method of determining the correct operating levels in the first place is required. In the first two cavities it may be possible to make some estimate of the required field level and phase by an "acceptance phase" plot. In subsequent cavities where phase oscillation wavelength is long compared with the cavity length this method is of little practical use.

It is possible by use of carefully made and calibrated cables and components to determine absolute phase to within ± 2° so that a measure of field level is the really difficult requirement. Direct methods of field level measurement are only accurate to about ± 5 or even ± 10%. Probably the best method of setting up the beam is to use the absolute phase method to adjust the phases of the cavities and to measure the beam energy of each cavity taken in sequence to determine the required field level. This requires a method of measuring the momentum of up to 200 keV protons to within ± 0.1%. The Time of Flight method of energy measurement[10] is capable of this accuracy if a flight path of about 50 m is used. This method requires a considerable amount of electronic equipment and a specially designed beam deflection system after the preinjector. Also it is difficult to calculate the actual energy quickly. The method is suitable for initial calibration but for continuous energy monitoring some other method is needed. One method is to use a Differential Ion Chamber[11]. This instrument could be calibrated by a Time of Flight measurement and should maintain its calibration indefinitely. Magnetic momentum analysis is also possible but existing results from experiments carried out in the Rutherford Laboratory P.L.A. indicate that a measured momentum accuracy of better than ± 0.[illegible]% is difficult to achieve.

Assuming that the phase errors can be maintained to within the specified limits it may be possible to use a beam excited resonant cavity after each tank to monitor the beam. This cavity would give a signal which could relate the centroid of the beam to the r.f. phase. This need not give the absolute phase of the beam as it could be calibrated by means of the Time of Flight measurement and this calibration should remain constant. Any change in the phase oscillation wavelength, resulting from a change in r.f. level in the cavity, would give rise to a shift of the beam centroid. Thus the relative phase would be maintained during operation by suitable adjustment of the r.f. field amplitude.

4. Phase Motion and Tolerances in the 200 MeV Linac

If $\Delta\phi = \phi_s - \phi$ is the phase of a particle with respect to the stable phase angle, the linearised equation for small amplitude phase oscillations is given by the well known equation:

$$\frac{d}{dt}\left\{ M_o \gamma_s^3 \frac{\lambda}{2\pi} \frac{d}{dt} (\beta_s \Delta\phi)\right\} + \frac{eE}{\beta_s} \sin(-\phi_s)\,(\beta_s \Delta\phi) = 0 \qquad \ldots 4i)$$

where the suffix s denotes the phase stable particle, and all other terms have their usual meanings. The acceleration rate is $eE \cos \phi_s$. If the variation of parameters is assumed to be adiabatic along the linac, the solution of equation 4i) is given by the W.K.B. solution:

$$= A \cos \left\{ \int \Omega\, dt + C^t \right\}$$

$$\left.\begin{aligned} \text{where} \quad A &\propto \left\{ (1-\beta_s^2)^{3/4} \Big/ \beta_s^3\, E \sin(-\phi_s)\right\}^{[illegible]} \\ \text{and} \quad \Omega &= \left\{ (1-\beta_s^2)^{3/2}\; 2\pi e E \sin \phi_s \Big/ M_o \lambda \beta_s \right\}^{\frac{1}{2}} \end{aligned}\right\} \qquad \ldots 4ii)$$

If the input phase amplitude to Tank 1 is $A_{1,i}$

$A_{1,o} = A_{1,i} \Big/ \left\{ (1-\beta_s^2)^{3/2} \Big/ \beta_s^3\, E_1 \sin(-\phi s)\right\}^{[illegible]}_{1,i.}$ Since $\beta r, o = \beta r + 1, i$ between tanks r and r + 1, conservation of phase space gives

$$(A^2\Omega)r, o = (A^2\Omega)r + 1,\ i$$

It follows that if E_n is proportional to the acceleration rate of the n^{th} tank (i.e. ϕs is constant along the machine), and $p_{n,o}$ is the output momentum.

$$A_{n,o} = A_{1,i} \left(\frac{E_1}{E_n} \right) \left(\frac{p_{1,i}}{p_{n,o}} \right) \qquad \ldots 4iii)$$

where $p_{1,i}$ is the input momentum to Tank 1. Taking $\beta_{1,i} = 0.03312$ (515 keV, as on the Rutherford Lab. P.L.A.), $E_1 \propto 1.704$ MeV/m; $\beta_{8,o} = 0.5662$, $E_8 \propto 1.645$ MeV/m; then

$$A_{n,o} = 0.1103 \ A_{1,i} \qquad \ldots 4iv)$$

For linear motion $A_{1,i} \sim 2\,\phi_s$; generally $A_{1,i} \sim 3\,\phi_s$, and can be greater or less than this depending on the degree of 'tilt' used in the tank. For $\phi_s = 26^o$, and taking $A_{1,i} = 78^o$ ($\phi_s = 30^o$, $A_{1,i} = 90^o$),

$$A_{n,o} = 9.06^o = \pm 4.53^o, \ \phi_s = 26^o$$
$$= 10.46^o = \pm 5.23^o, \ \phi_s = 30^o \qquad \text{... 4v)}$$

Since $\Delta\phi (\equiv A)$ and $\Delta\epsilon$ are canonical, $\Delta\epsilon_{out} = \Delta\epsilon_{in}/0.1163$. Now it can be shown[12]

$$\Delta\epsilon = \pm \left\{ 2 \beta_s^3 \, eE \lambda W_o c^2 (\sin\phi_s - \phi\cos\phi_s) \Big/ \pi (1-\beta_s^2)^{3/2} \right\}^{1/2}$$

In Tank 1, $eE\cos\phi_s = 1.704$ MeV/m, $\beta_{s,i} = 0.03312$, then

$$\Delta\epsilon_i = \pm 234.3 \left| \tan\phi_s - \phi_s \right|^{1/2} \text{ keV:}$$
$$= \pm 46.2 \text{ keV} \quad (\phi_s = 26^o)$$
$$= \pm 54.32 \text{ keV} \quad (\phi_s = 30^o) \qquad \text{... 4vi)}$$

and $\Delta\epsilon_{out} = \pm 2.015 \left| \tan\phi_s - \phi_s \right|^{1/2}$ MeV. Converting to momentum tolerance gives $\Delta p/p = \pm 5.515 \left| \tan\phi_s - \phi_s \right|^{1/2} \times 10^{-3}$, i.e.

$$\left(\frac{\Delta p}{p}\right)_o = \begin{cases} \pm 1.016 \times 10^{-3} & (\phi_s = 26^o) \\ \pm 1.303 \times 10^{-3} & (\phi_s = 30^o) \end{cases} \qquad \text{...4vii)}$$

and this compares with $(\Delta p/p) = \pm 1.5\times10^{-3}$ momentum tolerance required for injection into the 6 GeV 'booster' A.G.S.

Assume the linac to be correctly set up and on tune: i.e. each tank has the correct phase velocity, and the field and phase in each tank is correct to give the required output beam. Now let tank r have a field error ΔE and a phase error δ at the entrance, i.e. $E = E_r + \Delta E$ (where acceleration rate $= E_r \cos\phi_s$, and ϕ_s is constant throughout the linac) and $\phi = \phi_s + \Delta\phi + \delta$. It can be shown[13] that the equation for phase motion is now

$$\frac{d}{dz}\left[(\beta\gamma)_s^3 \frac{d}{dz}(\Delta\phi) \right] + (\beta\gamma)_s^3 \Omega_r^2 \Delta\phi = (\beta\gamma)_s^3 \Omega_r^2 \left\{ \frac{\Delta E}{E_r}\cot\phi_s - \delta \right\} \qquad \text{...4viii)}$$

where $\Omega = \left\{ 2\pi eE_r \sin(-\phi_s) \Big/ \lambda W_o c^2 (\beta\gamma)_s^3 \right\}^{1/2}$ is the phase oscillation angular frequency per metre, and $\Delta\phi, \Delta E, \delta$ are assumed small. According to equation 4 viii) a synchronous particle entering tank r will leave it with a phase error and a phase velocity error given by:

$$\Delta\phi = \left\{ \frac{\Delta E}{E_r}\cot\phi_s - \delta \right\} \left[1 - \cos\Omega_r L_r \right], \quad \frac{d}{dz}(\Delta\phi) = \left\{ \frac{\Delta E}{E}\cot\phi_s - \delta \right\} \Omega_r \sin\Omega_r L_r \qquad \text{...4ix)}$$

where L_r is the length of the tank. This added motion will propagate along the linac, and the resulting amplitude of phase oscillation at the output of the linac is given by (c.f. equation 4iii))

$$\Delta\phi_{n,o}^2 = \left(\Delta\phi^2 + \frac{1}{\Omega_r^2} (\Delta\phi')^2 \right) \left(\frac{E_r}{E_n} \right)^{1/2} \left(\frac{p_{r,o}}{p_{n,o}} \right)^{3/2}$$

$$\simeq \left\{ \left(\frac{\Delta E}{E_r}\right)^2 \cot^2 \phi_s + \delta^2 \right\} 2(1-\cos \Omega_r L_r) \left(\frac{E_r}{E_n}\right)^2 \left\{\frac{p_{r,o}}{p_{n,o}}\right\}^{3/2} \qquad \ldots 4x)$$

As pointed out in reference (14), since equation 4 viii) is linear in $\Delta\phi$ the effect of errors is additive, tank by tank. Taking $\frac{\Delta E}{E}$, δ to be r.m.s. values for the whole linac, and summing over the tanks, gives

$$\Delta\phi_T^2 = \left\{ \left(\frac{\Delta E}{E}\right)^2 \cot^2 \phi_s + \delta^2 \right\} \frac{2}{E_n^2 (\beta\gamma)_n^{3/2}} \sum_1^n E_r^2 (\beta\gamma)_r^{3/2} (1-\cos \Omega_r L_r) \qquad \ldots 4xi)$$

In equation 4xi) E_r is proportional to the acceleration rate in the r^{th} tank, and $(\beta\gamma)_r^{3/2}$ is evaluated at the output of each tank. The number of linear phase oscillations has been computed for each tank for values of $\phi_s = 26^o, 30^o$, giving:

Tank	Acc. rate (MeV/m)	$N\phi$ ($\phi_s=26^o$)	$N\phi$ ($\phi_s=30^o$)
1	1.655	1.487	1.618
2	1.620	2.14	2.329
3	1.498	0.946	1.029
4	1.271	0.692	.753
5	1.142	0.555	.604
6	1.082	0.459	.499
7	1.060	0.374	.407
8	1.045	0.322	.350

Evaluating equation 4xi) gives

$$\Delta\phi_T^2 = \left\{ \delta^2 + \left(\frac{\Delta E}{E}\right)^2 \cot^2 \phi_s \right\} \times \begin{cases} 14.168 & (\phi_s = 26^o) \\ 14.800 & (\phi_s = 30^o) \end{cases} \qquad \ldots 4xii)$$

Now $\Delta\epsilon_o = \Delta\phi_T / H$ where $1/H = \left\{ E_0 \sin(-\phi_s)\, \lambda\, W_o c^2 (\beta\gamma)_0^3 / 2\pi e \right\}^{\frac{1}{2}}$

Hence

$$\Delta\epsilon_o = \begin{cases} 6.0427\, \Delta\phi_T & (\phi_s = 26^o) \\ 6.5748\, \Delta\phi_T & (\phi_s = 30^o) \end{cases} \qquad \ldots 4xiii)$$

Converting to momentum tolerance gives

$$\left(\frac{\Delta p}{p}\right)_o = 0.6233 \left\{ \delta^2 + 4.2037 \left(\frac{\Delta E}{E}\right)^2 \right\}^{\frac{1}{2}} \qquad \phi_s = 26^o \qquad \ldots 4xiv)$$

$$= 0.06932 \left\{ \delta^2 + 3.00 \left(\frac{\Delta E}{E}\right)^2 \right\}^{\frac{1}{2}} \qquad \phi_s = 30^o$$

The machine was assumed to be correctly set up, so that the errors δ, $\left(\frac{\Delta E}{E}\right)$ in equation 4xiv) refer to variations during the pulse, and from pulse to pulse.

Injection into the 'Booster' A.G.S. requires that this momentum 'jitter' $\frac{\Delta p}{p}$ be not greater than $\pm$ 0.5 x 10^{-3}. Figure 1 shows values of δ, $\frac{\Delta E}{E}$ for ϕ_s = 20°, 30° to satisfy these limits: in particular for ϕ_s = 20° requires δ = 0.4°, $\left(\frac{\Delta E}{E}\right)$= 0.2..., and for ϕ_s = 30°, δ = 0.4°, $\left(\frac{\Delta E}{E}\right)$= 0.1...

The setting up and calibration of the linac by the possible use of time of flight method are discussed in section 5(e).

5. Mechanical Aspects of the Linac Design

The linac is seen to be in 6 tanks of diameter ranging from 97.5 cm to 76.5 cm, and the drift tube diameters (constant in each tank) ranging from 10.5 cm to 24 cm. Two methods of construction are well known:

i) Separate liner and vacuum vessel

ii) Integral vacuum vessel and liner made from copper clad steel.

The first method has been the one used in European linacs, whilst almost all linacs built in the U.S.A. have been built by the second. The actual costs of the two constructions are very similar, as indicated in section 2 in comparing the cost of structure with the Argonne ZGS injector. The choice here is dictated by the availability of copper clad steel (at the present time there appears to be one manufacturer in Europe, and two in the U.S.A.) the possibly high cost of transportation, and the cost of the appropriate vacuum system.

The main advantages of the copper clad steel construction follow from its simplicity: drift tube stems are mechanically supported from outside, frequency tuners move through only one wall, windows through the single wall permit visual inspection of components during operation, no wiring is exposed in the vacuum system, and the system is extremely rigid and mechanically reproducible. From the vacuum point of view the copper clad system is attractive since the total surface area exposed to vacuum is less by a factor ~ 3 than the separate vacuum tank and liner construction. The main disadvantage is in the accessibility of components. Towards the high energy end of the linac the drift tubes have diameters not much less than one third the liner diameter. Installation of drift tubes would be difficult. There would be little room for a man to get inside the tank to do maintenance or cleaning of drift tubes. For this reason a very clean vacuum system, probably using ion pumping, is essential for this system.

The advantages of the separate liner and vacuum tank system are in the separation of vacuum and r.f. joints in the liner, and the accessibility of components. Since there is a greater surface area than in the copper clad steel liner system, a greater pumping speed from the vacuum pumps is required. Oil or mercury diffusion pumps could be used though oil diffusion pumps are preferred since higher temperature baffles can be used, thus simplifying the cooling system. In either diffusion pump, it is not possible to eliminate back streaming completely, and sooner or later cleaning the structure becomes necessary. The use of these pumps is advisable only where the structure can be opened up easily, and the components are accessible.

Existing copper clad steel structures are made up from approximately 3 metre length tubes bolted together to form the long resonant cavities. There is some advantage to be gained by increasing the length of sections to 6 m (by butt welding two 3 m sections) to reduce the number of vacuum and r.f. joints. Thus a tank 24 m long would have 3 joints instead of 7. (If the length of sections is increased further the gain is no longer great). Six metre lengths are practicable in terms of transport. The separate liner and vacuum tank system allows manufacture of single resonators up to the maximum required length of about 25 m. This method, however, leads to transport difficulties, and it may be preferable to use shorter length of the order of 12 m and to weld the lengths together on site. Drift tube manufacture and alignment would be similar in both cases, though extra strengthening ribs for the copper clad vessel may be needed to prevent distortion, and misalignment, under vacuum.

Cost estimates have been obtained for the two methods of construction with their relevant vacuum systems. In each case the cost of the structure is similar, though there may be a large difference in transportation costs:

		£
(a)	Vac. Tank, liner construction (see section 2)	794,000
	Vac. system: oil diff. pumps and 2-stage gas ballast pumps; including safety and control system.	157,000
	Transport	?
(b)	Integral Cu-clad steel vac. tank and liner (see section 2)	610,00
	Vac. system: Varian pumps, primary, Kinney, pumps Secondary, Turbomolecular, pumps; including safety and control system.	250,000
	Transport	?

It is clear that the second system would increase the total cost given in section 2 by about 5%. Against this increase, is, inter-alia, the cleanness of the vacuum system, and hence increased reliability. It might be a compromise solution to have the first, and perhaps second, tank built on the separated system, where accessibility to maintain drift tubes (e.g. polishing after multipactor damage) is desirable, and the remainder of the linac built using copper clad steel.

One further item deserves mention. In the design given in this report, the drift tubes are right cylinders of constant diameter in a tank; of constant aperture, inner and outer profile radii along the whole linac. Alternative shapes, e.g. ellipsoidal drift tubes, or 'Christofilos' drift tubes as on the Brookhaven AGS and Argonne ZGS injectors, could be used, and may give marginally better values of shunt impedance, and hence cost factor. The use of right cylinder drift tubes suggested here has two advantages i) mechanical simplicity, so that standard templates and formers could be used. (This advantage is small since the cost of profiling is only about 5% the total cost of the drift tube); ii) quadrupoles of standard size (e.g. cross-section) could be used. The major part of the cost of the drift tubes is fabrication and encapsulating quadrupoles. In the total manufacture of about 250 drift tubes, standardisation in the mechanical design of quadrupoles could achieve considerable saving.

6. Machine Reliability

The total percentage operating time achieved by any machine is dependent upon a large number of factors, some of which are affected by the design and monitoring features of the machine. In many cases, with good monitoring facilities, it is possible to predict the on-set of a fault before it is sufficiently advanced to cause lost time. Into this category falls minor vacuum and water leaks, minor r.f. arcing, fall off in emission of the r.f. amplifiers and other electronic equipment, and loss of proton current due to trouble in the ion source.

Even though adequate monitoring is available, some of the above faults will lead to loss of operating time and some will inevitably develop into more major occurencies.

Experience on the Rutherford Laboratory Proton Linear Accelerator is that, for a three tank machine plus experimental area facilities, percentage operating times of up to 95% are possible over period of two to four weeks and an average overall percentage in excess of 80% is feasible. (Recent experience with this machine is that, for a six months period, overall operating percentages in excess of 90% have been achieved. This figure, in fact includes some time lost for the Polarised Proton Source, which of course will not be used on the new machine.)

The P.L.A. is quite a good model for the linac considered here since, although it is a high duty cycle machine (2% compared with about 0.1%) the average power levels per cavity, including beam power, are similar (about 20 kW compared with 10 kW). The design of quadrupoles and cooling for the cavities will be easier for the linac, but the r.f. system will be more complex to off-set this.

The relevant faults which have occurred on the Rutherford Laboratory P.L.A. during 1962 and 1963 are analysed in appendix B. From the figures presented it is possible to make an extrapolation for the linac considered here. Fault figures for beam lines, bending magnets and quadrupoles are included as being representative of the beam transport system. The lost time due to major faults mentioned in appendix B will not be included in the extrapolation, but will be included in the overall total. The percentages of time lost due to major faults for 1962 (1963) was 2.1% (2.8%). The Injector, Buncher, Mains Services, Ancillary Equipment, Beam Transport System and Common Drive System are all items which are repeated for the linac in a <u>similar</u> form to the Rutherford Laboratory P.L.A. Therefore the fault time for these items is totalled separately. The percentage of time lost on these items for 1962 (1963) was 6.2% (4.4%).

The total fault time for the three tanks of the Rutherford Laboratory P.L.A. is multiplied by a factor of 8/3 for the eight tank linac to give the effective percentage of time lost for 1962 (1963) as 26.6% (16.5%).

Thus on this basis the total percentage of experimental time to be expected on the eight tank linac for 1962 (1963) is 65.1% (76.3%).

It is probable that on the bigger machine, with a reliability comparable to that of the P.L.A. for 1963, a greater number of faults will occur together, so that the figure of 76% may well be increased to about 80% or even higher. It should be possible using known and tested components to achieve this order of reliability within the first year of operation of the new machine.

In common with existing machines, the injector linac would become more reliable as the operating staff become more skilled in diagnosing or even preventing faults. The overall reliability is very dependent upon the rating of individual components compared with their maximum rating. Experience also indicates that electronic equipment operates more reliably if the ambient temperature does not exceed 25°C. Therefore, subject to these requirements, percentage reliability of the order of 85% could reasonably be expected within the first two years of operation.

7. <u>Conclusions</u>

The basic criteria in the design of a proton linear accelerator have been established. In particular, the balance between shunt impedance and r.f. voltage breakdown at the required operating frequency has been formulated to give a cost optimum. In the 200 MeV Injector Linac design considered, the accuracy claimed is to within 5-10%, both in costing and dimensional calculation. A practical r.f. system design has been given, which by use of all available modulator power, achieves a considerable shortening of the total r.f. pulse length, with resulting reduction in duty cycle, and hence cost. Further, reliability of operation of the order of 85% can be reasonably expected within two years of commissioning.

Clearly much detailed work remains. Focusing requirements must be studied. Detailed dimensional data must be found by computation and model measurements. The precise matching of the r.f. source to the system will depend on the particular amplifier used, and will affect the final pulse length (to within ± 10% of the values quoted). The methods of calibration, control, and monitoring need much more detailed study. More dynamical calculation will give an accurate prediction of the linac performance. The fundamental problem of the effect of low energy velocity in the structure on axial field distribution, and hence on bea ion, under pulse and heavy beam loading conditions needs study. (Possible solutions are the use of multiple feeds, and a structure with high group velocity). Alternatives to the Alvarez structure are worth investigation, particularly in view of high group velocity as well as good shunt impedance. The Crossed-Bar Structure, which does have these features, and also good bandwidth, and r.f. breakdown capability, is at present being investigated to this end.

8. Acknowledgements

The authors would like to express their gratitude to Messrs. W. Walkinshaw and J. M. Dickson for much helpful discussion, also to Mr. D. Carpenter for assistance in computation. They would also like to express their thanks to members of Marconi Ltd., Great Baddow, for useful discussion on the r.f. system.

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Appendix A

Design of Tank 1

In the design of a Tank 1 covering so small an energy range (0.5 to 5 MeV), the requirements of good beam dynamics (i.e. good phase and radial acceptance, good output beam) are more important than economy. In particular the drift tubes must be designed for their ability to house a practicable quadrupole system with sufficient aperture rather than for, say, optimum shunt impedance. Further it has been the experience on most linacs that the low energy cells have been the most troublesome in terms of multipactor and spark breakdown, so that accessibility for easy maintenance is a very desirable feature. The new Tank 1 (0.5 to 10 MeV) of the Rutherford Laboratory P.L.A. has been designed with these features in mind, (6, for fuller details) for which the Tank 1 for this present design could be taken. It has the following parameters:

$D/\lambda = 0.65$, $d/\lambda = 0.121$

$r_1/\lambda = 0.00493$, $r_0/\lambda = 0.0131$ (= half length of 1st drift tube)

$g/L = .233 - .277$ (at 5 MeV)

Polarity $n = 2$, radial wave number $\mu = \pi/2$

Effective magnet gradient $G = k\,\beta^{-m}$, $1.2 \leq m \leq 1.6$

The drift tube aperture has been chosen according to the equation

$$a = 0.650928 + 0.047598\,N - 0.001104\,N^2 + 0.000008\,N^3 \text{ (N is no of cell)} \qquad A)$$

The variation of aperture according to A) results in a nearly flat axial field, thus enabling easy setting-up of the tank.

The distribution and amplitude of the E-field over the surface of the drift tubes has been studied using a wedge shaped electrolytic tank. Two maxima were found on each drift tube surface, at positions roughly where the profile radii blended into the drift tube flats. Curves of E_s (maximum surface field) and E_z (mean axial field) are shown in figure 13. It can be seen that, for an acceleration rate 1.704 MeV/m, no surface field greater than 12.8 MV/m, at the inner profile radius of drift tube number 1, is to be expected. (In the complete 10 MeV design, the value of E_s (inner) is seen to decrease, whilst E_s (outer) increases, becoming <u>dominant</u> at about 6.5 MeV). A report on the Redesign of the Rutherford Laboratory Tank 1 is to be published.

Appendix B

Fault analysis for the Rutherford Laboratory P.L.A.

The overall operating times for each month are shown as percentages of scheduled time in Figure 4. The machine operates on a schedule of ten days for experiment, followed by four days for machine maintenance and installation of experimental equipment. On alternate maintenance periods two days are set aside for testing of new equipment, and systems checks. In addition, it is sometimes possible to operate parts of the machine overnight during the maintenance periods. The last twelve hours, overnight, of any maintenance period is utilised to run up and optimise the machine in preparation for an experimental run. In addition, during 1962-63 some 17 hours of scheduled time was used for calibration and optimization of the machine. This time will be deducted from the overall total for our estimates. Some time which was lost due to faults in equipment associated with the experimental program has also been counted in the published figures for the P.L.A. This time will also be omitted from our calculations.

A long 4-6 week shut for installation of major items of new equipment is usually scheduled to include September of each year.

The faults encountered on the P.L.A. are l[illegible]low:-

		1962	1963	
(a)	Pre-injector			
	E.H.T. platform and ion source (including power supplies, cabling controls and E.H.T. "flash over")	53	33	hours
	Generator, alternator, platform blowers and gun resistors.	16	16	hours
	Vacuum and cooling systems.	4	5	hours
	Total	73	54	hours

Total for Pre-injector = 127 hours

		1962	1963	
(b)	Buncher	3	3	hours

Total for Buncher = 6 hours

		1962	1963	
(c)	General Services (compressed air, water, refrigeration and main electricity supply failures).	39	33	hours

Total for General Services = 72 hours

		1962	1963	
(d)	Run-up and calibration periods	5	36	hours

Total for Run-up and calibration = 41 hours

		1962	1963	
(e)	Ancillary Equipment			
	Bending magnets, quadrupoles, supplies for beam lines, remote controls and monitoring including the master trigger unit	27	30	hours
	Beam line vacuum system	10	2	hours
	Experimental equipment	17	18	hours
	Total	44	50	

Total for ancillary equipment excluding Experimental equipment faults = 69 hours

(f) Low Power Drive

	1962	1963	
Power supplies and r.f. valve replacement (including modulators, primary frequency source, frequency multiplier chain, sub-modulators, overload protection, controls and cabling).	89	51	hours
Co-axial lines	0	2	hours
Total	89	53	hours

Total for Low Power Drive = 142 hours

(g) Power Dividing Network

	1962	1963	
Power Dividing Network (includes coaxial line attenuators, phase shifters and water loads)	13	13	hours

Total for Power Dividing Network = 26 hours

(h) High Power Drive

	1962	1963	
Power supplies (including modulators, sub modulator, controls, overload protection and cabling).	32	45	hours
Grounded grid triode amplifier	20	8	hours
Coaxial lines.	4	0	hours
Total	56	53	hours

Total for High Power Drive = 109 hours.

(i) Tank 1

	1962	1963	
Power supplies (including modulator, sub modulator, controls, overload protection and cabling)	25	16	hours
Grounded grid triode amplifier	55	64	hours
Vacuum and cooling circuits.	17	148	hours
Ancillaries (including coaxial lines, Faraday cups, vacuum window assembly and tilt and frequency tuners).	28	16	hours
Total	125	244	hours

Total for Tank 1 = 369 hours

(j) Tank 2

	1962	1963	
Power supplies (including modulator, sub-modulator, controls, overload protection and cabling)	175	23	hours
Grounded grid triode amplifiers	52	47	hours
Vacuum and cooling circuits	4	58	hours
Ancillaries (including coaxial lines, Faraday cups, vacuum window assembly and tilt and frequency tuners).	44	3	hours
Total	275	131	hours

Total for Tank 2 = 406 hours

		1962	1963	
(k)	Tank 3			
	Power supplies (including modulator, sub-modulator, controls, overload protection and cabling).	80	26	hours
	Grounded grid triode amplifiers	5	56	hours
	Vacuum and cooling circuits	90	5	hours
	Ancillaries (including coaxial lines, Faraday cups, vacuum window assembly and tilt and frequency tuners).	33	25	hours
	Total	208	112	hours

Total for Tank 3 = 320 hours

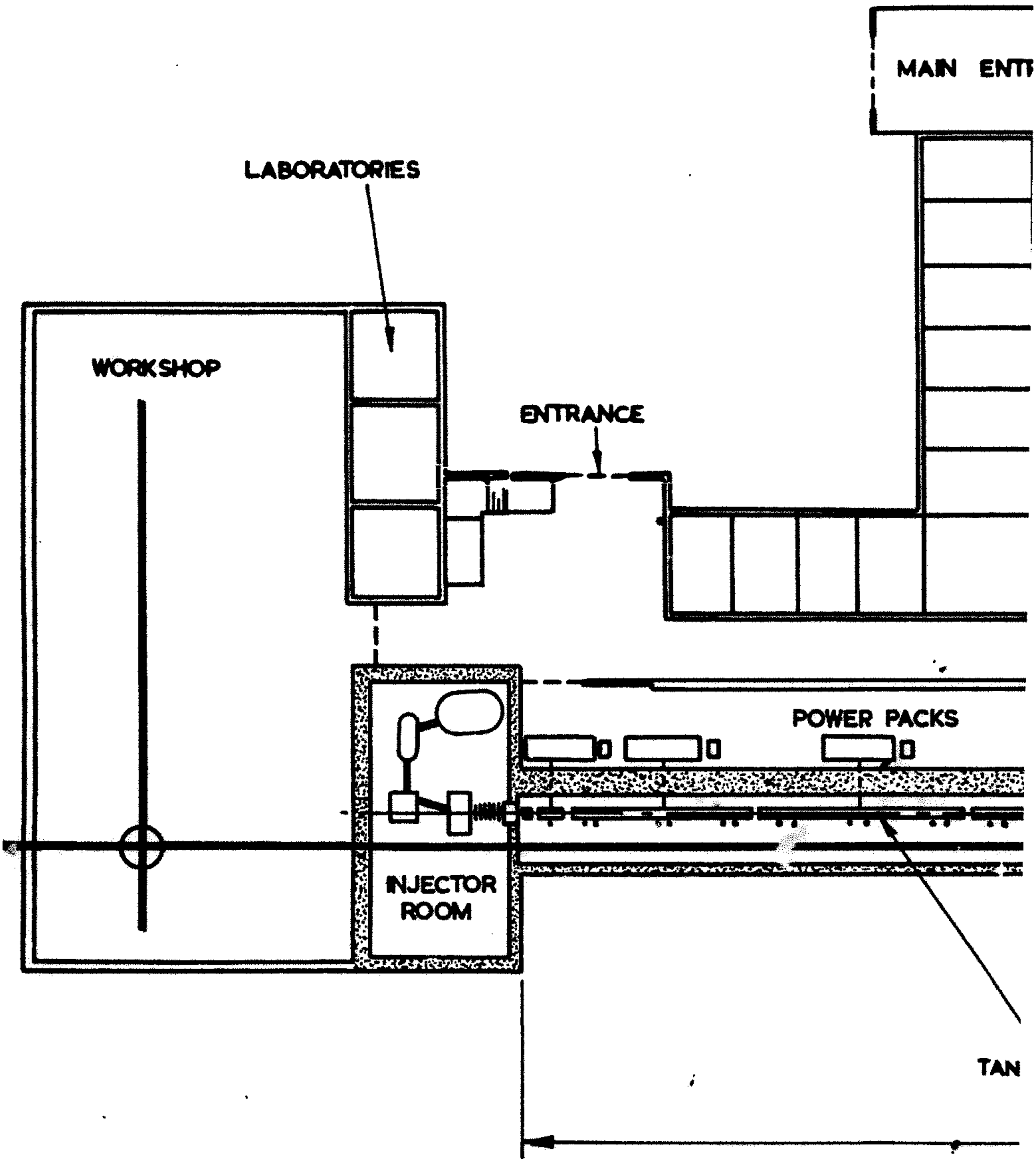
Total fault time for 1962	=	930 hours
Total scheduled experimental time	=	5040 hours
Percentage of scheduled time available for experiment	=	81.5 %
Total fault time for 1963	=	782 hours
Total scheduled experimental time	=	5465 hours
Percentage of scheduled time available for experiment.	=	85.6 %

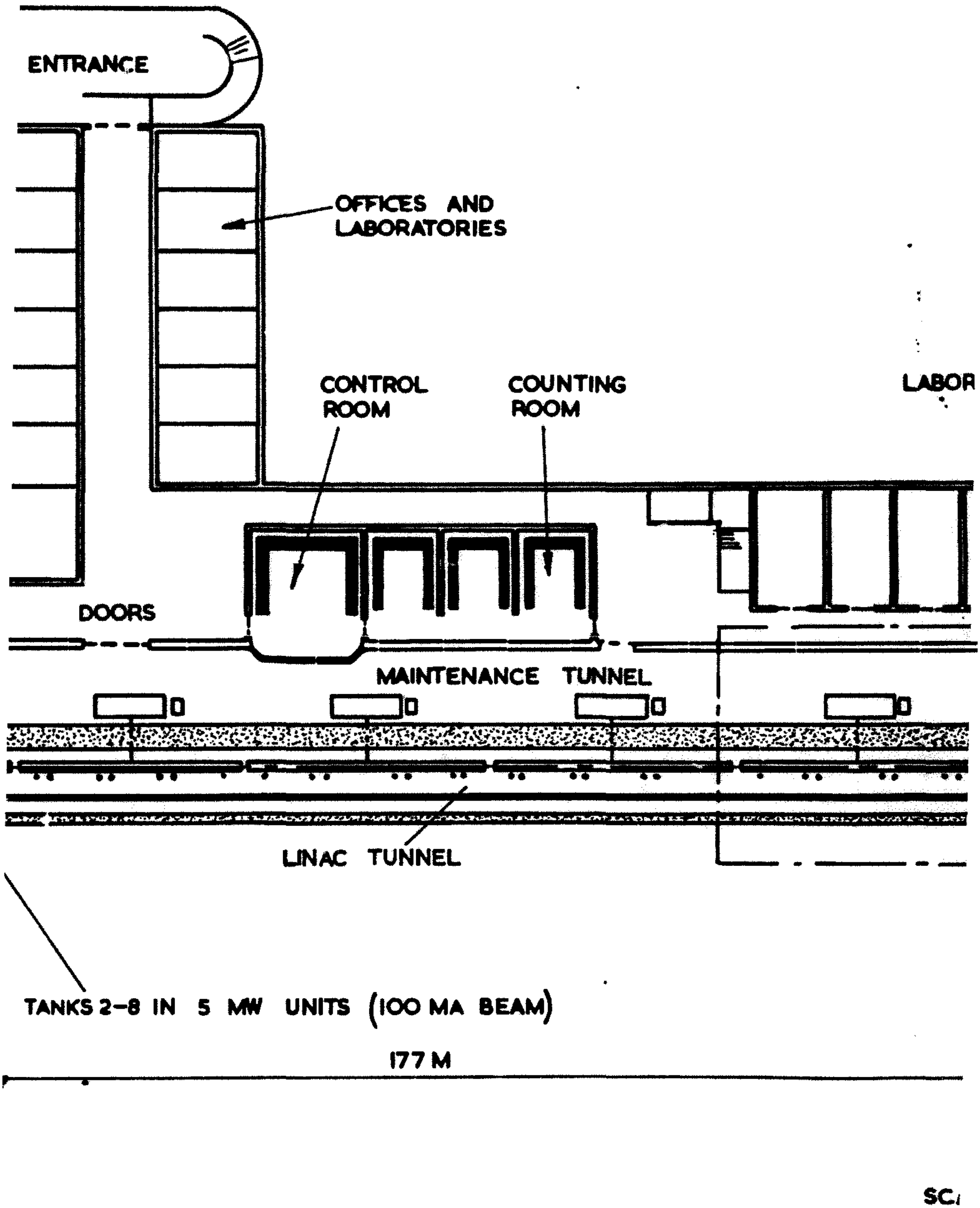
Note: These percentages are greater than the published ones (14) due to the omission of time lost on the polarized proton source which is, of course, not relevant to the application considered here.

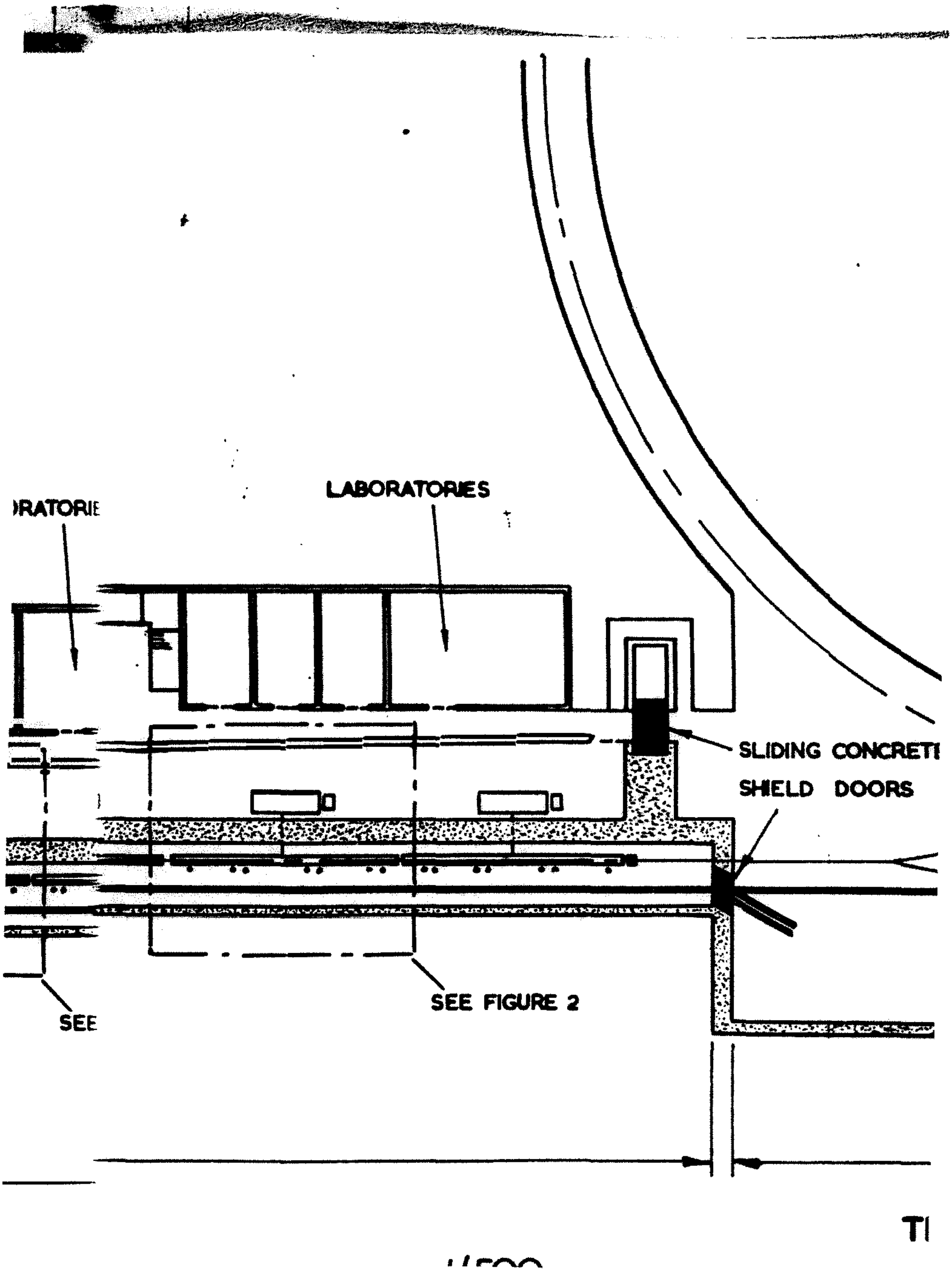
There are notable improvements in some of the figures for 1963 if compared with the corresponding ones for 1962. During 1962-63 improvements were made to the frequency tuner drive system and controls resulting in much lower figures for 1963. The ignitron switch tubes for the modulators for tanks 2 and 3 and, more recently, Tank 1, and the high Power Drive, have been replaced by new deuterium thyratrons with resulting improvement in fault time. Improvements have also been made to the grid control circuitry of the excitron power supplies for these modulators. However, this reduction in fault time has, to some extent, been off-set by water leaks in the cooling circuits of Tank 1 and Tank 2 which gave rise to an overall loss of 150 hours. Comparable losses for 1962 totalled 105 hours. It is possible that the figures for grounded grid triode valve replacement would be bettered in a machine using sealed off valves, but they may be off-set by faults in the external circuitry and more complicated control circuits. The average time for a valve change including run up and calibration was 17 hours. This figure is rather high due to the fact that in some cases the valve, the various component parts of which are replaceable, was repaired "in situ." Currently a valve change takes between 8 and 10 hours.

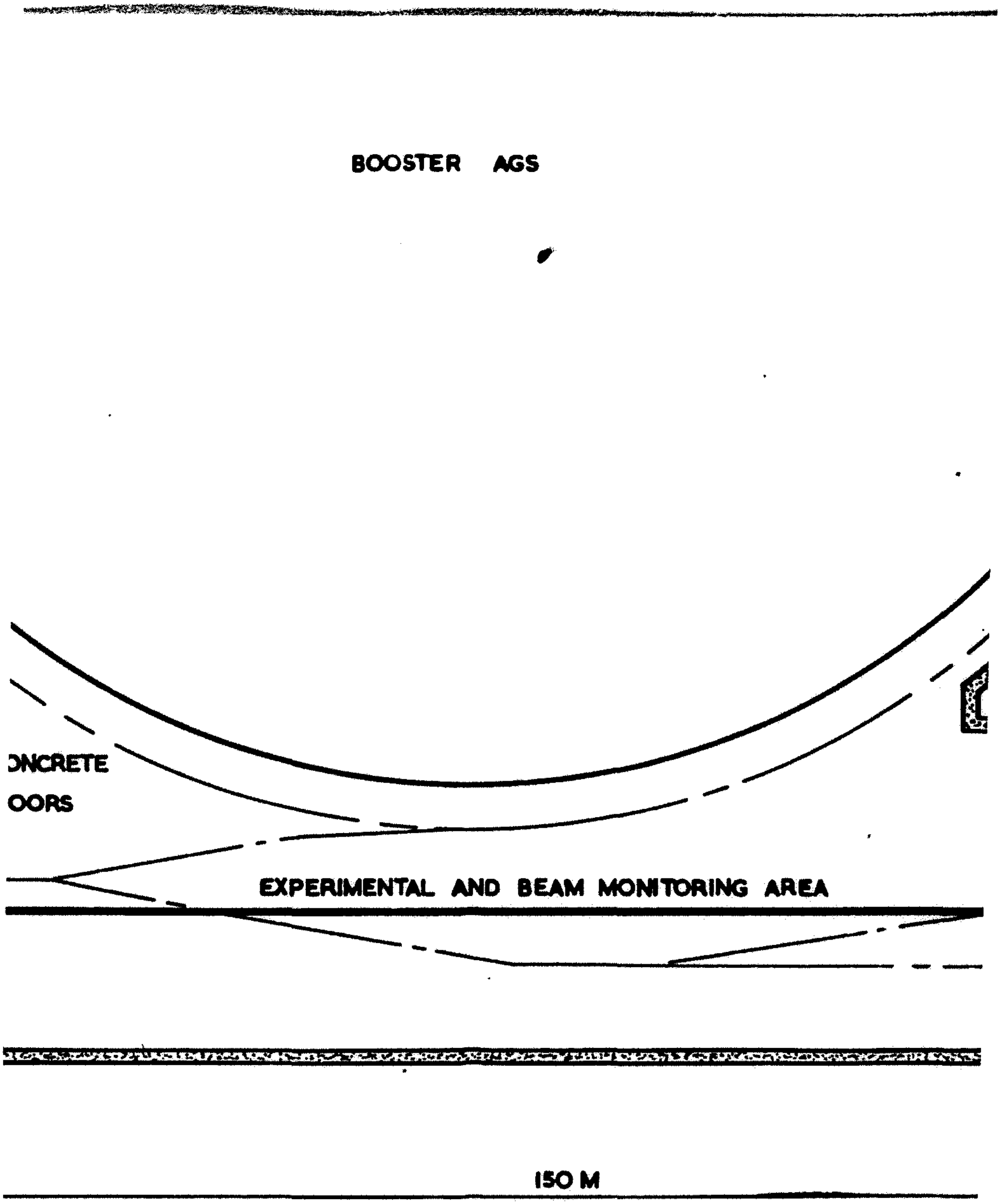
Comparing the total number of faults recorded of 819 in 1962 with the 383 of

1963 it is seen that the percentages of lost time do not bear a direct relationship to the totals for lost time. This is because faults do not always occur singly. The number of faults involving two or more items was 169 in 1962, compared with 29 in 1963, the total number of faults included in these figures being 534 and 61 respectively. Therefore the effective number of faults was 450 for 1962 and 351 for 1963. These numbers are in good agreement with the percentages given in section 6.

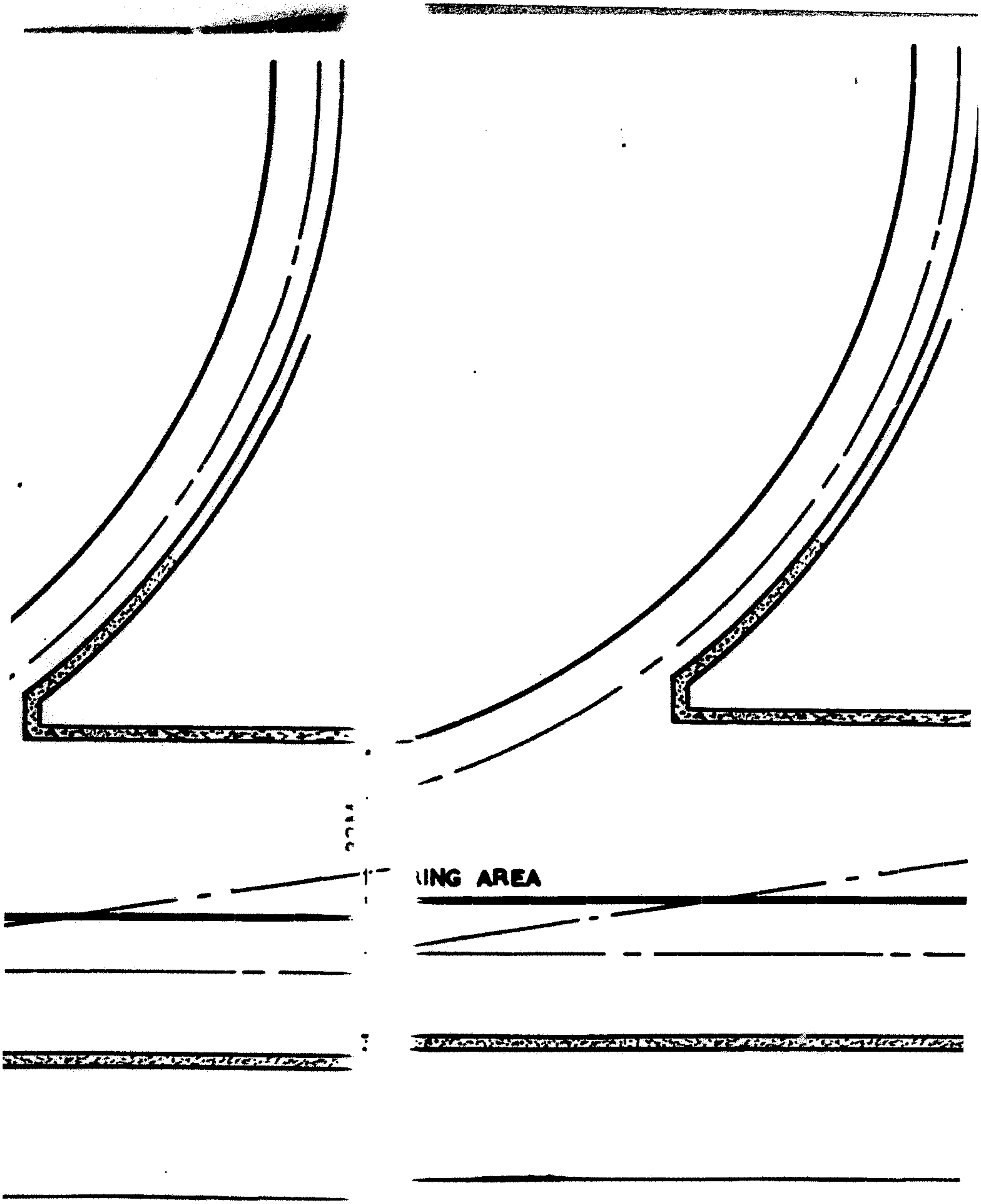

MAIN ENTI
LABORATORIES
WORKSHOP
ENTRANCE
POWER PACKS
INJECTOR
ROOM
TAN


ENTRANCE
OFFICES AND LABORATORIES
CONTROL ROOM
COUNTING ROOM
LABOR
DOORS
MAINTENANCE TUNNEL
LINAC TUNNEL
TANKS 2–8 IN 5 MW UNITS (100 MA BEAM)
177 M
SC


LABORATORIES
SLIDING CONCRET
SHIELD DOORS
SEE FIGURE 2

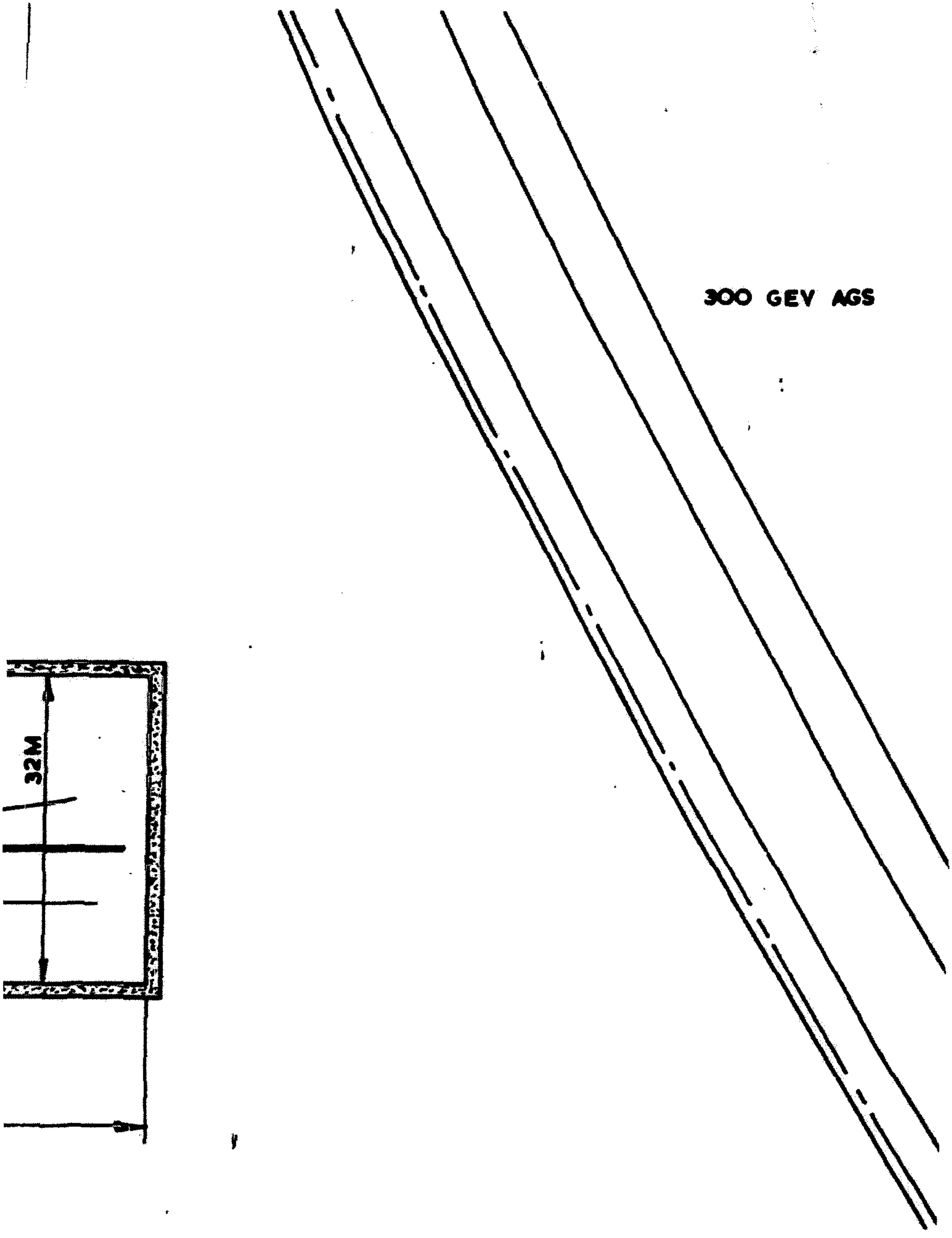


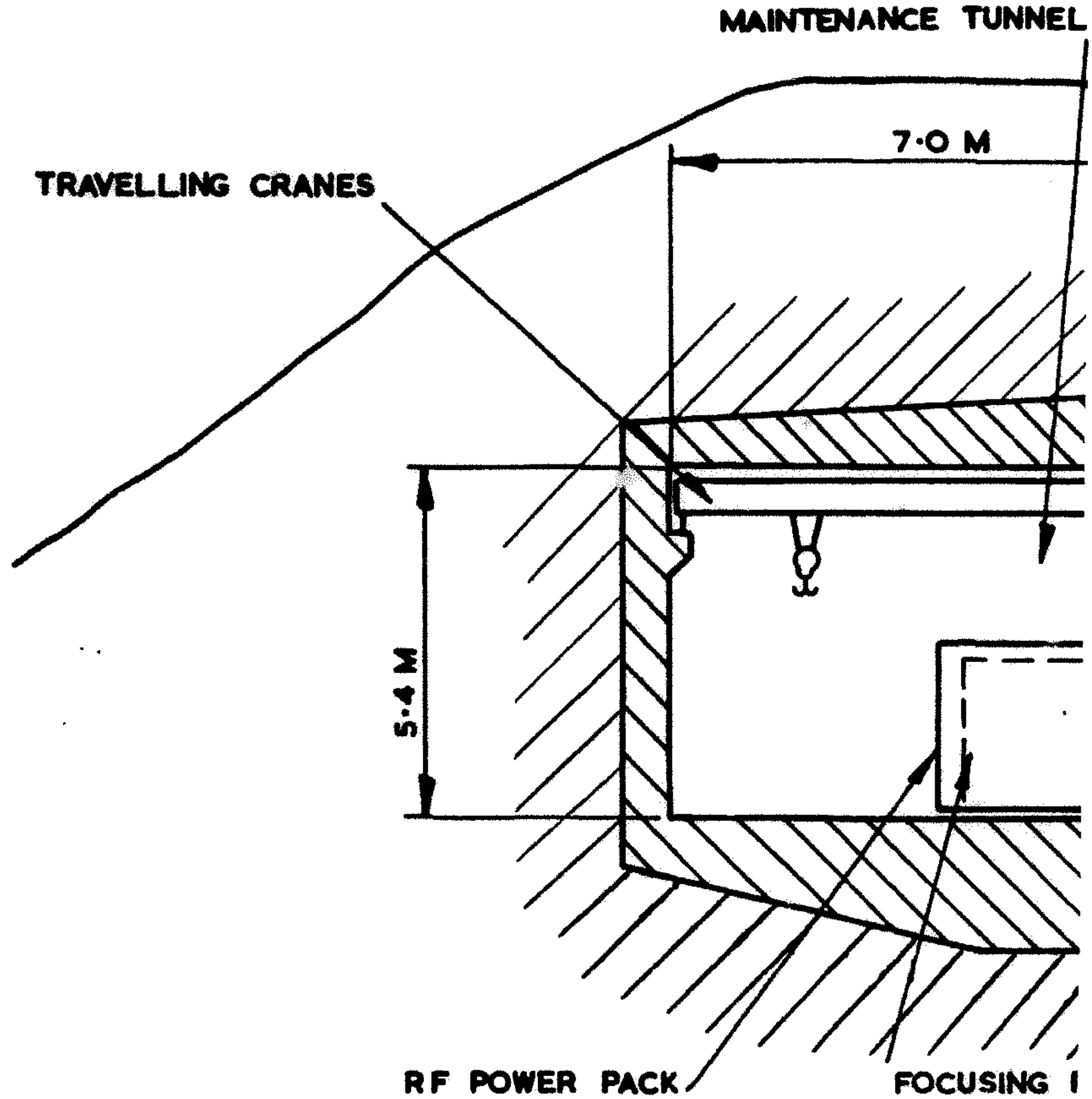
TENTATIVE LAYOUT FOR A 200 MeV LINAC.

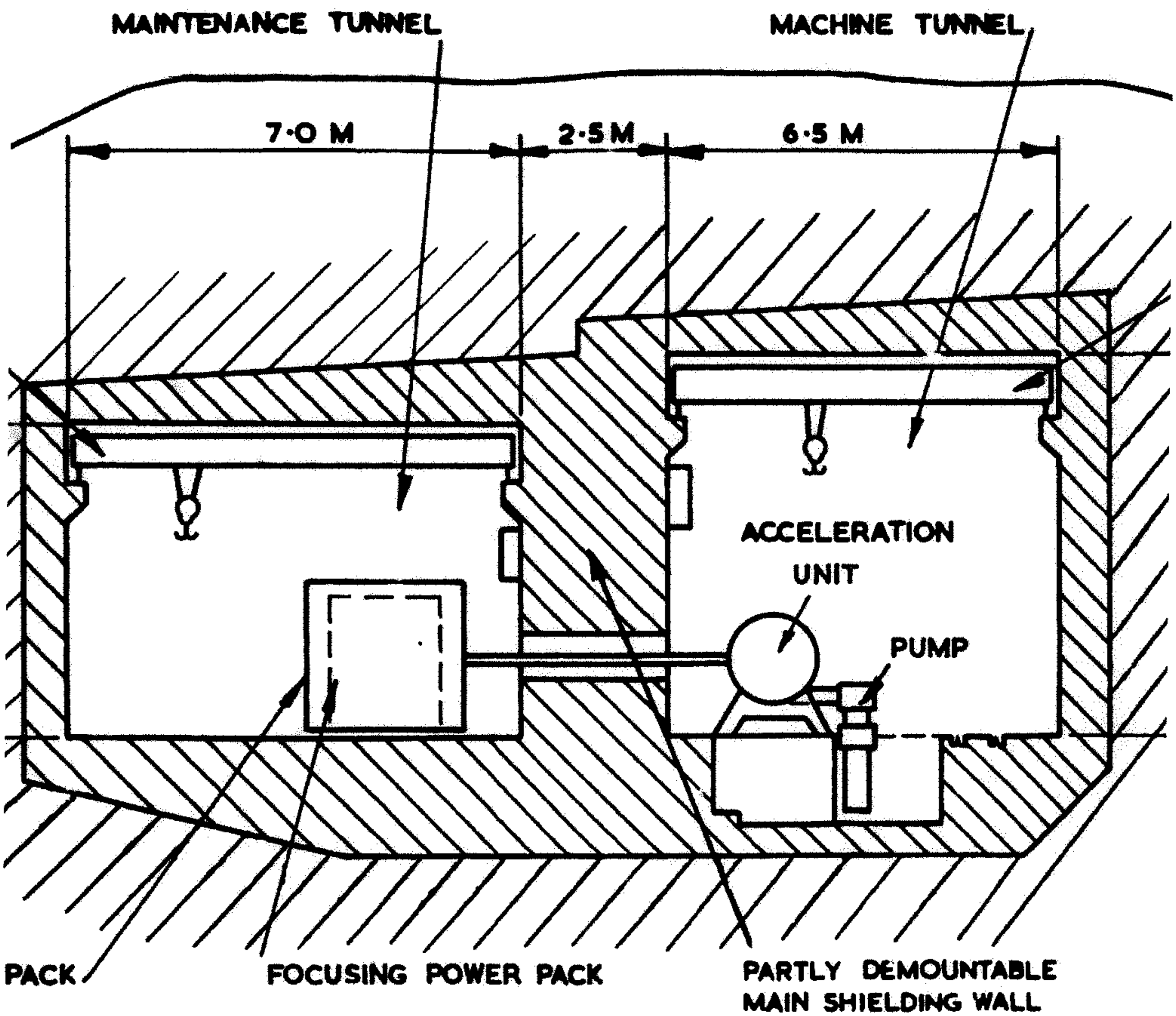


:. FIGURE 1

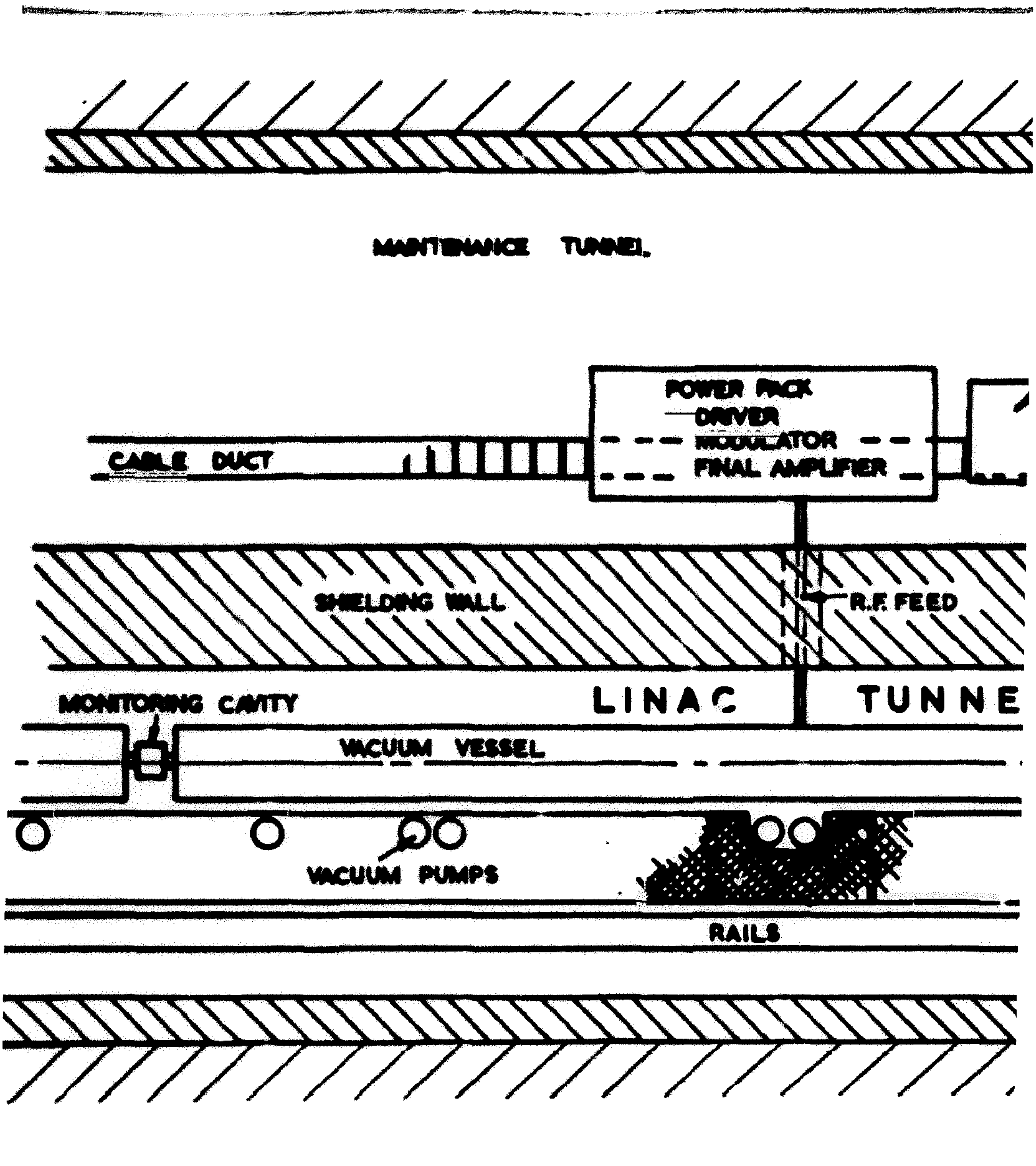
O MeV LINAC. FIGURE 1


300 GEV AGS
32M

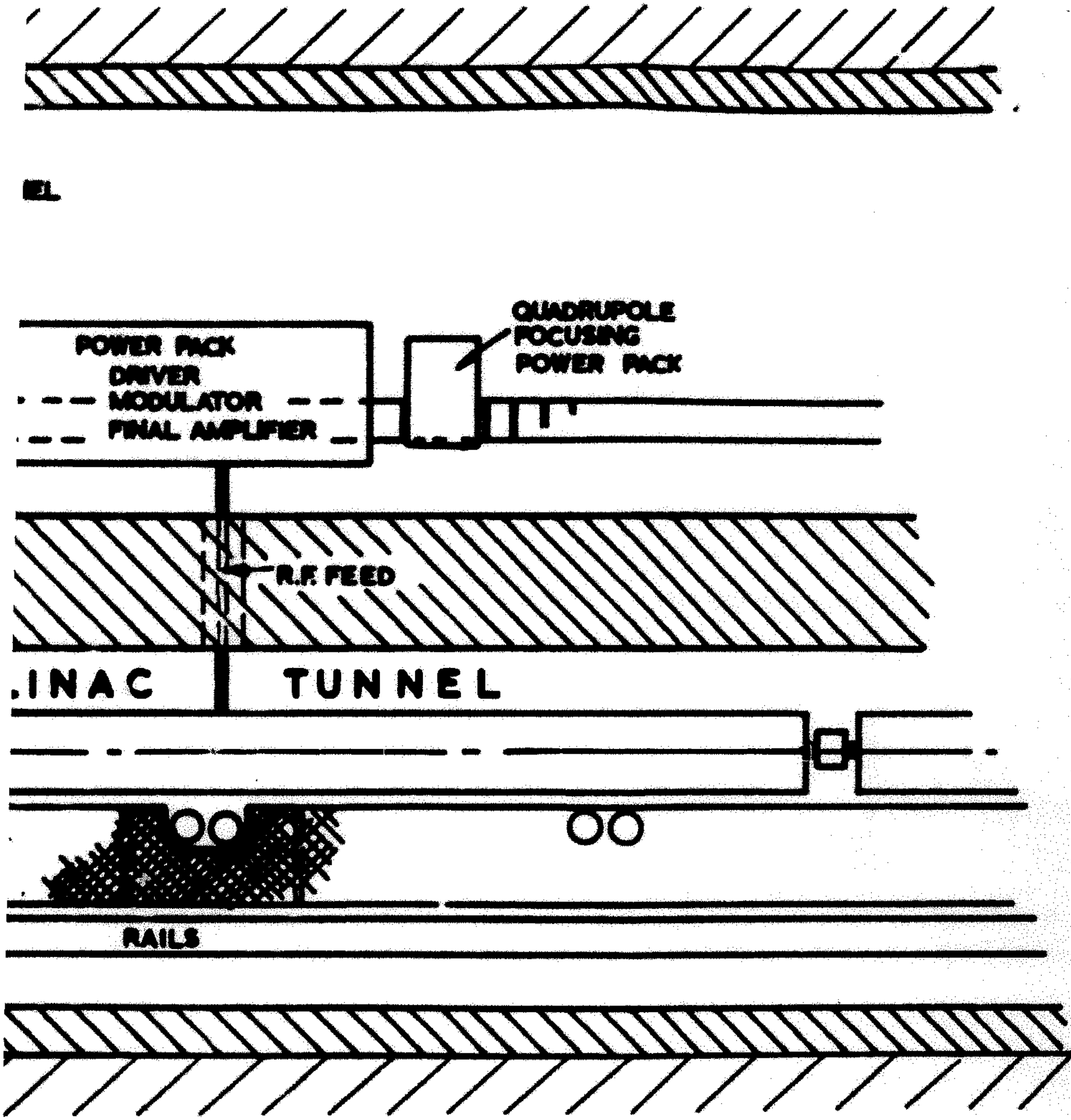

MAINTENANCE TUNNEL
7·0 M
TRAVELLING CRANES
5·4 M
RF POWER PACK
FOCUSING



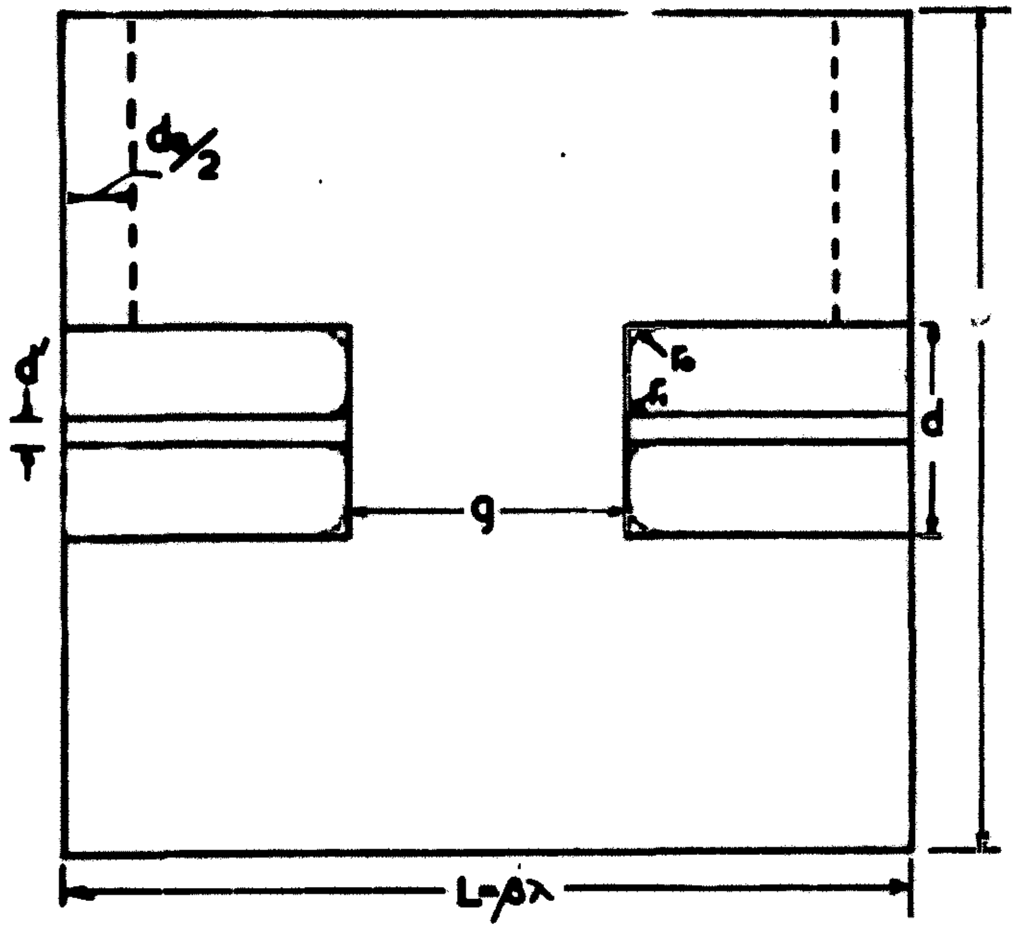
MAINTENANCE TUNNEL
MACHINE TUNNEL
7·0 M
2·5 M
6·5 M
ACCELERATION
UNIT
PUMP
PACK
FOCUSING POWER PACK
PARTLY DEMOUNTABLE
MAIN SHIELDING WALL



TENTATIVE LAYOUT FOR A 200 MeV LINAC. FIGURE 2

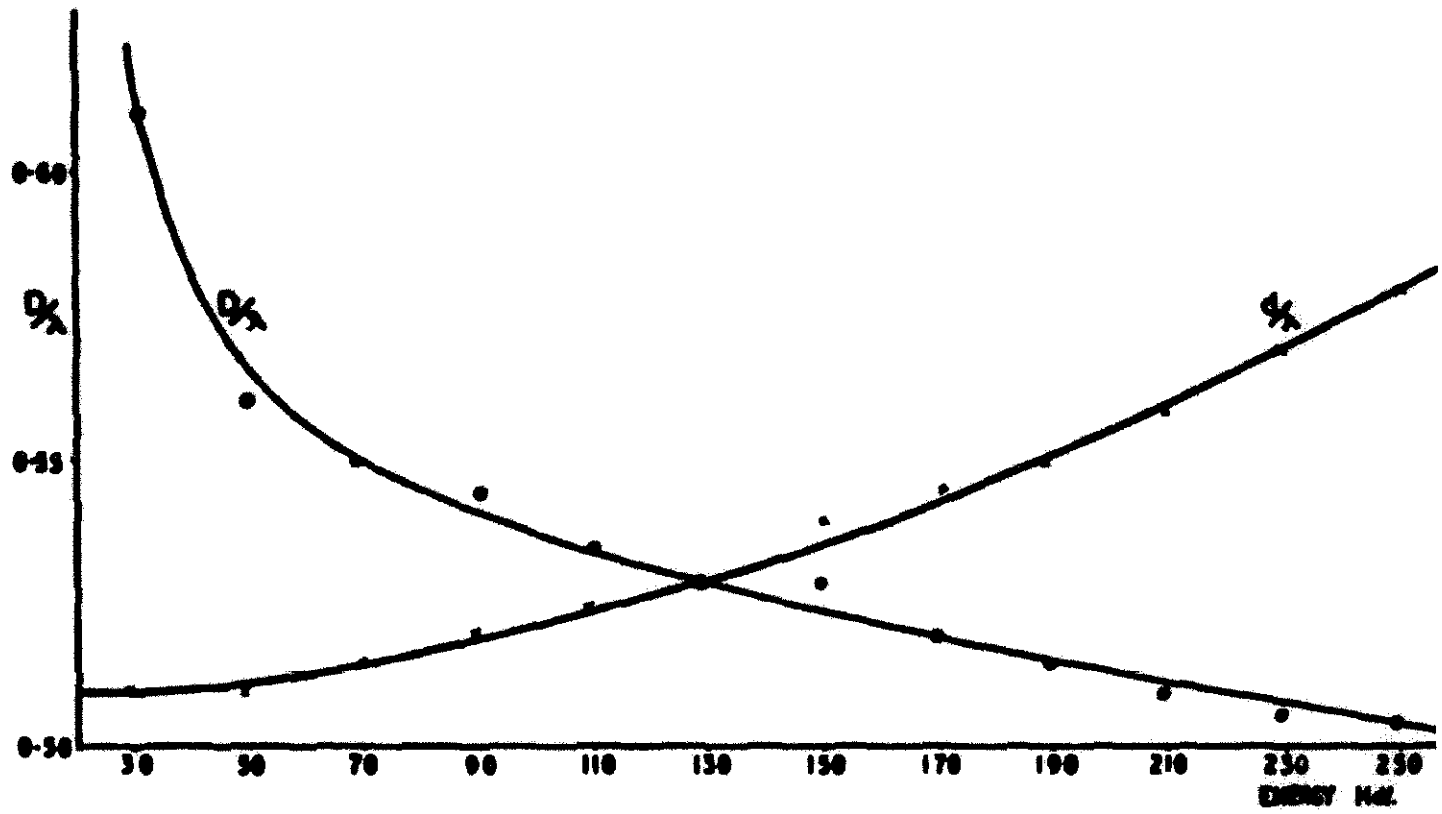


MeV LINAC. FIGURE 2



UNIT ALVAREZ CELL

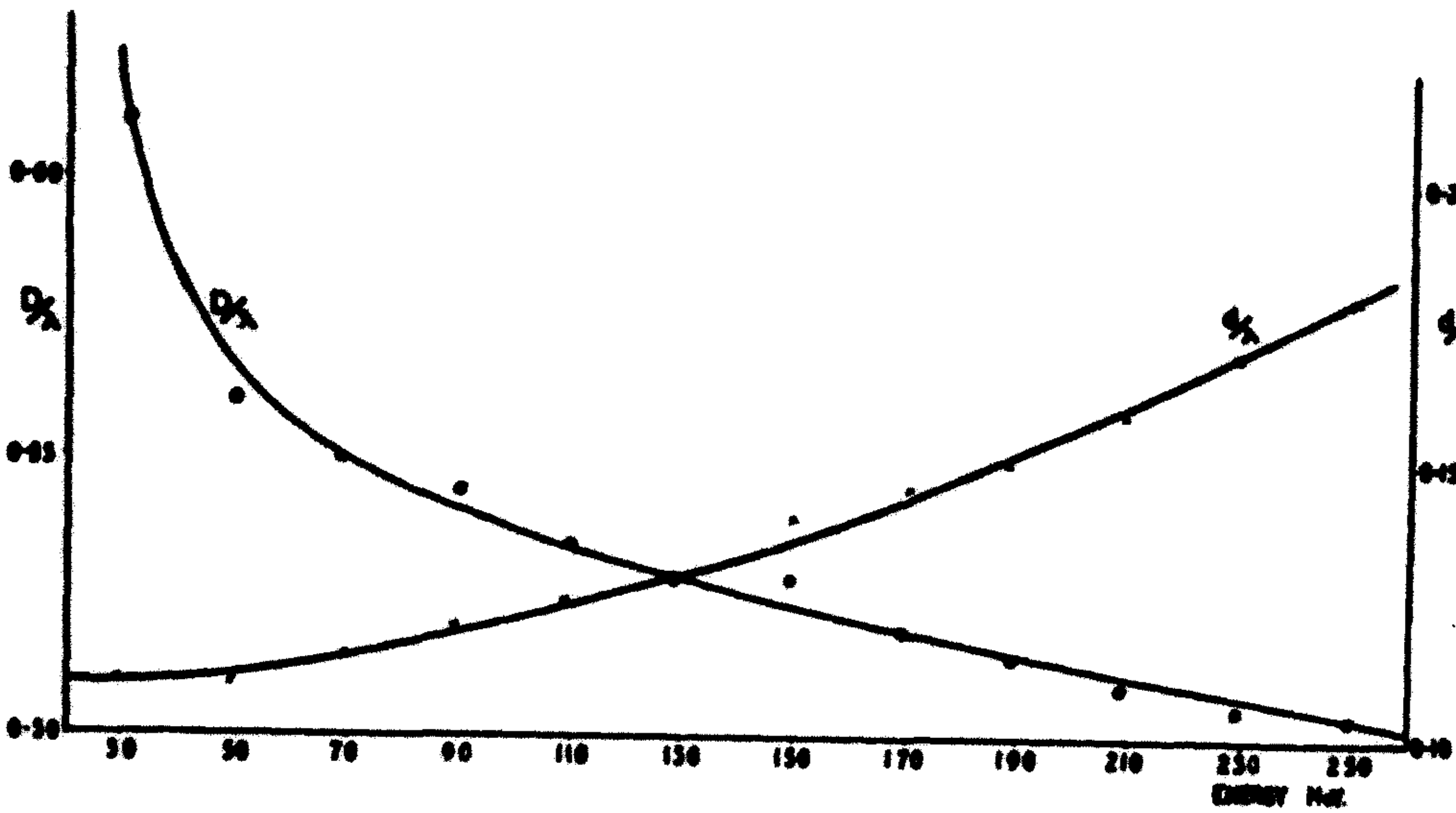
FIG. 3.



OPTIMISED D/λ & d/λ FOR 200Mc/s ALVAREZ STRUCTURE
(BASED ON $SP \cdot (A \cdot B/\beta)L$ AGAINST VARIATION OF D/λ, d/λ)

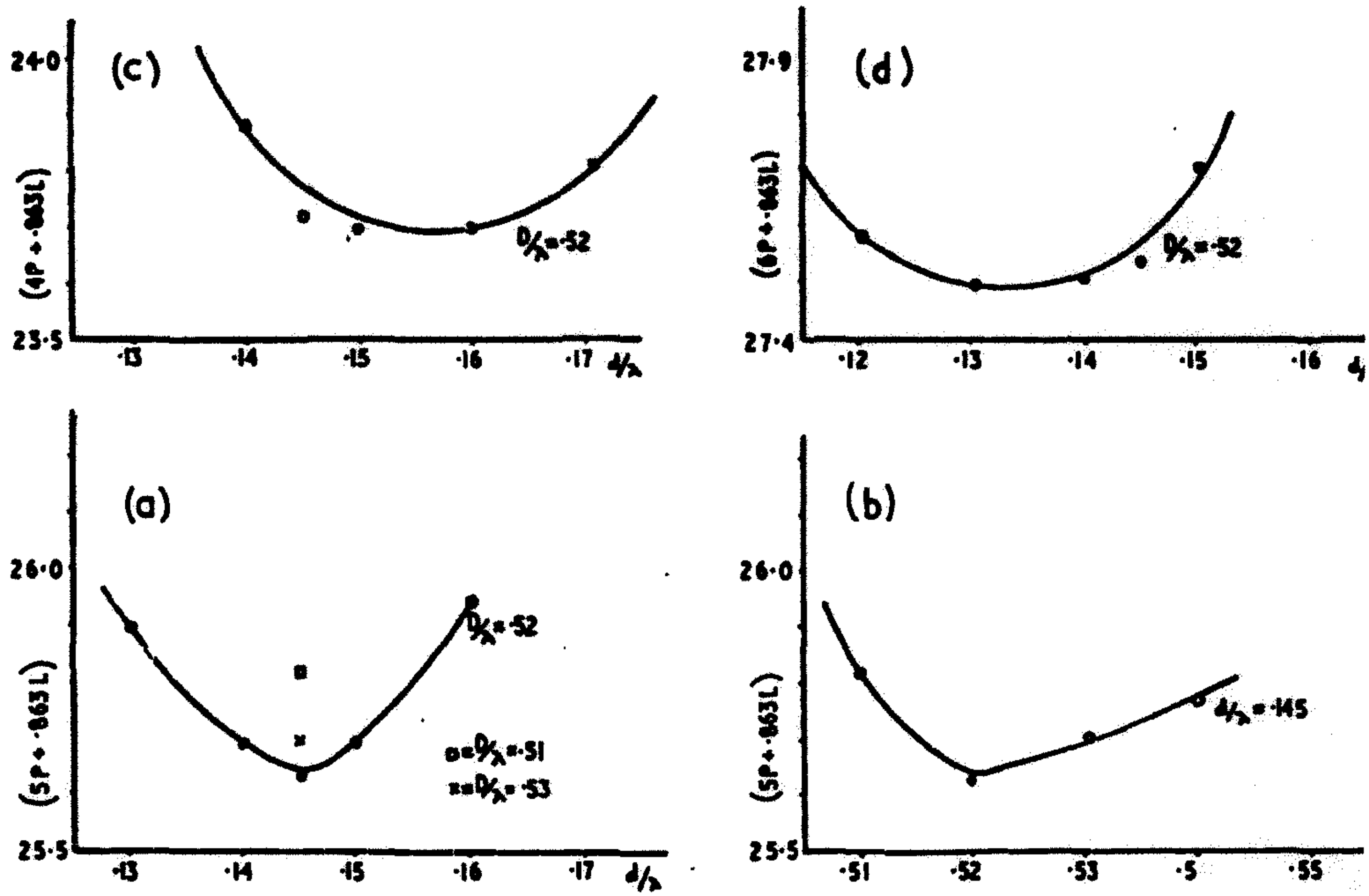
FIG. 4

TENTATIVE LAYOUT FOR A 200 MeV L



OPTIMISED D/λ & d/λ FOR 200Mc/s ALVAREZ STRUCTURE
(BASED ON SP·(A+B/β)L AGAINST VARIATION OF D/λ, d/λ)

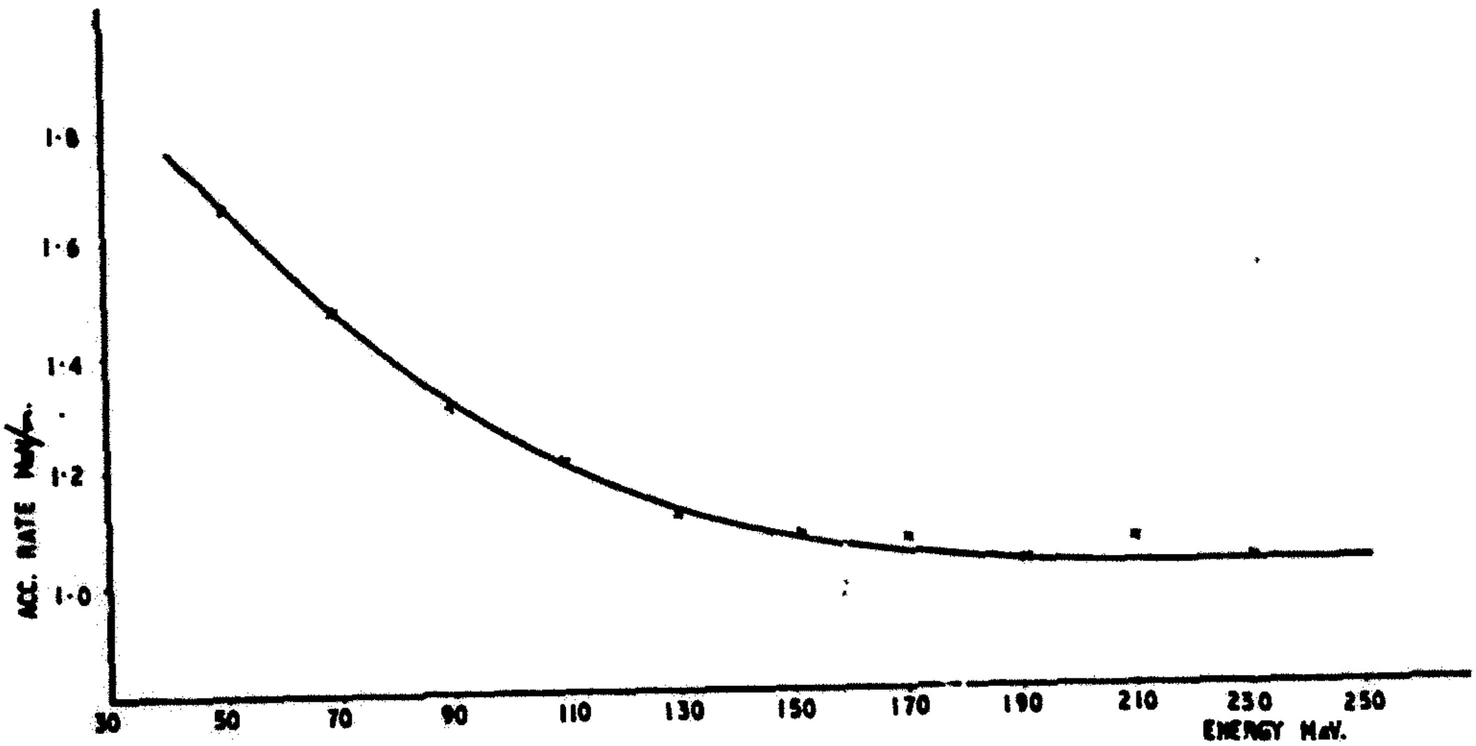
FIG. 4



COST OPTIMISATION WITH d/λ, D/λ AT 170 MeV.

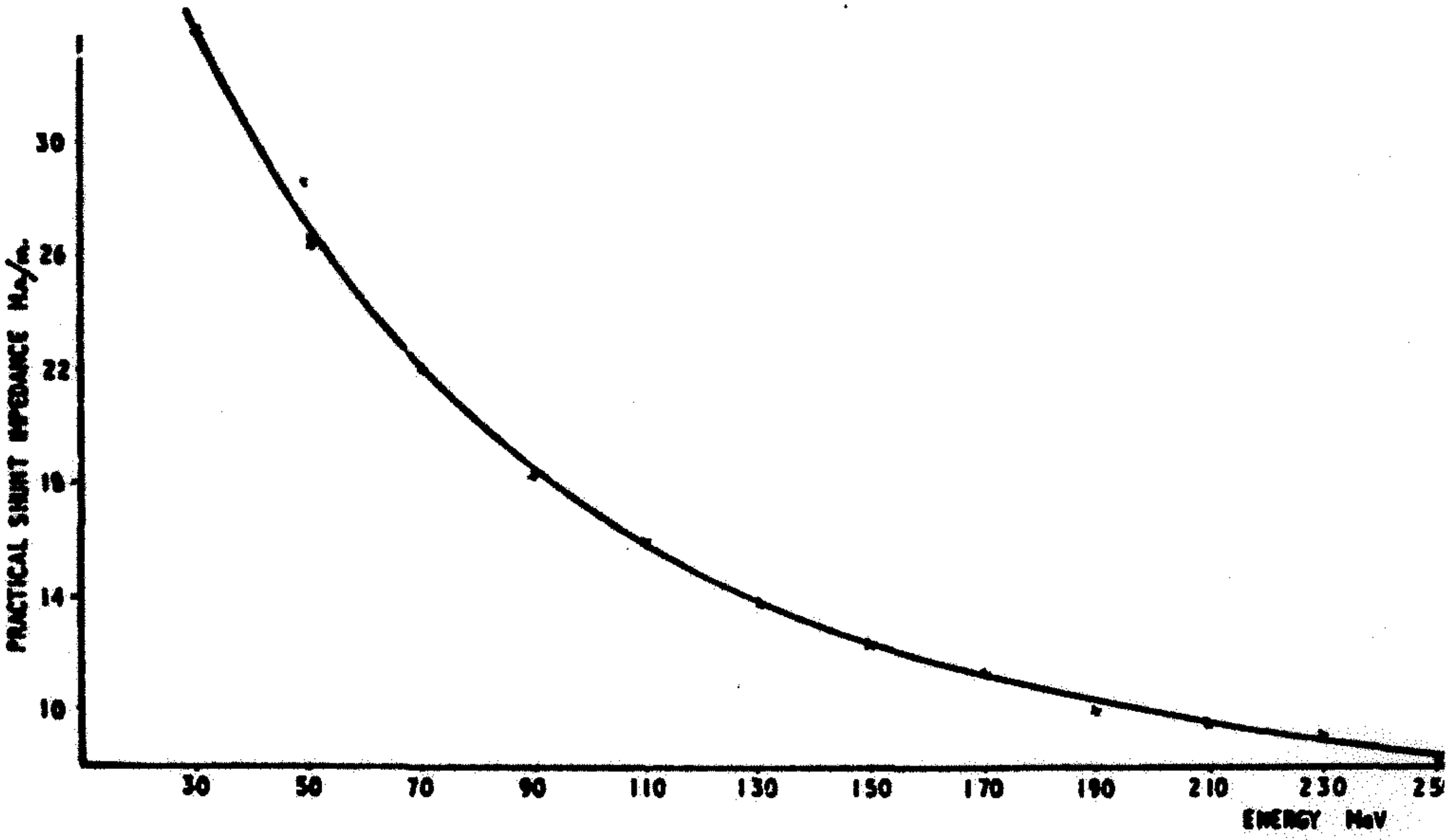
GRAPHS SHOW VARIATION OF COST WITH; (a) VARIATION OF d/λ, D/λ CONSTANT
(b) VARIATION OF D/λ, d/λ CONSTANT
(c) & (d) VARIATION OF POWER REQUIREMENTS OF ± 20%

FIG. 5



ACCELERATION RATE OF OPTIMISED STRUCTURE v ENERGY

FIG.6



PRACTICAL SHUNT IMPEDANCE OF OPTIMISED STRUCTURE v ENERGY

FIG. 7

200 MeV LINAC   8 TANKS, IN 5 MW UNITS

Tank number		1	2	3	4	5	6	7	8
Energy (start–end)	MeV	·66 – 5	5 – 37	37 – 67	67 – 98	98 – 124	124 – 151	151 – 178	178 – 200
β (start–end)		·035 – ·103	·103 – ·276	·276 – ·358	·358 – ·431	·431 – ·469	·469 – ·508	·508 – ·54	·54 – ·56
Length	m	2·718	17·41	20·05	22·85	24·57	24·54	23·96	23·27
Liner diameter	cm	97·5	88	82·5	81	79·5	78·75	77·25	76·5
Drift-tube diameter	cm	18·15	16·5	17·25	18	19·5	20·5	21·75	24
Drift-tube apert. diam.	cm	1·44 – 2·49	3·81	←	→	→	→	→	3·81
D/λ		·65	·58	·55	·54	·53	·525	·515	·51
d/λ		·121	·11	·115	·120	·130	·137	·145	·160
Range of g/L		·233 – ·277	— ·343	·230 – ·335	·330 – ·370	·367 – ·408	·417 – ·432	·420 – ·437	·432 – ·442
ro/λ		·0131	·0254	←	→	→	→	→	·0254
ri/λ		·0049	·00847	←	→	→	→	→	·00847
Total power	MW	1	5	←	→	→	→	→	5
Accelerat. rate	MeV/m	1·655	1·820	1·498	1·291	1·142	1·088	1·060	1·065
Q			61000	55000	52000	51000	50000	49000	48000
Effect. shunt impedance	MΩ/m	34·8	37·80	27·02	21·36	17·52	14·88	13·14	11·88
Practical shunt imped.	MΩ/m	29	31·50	22·52	17·80	14·60	12·40	10·95	9·90

FIG.8 PARAMETERS OF COMPLETE LINAC

N.I.R.N.S. RUTHERFORD HIGH ENERGY LABORATORY P.L.A. CLA 7

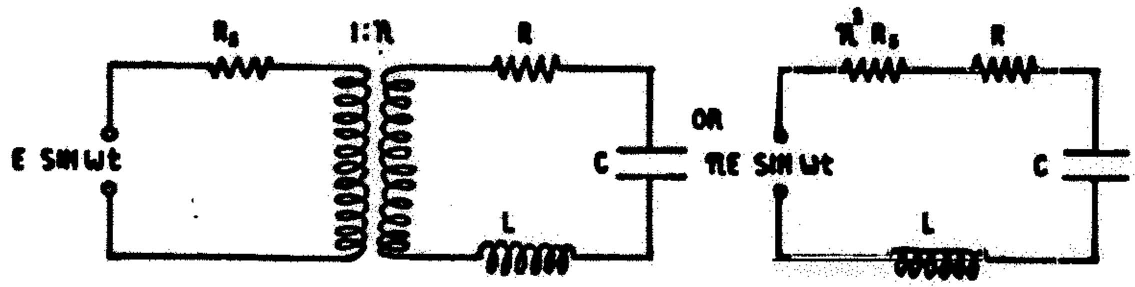


FIGURE 9a. EQUIVALENT CIRCUIT FOR A RESISTIVE SOURCE IMPEDANCE AT THE LOOP TERMINALS.

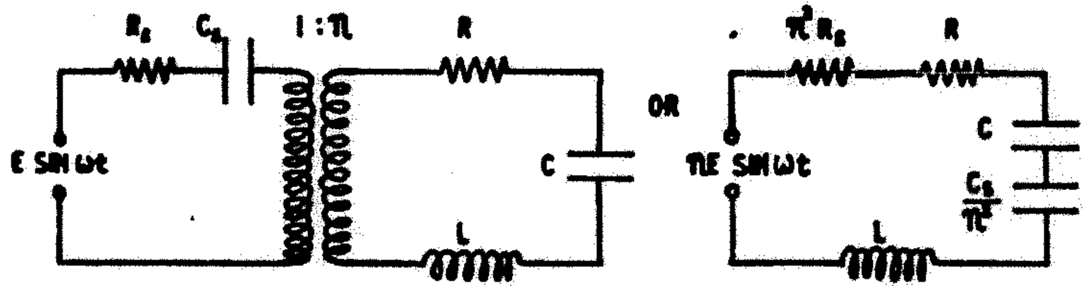


FIGURE 9b. EQUIVALENT CIRCUIT FOR A RESISTIVE AND CAPACITIVE SOURCE IMPEDANCE AT THE LOOP TERMINALS.

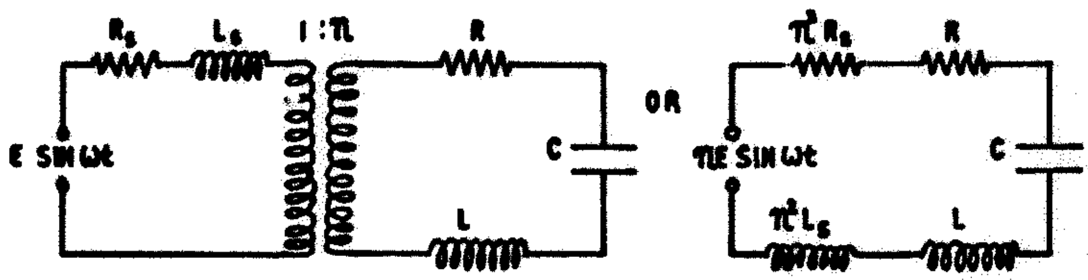
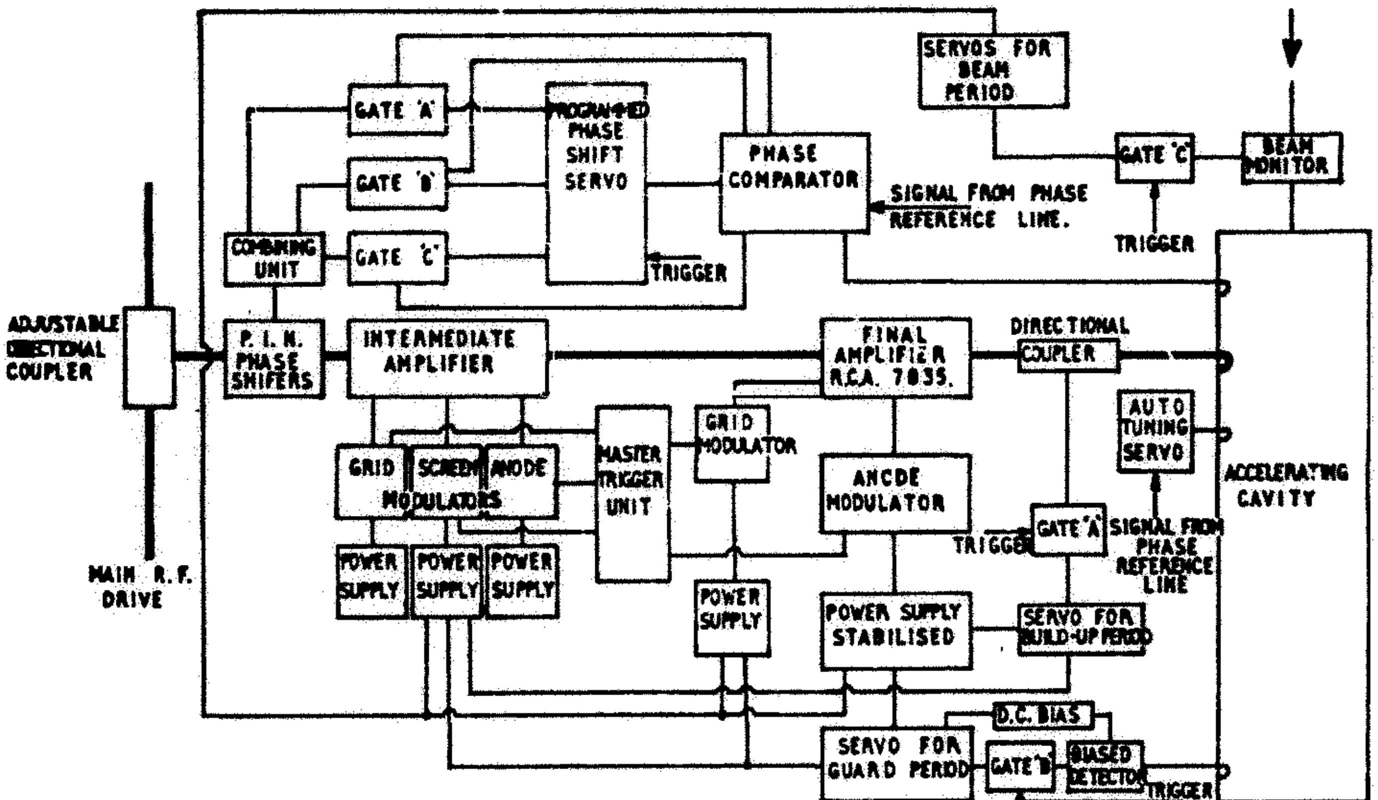


FIGURE 9c. EQUIVALENT CIRCUIT FOR A RESISTIVE AND INDUCTIVE SOURCE IMPEDANCE AT THE LOOP TERMINALS.

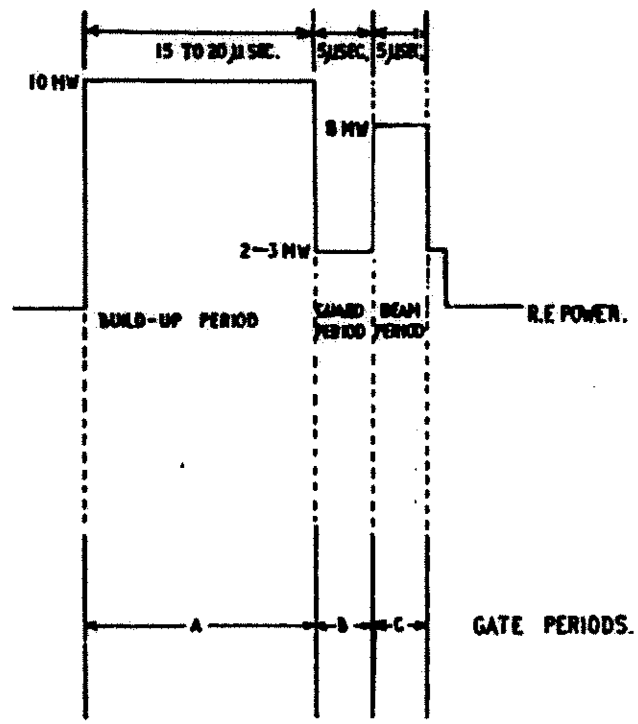
R.F. SYSTEM TANK EQUIVALENT CIRCUIT.

FIGURE 9.



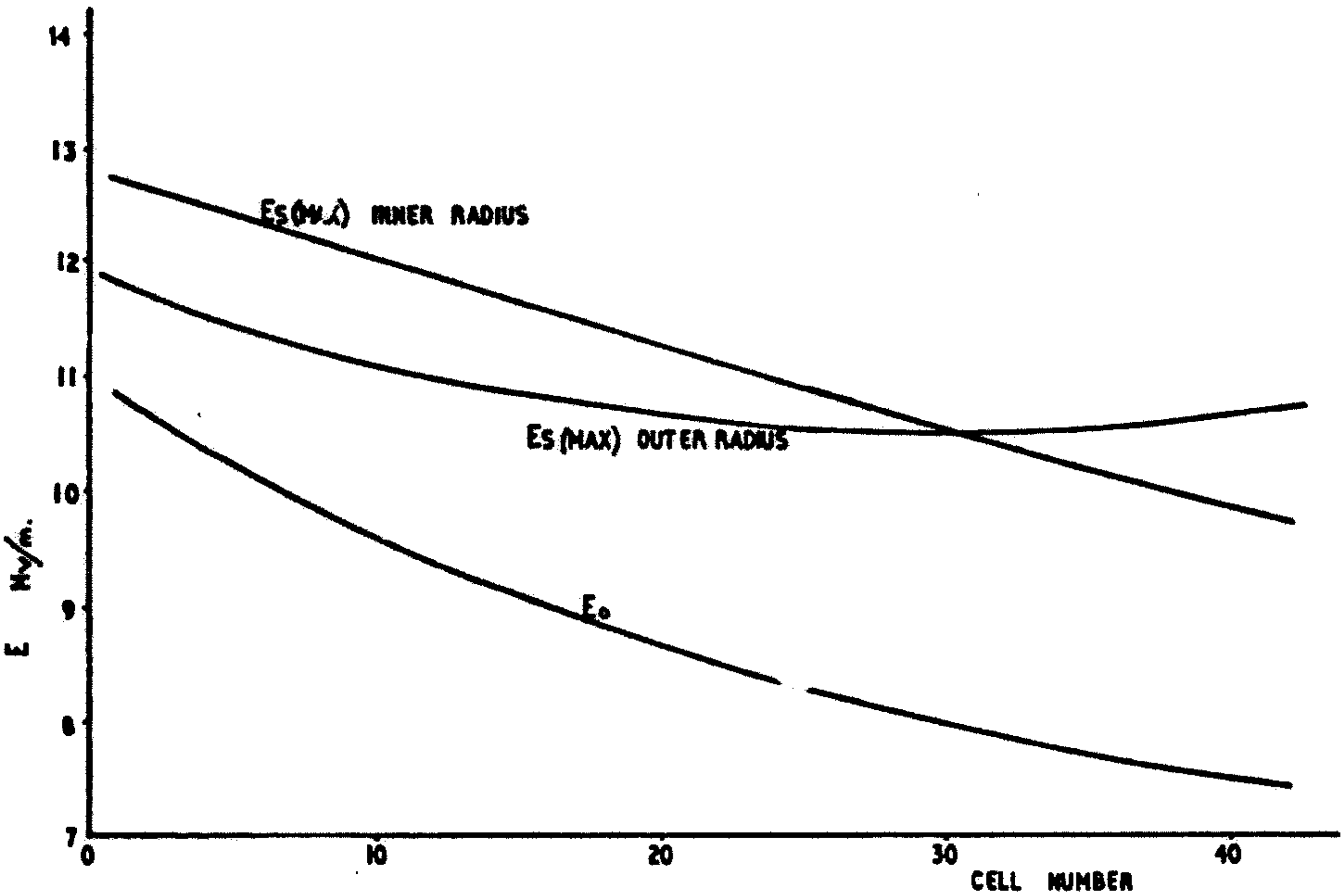
BLOCK SCHEMATIC OF A POSSIBLE R. F. DRIVE SYSTEM FOR AN ACCELERATING CAVITY.
[OVERLOAD PROTECTION HAS BEEN OMITTED]

FIGURE 10.



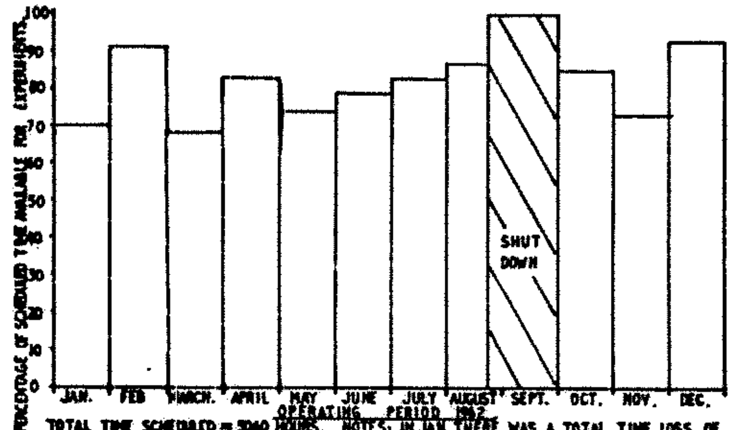
R. F. PULSE POWER PROGRAM.

FIGURE. II.



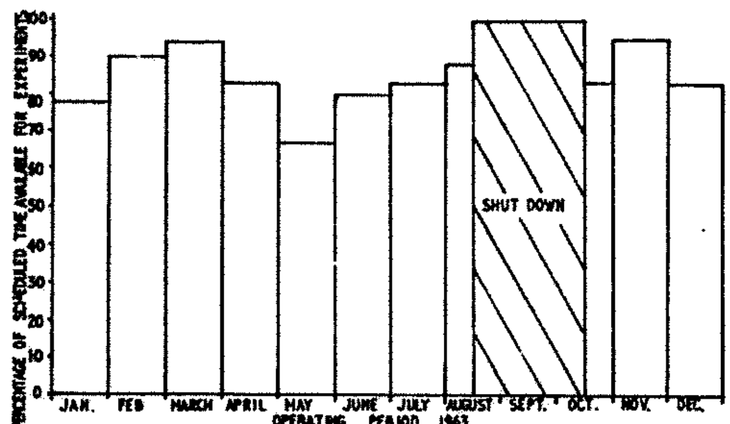
MAXIMUM SURFACE FIELD & AXIAL FIELD v CELL NUMBER TANK 1

FIG. 13



TOTAL TIME SCHEDULED = 5040 HOURS.
FAULT TIME = 971.25 HOURS.
PERCENTAGE ON TIME = 80.7%

NOTES: IN JAN. THERE WAS A TOTAL TIME LOSS OF 80 HOURS DUE TO PERSISTENT IGNITRON TROUBLES ON TANK 2 MODULATOR.
IN MARCH & MAY A TOTAL OF 105 HOURS WAS LOST DUE TO VACUUM LEAKS IN TANK 3.



TOTAL TIME SCHEDULED = 5465 HOURS.
FAULT TIME = 904.25 HOURS.
PERCENTAGE ON TIME = 83.5%

NOTE: IN MAY THERE WAS A WATER PIPE BURST ON THE LINER WATER COOLING FOR TANK 1 WHICH RESULTED IN A LOSS OF 112 HOURS.

RUNNING TIME FOR THE P.L.A. DURING 1962 AND 1963.

FIGURE 14.