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THE RUTHERFORD P.L.A. AND A LINAC FOR THE HIGH ENERGY ACCELERATOR DESIGN STUDY

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I will give some of the parameters of the new Rutherford Laboratory Tank 1 and also some information about the linac for the 300 GeV machine for CERN. I'll talk about the CERN linac first. The first tank of the CERN linac will be our redesigned Tank 1, so that this incorporates both at the same time.

Figure 1 shows a tentative layout of the 300 GeV accelerator, showing the main 300 GeV ring, 2.4 km in diameter, the 6 GeV booster synchrotron which is 160 m in diameter, and the 200 MeV linac, about 200 m long. When seen on this scale, it makes one adopt a very conservative attitude in the design of the linac, because it can be seen that the cost of the linac is going to be about 2% of the total cost of the total installation. For 2% one must design for maximum reliability, and one cannot afford to let the linac be responsible for too many hold-ups in the main machine.

The linac has been designed for optimum, i.e., minimum, cost. Dr. Young has mentioned some of the factors in the optimization to be considered. We have made similar considerations. If, for example,

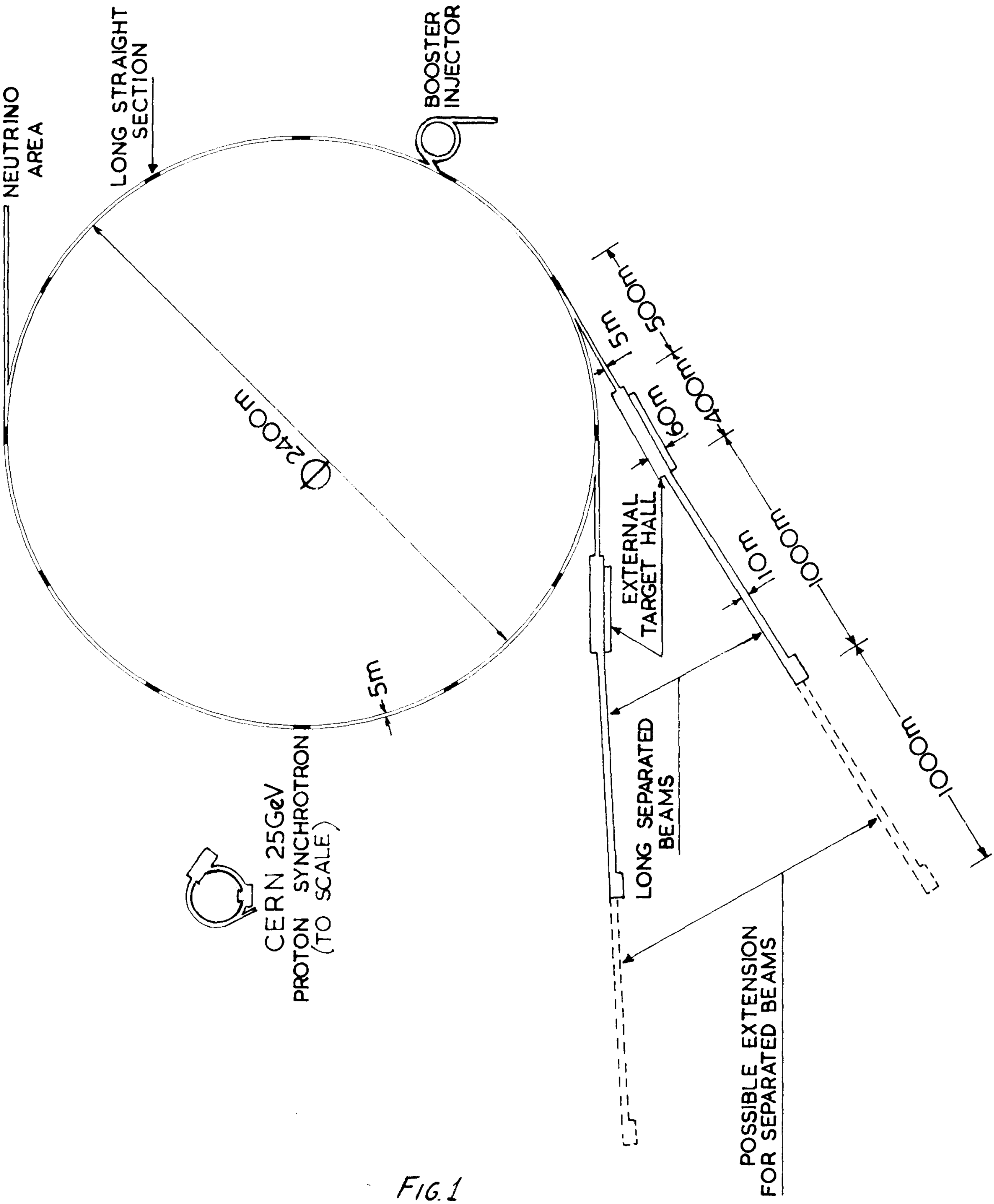


FIG. 1

LAYOUT OF A 300 GeV PROTON-SYNCROTRON

one chooses to have drift tubes of small diameter in a given tank, one gets a gain in shunt impedance. But at the same time the surface fields on the corners of the drift tubes increase, with resulting voltage breakdown problems. If one increases the diameter of the drift tubes to improve the voltage breakdown characteristic, one gets a lower shunt impedance. So there is obviously an optimum value for the drift tube diameter, which is the balance between shunt impedance and breakdown conditions. I think Dr. Young showed the following equation but I should like to write it down again. If V is the energy gain of the particles, then total capital cost can be written:

$$C_1 = C_P P + C_L L \tag{1}$$

Putting in the usual expression for energy gain per unit length

$$K = V/L = E_o \frac{g}{L} T_o \cos \varphi_s = \frac{g}{L} \propto T_o E_S \cos \varphi_s \tag{2}$$

and for the power

$$P = V^2 / \eta L$$

in which η is the shunt impedance, then

$$C_1 = C_P \frac{V}{\eta} K + C_L \frac{V}{K}$$

Now, in the optimization of the cost we have two things to consider: we must include the maintenance cost of the machine in addition to the capital cost. Equation (1) is capital cost, while the following Eq. (3) gives maintenance cost:

$$C_2 = C_P' P + C_L' L \tag{3}$$

The total cost to be optimized can now be written

$$C = (C_P + C_P') \frac{V}{\eta} K + (C_L + C_L') \frac{V}{K} \tag{4}$$

Estimates on the Rutherford Lab. P.L.A. indicate that C_P' and C_L' are in similar ratio as C_P and C_L. In Eq. (2) E_S is the maximum safe surface field at the operating frequency. At 200 Mc/sec we have taken $E_S \sim 14.7$ MV/m, so in fact, we have a small safety margin. We have taken the stable phase angle $\varphi_s = 26^\circ$ and g/L is the gap to pitch ratio. The term α is a constant which depends on the geometry of the cell:

$$\alpha = E_o/E_S$$

and E_o is the maximum field across the flats of the drift tubes.

A further criterion is that no drift tube should have a diameter less than 0.1 of one wavelength. This ensures sufficient room for the drift tubes to contain the focussing quadrupoles.

Now, we have taken the relations of Eqs. (2) and (4) and considered various kinds of radial geometry. In particular, we have considered variations of outside diameter and drift tube diameter. Doing this at intervals over the whole energy range, we have developed an optimized geometry for the whole linac. The results are given in Fig. 2, showing values of the drift tube and liner diameters, optimized in the sense of giving minimum cost. The d/λ curve is for the drift tube diameter, showing that in order to get optimized cost, the dominating factor in the high energy region is voltage breakdown on the drift tube. Thus, to control breakdown, the drift tube diameter must, in fact, increase. Figure 3 is a curve of optimized acceleration rate. Again, because voltage breakdown becomes important in the high energy region, the acceleration rate must progressively fall to keep this under control. Figure 4 is the resulting shunt impedance for the optimized structure, showing again the progressive fall of the shunt impedance toward higher energies.

Now having worked out all other dimensions, we consider the choice of tank length. There are obviously several possibilities. First, one could make the tank so that the gain in energy per tank is constant. This has a degree of simplicity but, in fact, is not really worthwhile. Another possibility is to design the tank length to be units of a quarter of a phase oscillation wavelength. The reason would be to provide

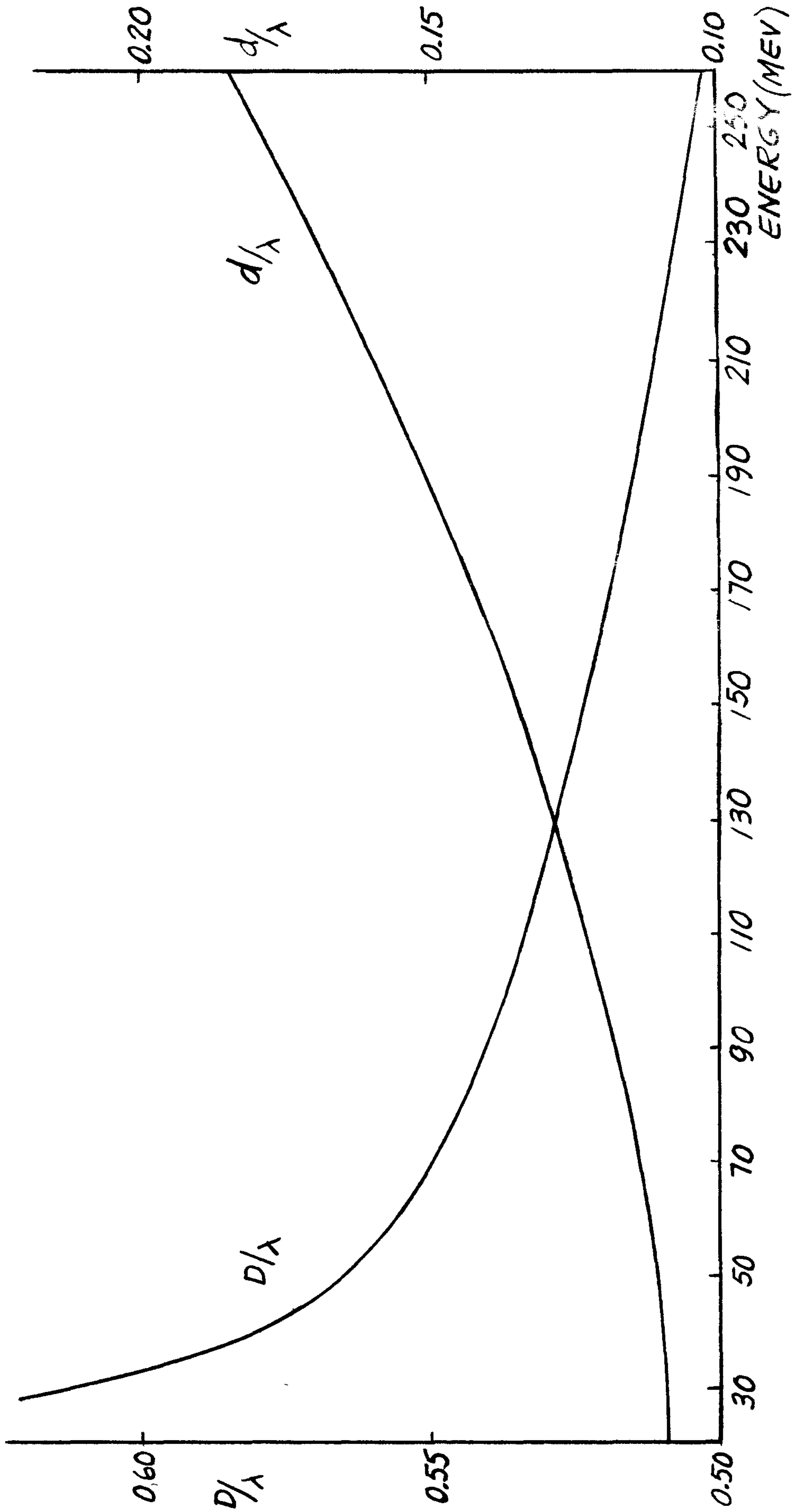


FIG. 2

(BASED ON $5P + [A + B/\beta]L$ AGAINST VARIATION OF D/λ, d/λ)

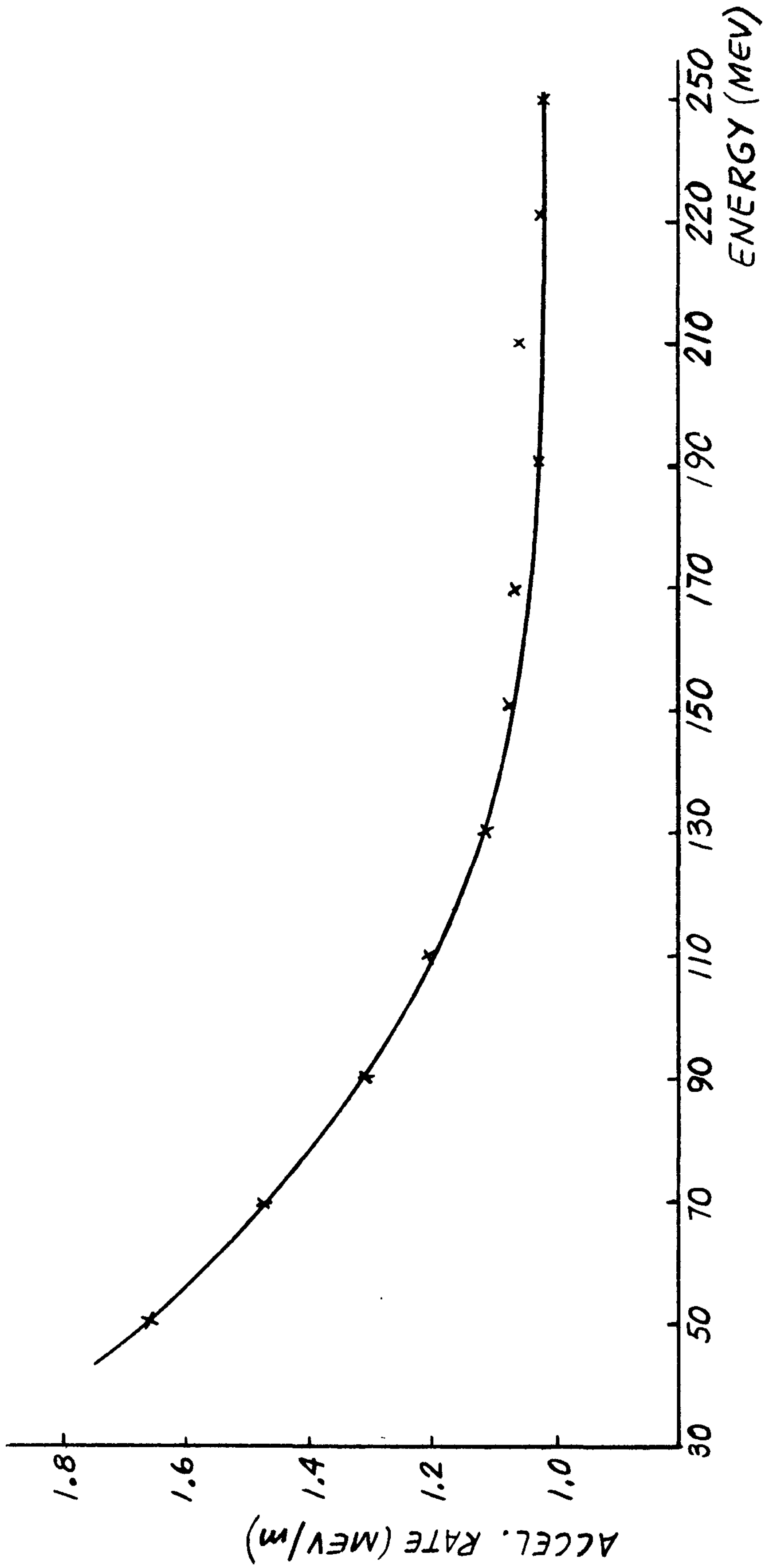

ACCEL. RATE (MEV/m)
1.8
1.6
1.4
1.2
1.0
30
50
70
90
110
130
150
170
190
210
220
250
ENERGY (MEV)

FIG. 3

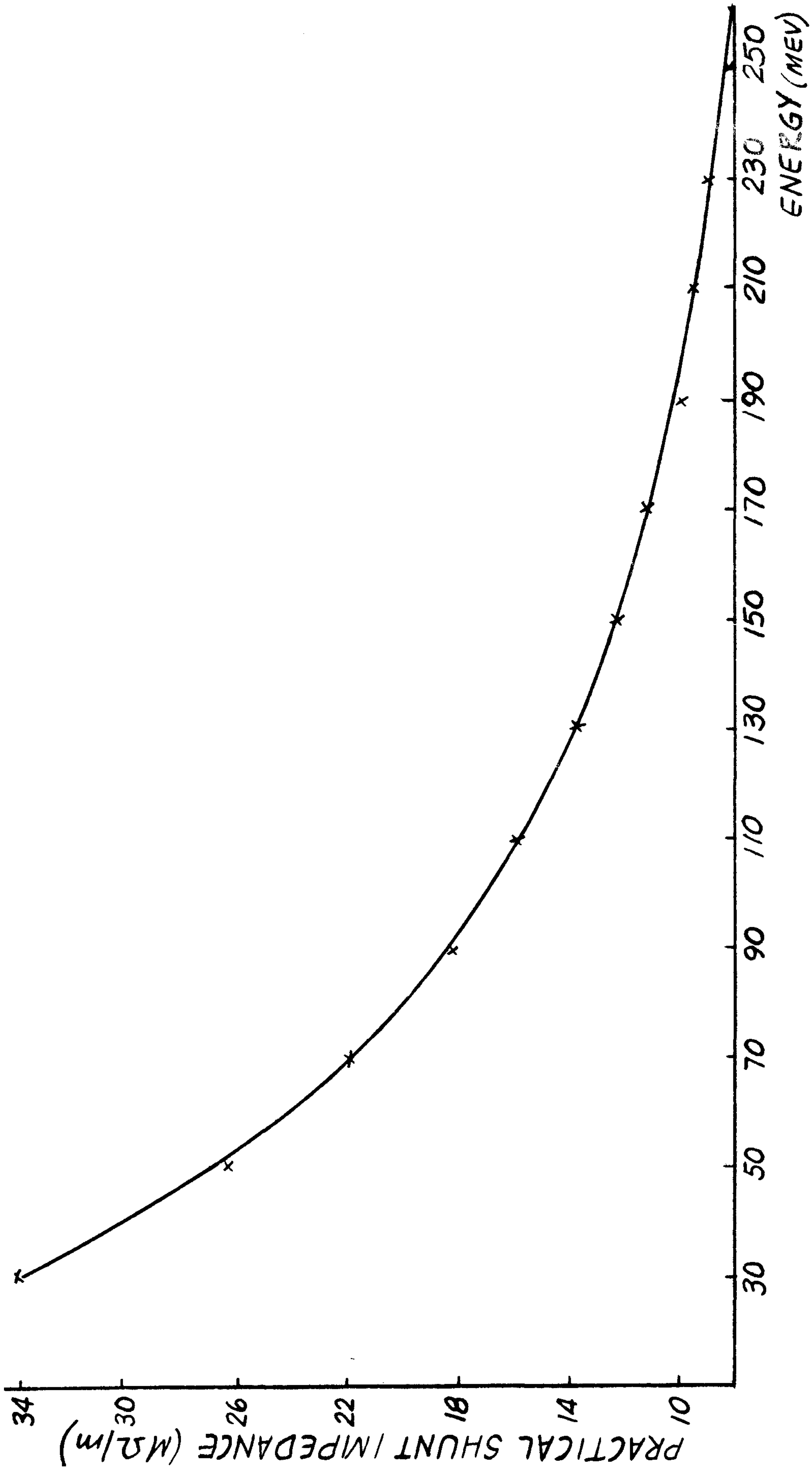

34
30
26
22
18
14
10
PRACTICAL SHUNT IMPEDANCE (MΩ/m)
30
50
70
90
110
130
150
170
190
210
230
250
ENERGY (MEV)

FIG. 4

one means of calibration and control of the machine: if one tank of the linac is a quarter phase oscillation wavelength long, then a certain phase spread at the beginning of a tank will show up as an energy spread at the end of the tank, and this is something that is readily recognizable. A third possibility (and the one adopted), is the arrangement where the total power taken by the tank plus the beam power is matched to the power amplifier output. For this purpose we've assumed RCA 7835 valves producing 5 MW, and a beam current of 100 mA. In fact, the beam current will probably be increased by a factor of 2, but we won't change the design of the machine. We can work out the length of the tank according to this simple formula. The total power required is

$$P = \frac{V}{\eta L} + IV = \frac{VK}{\eta} + IV$$

where I is the beam current, and V the voltage.

This is set equal to 5 MW. From this we get

$$V = \frac{5}{(\frac{K}{\eta} + I)}$$

in which K is the acceleration rate, as taken from Fig. 3, and η is taken from Fig. 4 and the length of each tank is simply equal to V/K. We would not like the length of the tank to be greater than about 20 wavelengths, to avoid difficulty in "flattening." In fact, none of the tanks is greater than 25 m long, so that we should not run into any problems. The resulting design is shown in Table I.

We started at 200 MeV and worked backwards to find out the length of each tank. It so happens that doing it this way, the length of the first tank is conveniently very short, and has only a 5 MeV gain. In the case of the first tank we are not concerned about cost optimization, but about reliability, ease of fabrication, accessibility, and good beam dynamics. It has been past experience that the first tank is always difficult to operate. The rest of the tanks, as can be seen, are not more than about 24 m long, and cover varying energy gains depending on the voltage breakdown. The maximum energy gain is about 30 MeV in one tank. The acceleration rate, in fact, goes down from 1.8 MeV/m down to just over 1 MeV/m for the eighth tank.

In some ways, the optimization was restricted in that the outer radius of curvature of the drift tube profile was kept constant, equal to that for the drift tubes of Tanks 2 and 3 of the existing P.L.A., and for which much information on surface fields exists. But certainly, by increasing the outer drift tube radius, one can probably improve the gap to pitch ratio and the shunt impedance and, hence, cost. Nevertheless, we're fairly satisfied with this design. Also the cost optimization was actually based on figures we have from

TANK NO									
FINAL ENERGY (MEV)	.515	5	37	67	96	124	151	176	200
β	.033	.103	.276	.358	.421	.469	.508	.54	.566

TANK NO	1	2	3	4	5	6	7	8
LENGTH (m)	2.718	17.41	20.05	22.95	24.57	24.54	23.96	23.27
LINER DIA (CM)	97.5	86.0	82.5	81.0	79.5	78.75	77.25	76.5
D.T. DIAMETER (CM)	18.15	16.5	17.25	18.0	19.5	20.5	21.75	24.0
D.T. APERT. DIA (CM)	1.4-2.49	3.81	3.81	3.81	3.81	3.81	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	—/.243	.230/.335	.330/.370	.367/.408	.417/.432	.420/.437	.432/.442
r_o/λ	.0131	.0254	.0254	.0254	.0254	.0254	.0254	.0254
r_i/λ	.0049	.00847	.00847	.00847	.00847	.00847	.00847	.00847
TOTAL POWER (MW)	1.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
ACCEL. RATE (Mev/m)	1.655	1.820	1.498	1.271	1.142	1.086	1.060	1.045
Q		61000	55000	52000	51000	50000	49000	48000
EFF. SHUNT IMP. ($M\Omega/m$)	34.8	37.80	27.02	21.36	17.52	14.88	13.14	11.88
PRACT. SHUNT IMP. ($M\Omega/m$)	29.0	31.50	22.52	17.80	14.60	12.40	10.95	9.90

TABLE I

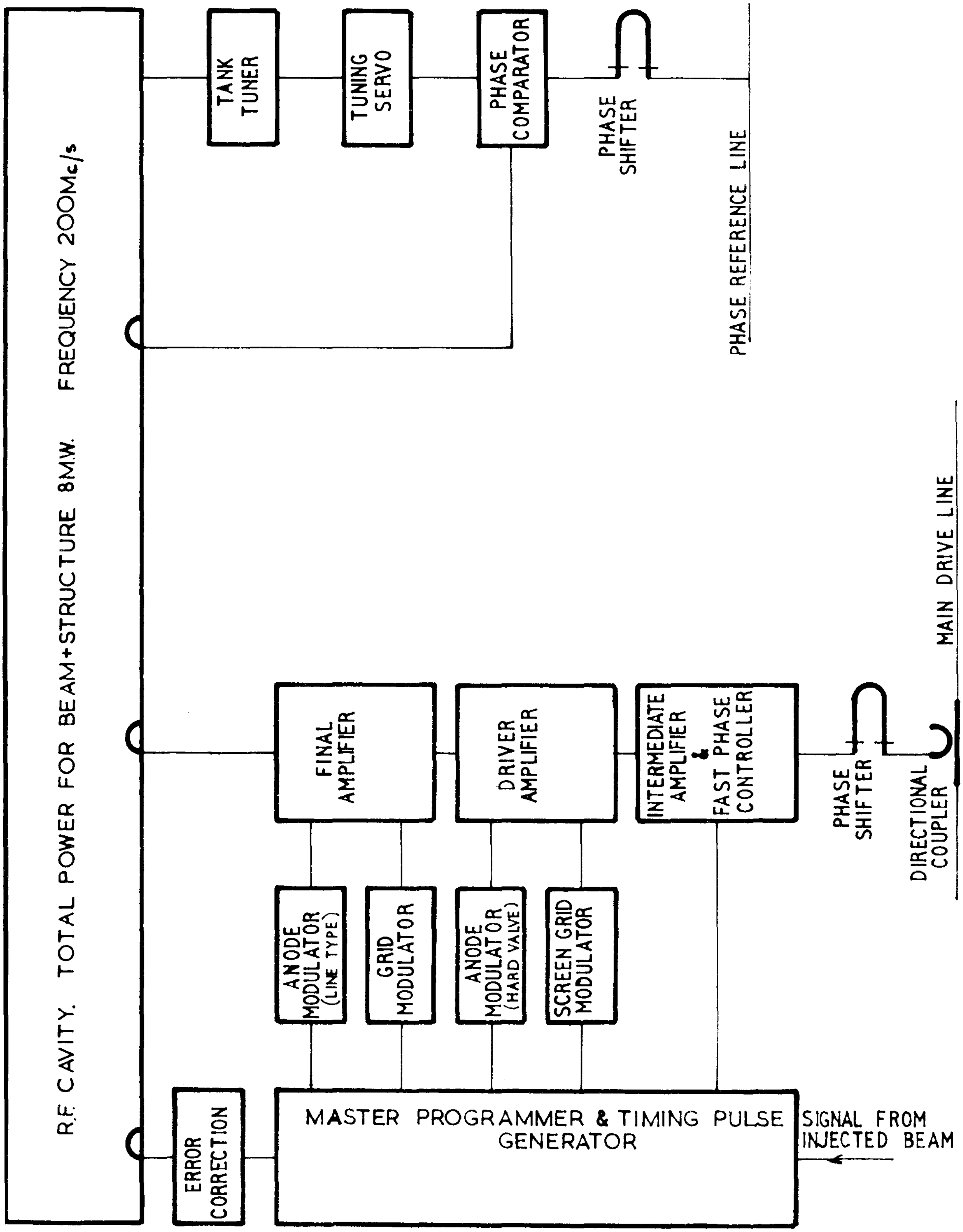
DATA FOR A 200 MEV LINAC FOR CERN:
TANKS IN 5 MW UNITS

the machines we have at the Rutherford Laboratory, and what other information we could glean. We have based our optimization on a separate liner and vacuum system. In actual fact, we will build the machine (as is now the American practice) using copper clad steel liners, in spite of the fact that copper-clad steel does not appear to be available in Europe.

One further point about the optimization is that in the cost of power C_P, is in fact, a function of duty cycle. If we can cut the rf duty cycle down then we can save quite a lot of money. In reducing the effective duty cycle for the rf power, the cost of power turns out to be about 33,000 £/MW. The scheme that we have in mind is shown in Fig. 5.

The total power taken by one tank was originally assumed to be 5 MW, but in fact, will operate at 8 MW because of the possibility of a 200 mA beam. The figure shows a phase reference line and the usual tank tuners and phase comparators. RF power from the main drive line is fed through a phase shifter and an intermediate amplifier and fast phase control, into a driver amplifier, fed from a hard valve modulator. The final amplifier will be fed from a line type modulator. The amplifiers and their modulators are controlled from a programmed modulator with a fast acting pulse amplitude control. A variable load whose value depends on the beam current could also be used. If there is any variation in beam current, both within the pulse and pulse to pulse, then we must correct levels very rapidly by use of correction signals added from the pulse amplitude control to those already generated in the programmed modulator.

Now, the 200 mA beam pulse is only 5 μsec long. At 200 Mc/sec it normally takes about 200 μsec for a tank to build up to normal level for acceleration. In the usual system one has a build up of rf power in a couple of hundred μsec, a flat top of duration of the beam pulse, and an exponential tail-off. This gives a fairly large duty cycle. Now obviously with the kind of beam loading that we're going to have where the beam is taking rf power of the order of twice that drawn by the cavity, the beam cannot take its power from the stored energy of the tank, since this would cause something of the order of a 5% sag of cavity field. Now the modulator must be "matched" to the valve load during the operating cycle, so that to provide such large quantities of extra power to cope with the voltage sag caused by beam loading brings in difficult mismatch problems. Since we have 8 MW available, it was thought to be worthwhile to use this full power to drive the tank very hard to increase the rate of build-up. So in fact, the final amplifier provides 8 MW to drive toward the 8 MW level in the tank. Thus we can reduce the build-up time to operating level to something of the order of 30 to 40 μsec. So we are getting a reduction of a factor of 5 in the duty cycle. At the 2 MW level, which is the power level required by the tank for the correct voltage, we then put in the beam and, the beam itself absorbs the rest of the power. This obviously



R.F. SYSTEM FOR AN ACCELERATING STRUCTURE

FIG. 5.

requires a very accurate timing system, but in fact, the problems are not impossibly difficult. The great advantage of this system, in addition to cutting down the effective duty cycle, is also that the modulator is always matched. It is always pumping 8 MW into the system, and of course, the distribution of the energy between beam and tank doesn't matter as long as it is 8 MW. There are one or two problems, like the reactive detuning effect of the beam; again this is not too difficult to control fairly readily, with the tuning and fast phasing system. Of course, we must be careful about transient effects at the instant of injecting the beam. This we are looking into, including the use of possible "guard periods" during the pulse.

GLUCKSTERN: Will the tank take 8 MW without breaking down if it misses a pulse?

CARNE: This is where our pulse amplitude box comes in. We've obviously got to watch this very carefully. A beam monitor box will watch the beam current as it enters the machine. If something goes wrong, for example a missed pulse, or drop in intensity, then of course, we can't push the power in, and the programmed modulator is set accordingly. But the tank itself only has the voltage equivalent to 2 MW.

BLEWETT: The breakdown may be when mismatched at the beginning of the pulse.

CARNE: Yes, but unless there is something the matter with it, the valve is always pumping out 8 MW, and you have just the mismatches you usually have anyway.

I agree there is some difficulty about this. Certainly, the tank is going to be uncoupled for quite a long time, but I think this actually improves the rate of build-up.

BERINGER: This sort of thing has certainly been done; the little tank in the Heavy Ion Machine here has a high voltage drive amplifier which changes the rise time by a factor of 3.

I would like to make a comment about the cost minimization. These curves are very flat with respect to all parameters, and yet we find in both Don Young's and in this discussion the use of peak gradients, as if these were numbers that we could believe, and yet everybody who has run a machine knows that it is only the early gaps, in a uniform gradient machine, that give any trouble. Consequently, I don't believe these minimizations even approximately.

CARNE: This is quite a valid argument. But it depends on what your basic design philosophy is. Ours is one of feet-on-the-ground reliability because we've got to feed something which costs many times as much money. If we have a conservative design, it would work out to something like 14 MV/m, and we may be able to get a little higher. It doesn't matter because if we design conservatively then we have a machine which is reliable and that means a saving of money.

BERINGER: To get a conservative design, I suggest that someone should do the appropriate work to learn a little more than Kilpatrick did about this sparking problem, because there is a lot of money and effort involved.

FEATHERSTONE: But you could guess that this might not be conservative enough.

BERINGER: It might not be at all conservative; in other words, possibly you would develop some other function -- perhaps Kilpatrick's plus a length correction -- and get a really conservative criterion.

YOUNG: That's why we are building a power cavity, because we feel just as strongly as you do about this, but until you've got the hardware, it is nice to have other criteria to judge where you want additional computer runs.

CARNE: I think this is also true at very low energy, as in the case of our first tank which goes up to about 5 MeV. This is an even more conservative rating because we plan to accelerate at 1.6 MeV/m. The maximum surface gradient we are expecting is just under 13 MV/m, and we hope it's a very safe design.

BITTNER: Have you done a lot of theoretical work on the transient build-up in the tank? How does the tank flatness change when the field is increasing in the tank, as contrasted with a steady state condition?

CARNE: This is something we are investigating. We've certainly found on our existing machine that if you tilt the field to give a fairly large phase acceptance at the beginning, the beam quality is poor at the end of the tank.