REDUCTION OF ENERGY SPREAD ON THE RUTHERFORD LABORATORY P.L.A.

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1. Introduction

In previous operation of the Rutherford Laboratory P.L.A. typical figures for the output beam were: intensity 300 μA peak, energy spread 110 keV (FWHH), 400 keV (FWFH) at 30 MeV, and 134 keV (FWHH), 500 keV (FWFH) at 50 MeV. Whilst these energy spreads can never be made comparable with those of a Van de Graff accelerator, there was nevertheless plenty of scope for improvement. In doing so it was also a necessary requirement that the output beam intensity should at least be maintained. The energy spread can be reduced in two ways, both of which were employed:

(i) Shaping the fields along the linac to control the energy acceptance along the machine. In practice this was done in the first tank (Tank 1) only, since the fields in the remaining two tanks would have been impracticably small.

(ii) The use of a debuncher. It will be seen later that the efficiency of the debuncher depends on the ability of the shaped field of Tank 1, in particular, to control the shape ($\Delta E/\Delta\phi$) of the beam itself.

Since the new field shape in Tank 1 required a smaller phase acceptance than usual it was necessary to increase the efficiency of the injector by redesigning the LEDS to include two focussing triplets to improve beam transport and matching into Tank 1; and a new double-drift buncher based on two double-gap half-wave coaxial cavities, together with a new phase stabili er using $\lambda/4$ bridges and varactor diodes.

The outcome of all this development on the P.L.A. was that the output beam had the following characteristics: intensity 400 - 450 μA peak energy spreads 27 keV (FWHH), 70 keV (FWFH) at 30 MeV, and 45 keV (FWHH), 130 keV (FWFH) at 50 MeV - i.e. an increase of ~30% in beam intensity, and a general reduction of energy spread by a factor 3-4. Many of the features are novel and are of general interest to linac development. They are described here with the logical beginning at Tank 1 within the linac, and then the development outside the linac (fuller details may be found in the Rutherford Laboratory P.L.A. Progress Report 1967 (1)).

2. Dynamics of Tank 1

Under the normal "flat field" conditions of Tank 1 ($\phi_s \sim -27°$), the energy spread at output is of the order of 300 keV, and this value is increased under the near-linear phase motion in Tanks 2 and 3 to the figures already quoted. External limiting devices alone are inadequate to restrict the input beam to Tank 1 to a sufficiently small acceptance region for linear motion alone to take place (even if this were good enough). This is especially true for this particular Tank 1, which has grid-focussing, and the beam tends to fill the acceptance bucket along the whole length. The alternative is to shape the field within the tank itself to control the motion of the beam.

Consider the motion of a beam along the axis of a travelling wave accelerator. If $\Delta\phi = \phi - \phi_R$, $\Delta W = W - W_R$, where W, ϕ refer to a general particle, and the suffix R refers to a reference particle (as distinct from a stable (i.e. constant) phase particle), then similarly to usual equations for phase motion:

$$\frac{d}{dz}(\Delta\phi) = \frac{2\pi}{\lambda}\left(\frac{1}{\beta} - \frac{1}{\beta_R}\right) \qquad (2i)$$

$$\frac{d}{dz}(\Delta W) = \mathcal{E}\left(\cos\phi - \cos\phi_R\right)$$

where the terms (save suffix R) have their usual meanings. With $\Delta W = W_0 \beta_R \gamma_R^3 \Delta\beta$, the above equations combine to give a single equation for phase:

$$\frac{d}{dn}\left(\beta_R^3\gamma_R^3\frac{d}{dn}(\Delta\phi)\right) + \frac{2\pi\lambda\beta_R\mathcal{E}}{W_0}\left(\cos\phi - \cos\phi_R\right) = 0 \qquad (2ii)$$

where n is the number of cycles $\equiv$ number of cells. With $\frac{d}{dn}(\Delta\phi) = -\frac{2\pi\Delta W}{W_0}\beta_R^3\gamma_R^3$, then, at a given energy, equation (ii) leads to ΔW is a maximum at $\phi = \phi_R$, given by

$$\Delta W_{max} = \pm\left[\frac{2\beta_R^3\gamma_R^3\mathcal{E}\lambda W_0\left(\phi_R\cos\phi_R - \sin\phi_R\right)}{\pi}\right]^{1/2} \qquad (2iii)$$

For a constant acceleration rate (as indeed the PLA has) $\mathcal{E}\cos\phi_R = \Gamma$

and (iii) becomes

$$\Delta W_{max} = \pm \left[\frac{2\beta_R^3 \gamma_R^3 W_o \lambda \Gamma (\phi_R - \tan\phi_R)}{\pi} \right]^{1/2}$$

and for Γ constant,

$$\frac{\Delta W_n}{\Delta W_1} = \left[\frac{(\beta_R \gamma_R)_n^3 (\phi_R - \tan\phi_R)_n}{(\beta_R \gamma_R)_1^3 (\phi_R - \tan\phi_R)_1} \right]^{1/2} \qquad (2iv)$$

The ratio $\Delta W_n / \Delta W_1$ can be controlled by varying the phase of the reference particle at cell n, $\phi_{R,n}$ according to equation (iv). Figure 1 shows the variation of ϕ_R with cell number in Tank 1 for $\Delta W_n = \Delta W_1$ for $\phi_{R,1} = -10$ to -50° (corresponding values of ΔW constant are $\pm$ 9.92, $\pm$28.5, $\pm$54.1, $\pm$87.7, $\pm$ 132.2 keV respectively). It can be seen that ϕ_R at the output is very small: this puts tight (but practicable) tolerances on Tank 1 itself, but extended use beyond Tank 1 would be very difficult indeed. The alternative of using a debuncher for the higher energies is much easier.

The axial acceptance is given by equation (iii) and the phase width ($\sim 3\,\phi_R$ with no acceleration). With $\phi_R = \phi_s$ constant the energy acceptance grows as $(\beta_R \gamma_R)^{3/2}$, but with ϕ_R chosen according as 2iv), the bucket actually shrinks along the tank to maintain ΔW_{max} constant, the ratio of the areas being roughly $\phi_{R,out} / \phi_{R,in}$. Hence some loss of beam is to be expected, and it is for this reason the double buncher (Section 3) is employed to bunch the maximum possible beam into the 30° or so available phase width to reduce this loss. However a more detailed study of the beam motion showed the loss would be rather less than the ratio given above, and in fact the radial acceptance was found to be some 50% larger than for the more usual flat field ($\phi_s \sim -27^\circ$) case. The reason for this is that with such a small value of ϕ_R along the tank, the radial defocussing force is reduced; it is also likely that resonance coupling between phase and radial motion is reduced.

The field laws for the tank itself are shown in figure 2. Only the lower two cases are of interest, where the energy spreads are least, and where in the cases with large $\phi_{R,in}$ there is a possibility of voltage breakdown. In practice the field was set for $\phi_{R,in} = -10^\circ$, but with the tilt tuners available, a good approximation to the original field could be obtained, also a somewhat poorer approximation to field $\phi_{R,in} = -20^\circ$. With this setting, the total radial acceptance (theoretical) was 120 mm-mrad, and was found to be remarkably phase-independent (over the phase range considered), unlike the old setting for the tank. With the total motion included, the output beam from Tank 1 was expected to have an energy spread $\sim$80 keV, phase spread $\sim 23^\circ$ (based on "worst case" particles), compared with 20 keV, 7.5° of the simple travelling-wave theory above. Assuming linear motion through Tanks 2 and 3 (and it is our experience on the P.L.A. that this is a very fair assumption), these energy spreads would become 120 keV, and 145 keV at 30 and 50 MeV respectively; and with the debuncher (Section 4), these figures would become 38 keV and 96 keV.

As mentioned, the field was set up for $\phi_{R,in} = -10^\circ$. During the setting up procedure it was found that many of the drift tubes were axially misaligned with an RMS error of 0.009 inches. Time was not available to correct the gaps, and the mid-gap fields were set to the required law. Some computations were done to see the effect of these errors: over the input phase range of interest ($\sim 20^\circ$), the mean output energy of axial particles was seen to shift by 30 keV, and the spread to increase by $\sim$30 keV. (No serious effects were seen on the radial motion). These errors were considered acceptable.

Attempts to measure the energy spectra of the beam at 10 MeV with the old and new field laws had to be abandoned due to difficulties with the spectrometer magnet and the beam line to it. These difficulties were resolved at 30 and 50 MeV as will be seen later. Plots of the transmission of Tank 1 as a function of the injection energy showed that the energy dimension of the (E, ϕ) acceptance had been reduced, as expected. Thus, a $\pm$ 15 keV change in injection energy gave decreases in transmission of about 17% (old flat field) and 47% (new shaped field) from the peak values.

3. The L.E.D.S. and Double Buncher

With the input acceptance of Tank 1 $\pm$ 10 keV $(= \pm \Delta W_{max})$, $\sim 30^\circ (= 3\,\phi_R,\ \phi_R = -10^\circ)$, a better LEDS and more efficient buncher were required to avoid any reduction in output beam intensity.

The LEDS was redesigned to take (inter alia) two new triplets, the first was located in the vacuum manifold of the injector column to steer the beam through the various components of the LEDS, including the two bunchers, and permanent time of flight apparatus; the second to match the beam into Tank 1. In practice the triplets were made from the doublets used on the old LEDS, and were wound so that the magnetic centres, and the relative fields of the inner and outer quadrupoles could be varied.

The buncher system chosen for the P.L.A. is a simplification of the double buncher scheme suggested by Blewett (2), and shown in figure 3. In general, the frequencies of the two cavities are harmonically related; but for the P.L.A., where there are many constraints in the LEDS, (e.g. overall length D was fixed, location of the T.O.F. apparatus was fixed), there was no advantage to be found in having other than equal frequencies for the two cavities. Indeed a common frequency equal to the linac operating frequency gives a simpler buncher r.f. system.

Since input beams to the P.L.A. are less than 10 mA, the effect of space charge in the buncher design was assumed negligible. This assumption was confirmed for us by Emigh and Crandell of L.A.S.L. whose M.R.A. program (3) showed there is little variation in $\Delta\phi$ with space charge with currents up to 20 mA (the authors thank Drs. Emigh and Crandall for private communication on this matter). Nevertheless, a generous safeguard was made by choosing the phase interval to be 20°, rather than the 30° available, leaving $\pm 5^\circ$ for space charge effects, and tolerances. The energy spread ΔE acceptable by Tank 1 is $\pm$ 10 keV and this will be little affected by space charge. With the notation of figure 3, the output velocities at cavities 1 and 2 are given by the usual equations for velocity modulation

$$eV = e\left(V_0 + V_1 \sin(\omega t_0)\right)$$

where (ωt_0) is the phase at cavity 1 (3i)

$$u_1 \approx u_0\left(1 + (V_1/2V_0)\sin\omega t_0\right) \qquad (3ii)$$

$$u_2 \approx u_1\left(1 + V_2 \sin\left(\omega(t_0 + d_1/u_1) + \psi\right)/2V_0\left(1 + (V_1/V_0)\sin\omega t_0\right)\right) \qquad (3iii)$$

In equation (iii) ψ is the arbitrary phase of buncher 2 w.r.t. buncher 1, and because of it no synchronous particle, in general, exists (i.e. a particle which crosses cavity 1 with zero phase does not necessarily cross cavity 2 at zero phase, and vice versa). A particle arrives at the centre of the first gap of Tank 1 with velocity u_2, and phase

$$\phi = \omega\left(t_0 + (d_1/u_1) + (D - d_1)/u_2\right) \qquad (3iv)$$

A program was written to compute u_2, ϕ over the input phase interval -180° to $+180^\circ$. Since there is no synchronous particle, it was necessary to consider final phases within a large overall range, divided into 20° intervals. The number of particles in each 20° interval was counted, and to ensure the overall range was adequate, the total numbers of particles were summed. For one set of bunchers parameters V_1, V_2, d_1, ψ the interval containing the maximum number of particles was noted, and the procedure repeated until a set of parameters was found which gave an overall maximum number of particles contained in some 20° interval. The maximum percentage of particles contained in a 20° interval was 66%, with the following parameters

$$\begin{aligned} V_0 &= 515 \text{ keV} \mp 200 \text{ eV} \\ V_1 &= 6 \text{ kV} \pm 120 \text{ V} \\ V_2 &= 10 \text{ kV} \pm 200 \text{ V} \\ \psi &= 20^\circ \pm 2^\circ \\ d_1 &= 71.675 \mp 0.02 \text{ cm} \end{aligned}$$

The tolerance figures allow for a $\pm 2^\circ$ variation on the centroid of the output bunch, due to an individual parameter, and indicate rather tight stability requirements on the individual components. Figure 4 shows the bunching process along the system, the last two diagrams showing clearly the redistribution of particles into the small phase spread. The output energy spread is 20 keV, thus fitting nicely into the energy acceptance of Tank 1.

The actual buncher cavities are as described in the P.L.A. Progress Report of 1966 (3); Each is a foreshortened coaxial $\lambda/2$ resonator loaded at its centre by two drift tube-gaps. The gaps are spaced approximately $3\beta\lambda/2$ so that bunching takes place in both gaps. The drift tubes carry grids to improve the gap fields. The "shorting planes" are in fact $\sim\lambda/4$ low impedance open circuited lines to allow d.c. bias. Cavity characteristics are $Q_0 \sim 1000$, η (eff) = 136.4 kΩ, T.T.F. = 0.851.

The tight inter-buncher phase tolerance necessitated an r.f. system with phase stabilisation. A schematic diagram of the r.f. system is given in figure 5. Signals from the two bunchers are compared in a 4-arm coaxial bridge, where the output signal is proportional to the phase difference. This signal is amplified and fed to varactor diodes as the reactive elements in a further 4-arm phase shifting bridge. The total phase range available was 22°, and the phase was held constant to 0.5° during the 400 µS r.f. pulse. It might be noticed from Figure 5 that the varactor bridge controlled the phase of buncher 1, rather than buncher 2 which would give a rather simpler system. This is because the power required for buncher 1 is less than for 2, so the range of phase control becomes greater.

The tolerance on injection energy also called for an examination of the short term stability of the injector (the long term stability was known to be satisfactory). This was done using a single buncher (before the second was installed) and a beam collector as the high current point of a half wave coaxial resonator. (The measurement was indeed improved when later the second buncher cavity was used as the pick-up cavity). The phase of the r.f. signal generated in this cavity by the bunched beam was compared (to $<\frac{1}{2}^{\circ}$) with a reference phase from the r.f. system of the P.L.A. The phase sensitivity of 1° per 100 V was easily measured. A peak-to-peak fluctuations in EHT of about 1000 V were reduced to 300 V by the existing fast stabiliser, so that the quoted tolerance was satisfied. This was later confirmed by the fact that no adverse effects on the beam accelerated through the P.L.A. could be attributed to instability in the EHT, when the double bunchers and EHT stabiliser were properly adjusted.

To obtain optimum operation of the bunchers 6 parameters had to be set-up, namely V_0, V_1, V_2, ψ ; the phase of the buncher system relative to tank 1, and the r.f. power in tank 1. A 6 parameter optimisation by trial and error would have been impossible. The procedure adopted was (1) to adjust V_1, V_2, ψ by r.f. power and phase measurements to the calculated values, (2) to find the optimum injection energy and tank RF power by maximising the transmission of the tank (with no power in the bunchers) and (3) to adjust the buncher system phase. This procedure would have given the optimum conditions, if the injection energy V_0 had been 515 keV, but absolute value of V_0 was not known to better than ± 10 keV. However, the main effect of changing the injection energy is to change the required inter-buncher phase, so step (4) involved a successive adjustment of the two phase parameters. Finally, the other parameters were varied by small amounts about the initial values to obtain a working set of conditions. With the LEDS quadrupoles energised the bunchers then gave a bunching factor of 4, and an accelerated beam of 400 μA for a 5 mA beam at the entrance to tank 1.

The phase width of the bunched beam and the phase acceptance of Tank 1 could not be measured independently; but in combination they should give a measurable plane acceptance of about 50° at half maximum (assuming a 20° probe, and $3\phi_{R,in} = 30^{\circ}$). The observed phase acceptance was 47° at the optimum power in tank 1. At lower levels the phase acceptance (and the accelerated current at full energy) was less, and at higher levels the plane acceptance was greater, but the maximum current was less. It was concluded, therefore, that the settings which gave maximum current also gave reasonable operation of the bunchers and Tank 1.

As already mentioned, energy spectra measurements at 10 MeV were not practicable, but at 30 and 50 MeV the FWHH energy spreads were 70 and (less than) 110 keV, respectively compared with 110 and 134 keV with the old (flat field) law.

4. <u>The Debuncher</u>

Assuming the output beam can be represented in E,ϕ space as an initially right ellipse which shears with distance along the ϕ -axis, the action of the debuncher is to impose an r.f. voltage of appropriate amplitude and phase to a shear along the E -axis and so reduce the energy spread. In general the greater the drift distance, the greater the possible reduction in energy spread (and the smaller the r.f. voltage required), the limit being when the ellipse fills the linear portion of the voltage waveform (i.e. $\not> 90^{\circ}$). For the P.L.A. the available drift distance, D, from the end of Tank 3 is less than the optimum (being 12.5 m), but also, from the operation of the double bunchers and Tank 1 with its shaped field, the ellipse is small (the phase spread at the debuncher being $\leqslant 15^{\circ}$). Minimal energy spread also requires the zero phase of the r.f. voltage to coincide with the centre of the ellipse (and the voltage/phase gradient "matched" to the shear angle). For other values of phase there is a resulting shift of beam energy, but (since the beam ellipse is small) with small effect on the reduction of energy spread, until the phase enters the non-linear regions of the voltage waveform (see Figure 6).

Following Walsh (4), the energy spread at the output of the debuncher is $\Delta E' = \Delta E/p$, where ΔE_0 is the initial energy spread, and the improvement factor p is given by

$$p = (1 + t^2/T^2)^{1/2} \qquad (4i)$$

where $t = D/v_0$ is the debuncher transit time, and $T = \frac{\Delta\phi_0}{\omega(\Delta v/v)_0} \approx \frac{2E_0}{\omega}\left(\frac{\Delta\phi}{\Delta E}\right)_0$ is the initial phase constant. It is clear from this equation that the reduction in energy spread is greater, the larger D is, or, more important for the P.L.A. the smaller $(\Delta\phi/\Delta E)_0$.
Now, as already indicated, experience in operation of the P.L.A. suggests the motion in Tanks 2 and 3 is essentially linear. This being so, from the output of Tank 1 onwards

$$\Delta\phi \propto (\beta\gamma)^{-3/4}, \quad \Delta E \propto (\beta\gamma)^{+3/4} \quad \text{so that}$$
$$(\Delta\phi/\Delta E) \propto (\beta\gamma)^{-1.5}$$

Hence equation 4i) may be written (for constant acceleration rate).

$$p = \left[1 + \left(\frac{D}{v_0}\right)^2 \left(\frac{\omega}{2E_0}\right)^2 \frac{(\beta\gamma)_0^3}{(\beta\gamma)_{10}^3} \Big/ \left(\frac{\Delta\phi}{\Delta E}\right)_{10}^2\right]^{1/2} \qquad (4ii)$$

Where the suffix 10 indicates the output values of Tank 1.

It is clear from equation (ii) that the reduction of energy spread at the output of Tank 1, together with the reduction of phase spread also achieved, improve the efficiency of the debuncher. Comparable theoretical energy spreads (full width at the base) are:

	Tank 1	Tank 2	Tank 3
Tank 1 (shaped) + 2-buncher, no debuncher	80 keV	120 keV	145 keV
Tank 1 (old flat field), no bunchers, plus debuncher		109 keV	310 keV
Tank 1 (shaped) + 2-buncher, plus debuncher	80 keV	38 keV	96 keV

It is seen that the energy spread due to Tank 1 plus 2-bunchers alone is smaller by a factor 2 over the debuncher alone at 50 MeV, and at 30 MeV they are comparable, but the combination gives the energy spreads of the order factor 3 over the debunchers alone at both output energies.

The debuncher was constructed from the old re-entrant cavity buncher of the P.L.A. and from spare drift tube components for Tank 3. Thus the radial dimensions of the debuncher cavity were fixed and the length dimensions were obtained by calculations and by half-cell model measurements. The vacuum tank was made by cutting the ends off the old buncher vacuum tank and welding in a longer cylindrical section containing suitable ports for the r.f. feed line, the manual and auto-tuners, monitoring loops and vacuum gauges.

The expected values of the Q and shunt impedance (from model measurements) were 27,150 and 13 MΩ/m, while the values obtained were 17,300 and 11.3 MΩ/m. The power required for debunching is about 5 kW at 30 MeV and 40 kW at 50 MeV. No difficulty was encountered in powering the cavity for 50 MeV operation, but there is multipactoring in the cavity at 5 kW and below, so at 30 MeV the debuncher has to be operated at about 10 kW, giving a debunching ratio slightly less than optimum.

The energy spectra were measured with a beam line of 200 keV acceptance and the double focussing ($n = \frac{1}{2}$) spectrometer (which has a resolving power of better than 10 keV). The resolution of the measuring system was dictated by the height (orthogonal to the spectrometer magnetic field) of the target used to scatter protons into the spectrometer, but it was adequately small when a 0.5 mm target was used. Fig. 7 shows the final spectra obtained and the effect of using a "full height" and a 0.5 mm target at 50 MeV.

With the "$n = \frac{1}{2}$" beam line set up for a wide energy acceptance at 50 MeV the energy spectra were measured for a range of debuncher phases with the power level set at 35 kW. Fig. 6 shows the expected features, namely the mean energy and the energy spread are both a function of the debuncher phase. At this power level the narrowest spectra were obtained at zero phase, but there is not much change in the FWHH of the spectra over a range of $\pm 60^{\circ}$.

A similar series of measurements at 30 MeV with the power level at 40 kW (i.e. 8 times the nominal level) showed the effect of over-debunching. The best spectra were at $\pm 70^{\circ}$, where the energy spread was 50 keV and the mean energy was displaced by $\pm$ 380 keV. At zero phase the energy spread was 125 keV compared with 90 keV without the debuncher. (These measurements used the full height target in the spectrometer).

These results show that the debuncher can give a useful reduction in energy spread of the beam and at the same time (by suitable adjustments) the mean energy of the beam can be changed if desired without much loss of resolution.

Conclusions

The combined effect of the double bunchers, the shaped field in Tank 1 and the debuncher has been to greatly improve the energy spectra available in the epxerimental area of the P.L.A., while the beam intensity has been increased. The energy resolution now is such that target and detector effects contribute significantly to the realisable experimental energy resolutions.

Acknowledgements

We wish to thank all our colleagues in the P.L.A. Division who contributed to the work described here, in particular, G. E. Gallagher-Daggitt, N. M. Fewell, M. W. Dean, and L. Goodall in the Accelerator Physics Group and J. B. Marsh, J. E. Boon, J. Stanhope, B. Parkinson and J. J. Rockett in the Engineering Group.

References

1. "P.L.A. Progress Report 1967" RHEL/R156 1967.
2. J. P. Blewett "Phase Acceptance and Bunching in the AGS Linac", BNL AGS Int. Report JPB-18 1963.
3. "P.L.A. Progress Report 1966" RHEL/R 136 1966.
4. T. R. Walsh "The Optical Design of Beam Matching Systems".

DISCUSSION

(A. Carne)

WATERTON, AECL: What is the power consumption of the debuncher?

CARNE, RHEL: The design values were 40 kW for a 50 MeV beam and 5 kW for a 30 MeV beam. However, the shunt impedance was lower than expected because of a lower Q than expected. There was no difficulty in getting 40 kW into the debuncher for 50 MeV particles, but we experienced difficulty with multipactoring with only 5 kW at 30 MeV. So we had to run it at 10 kW for 30 MeV, which resulted in some over-debunching.

SLUYTERS, BNL: In referring to your remark concerning our linac: Normally operating at 50 MeV with 20 mA we get about 250 keV energy spread, when injecting 60 mA. We were running the buncher at approximately 18 or 19 kV. The buncher distance to the linac is 0.5 meters. We reduced the buncher voltage to 15 kV and we obtained an energy spread of 190 keV. We think with a single buncher this is quite good.

CARNE, RHEL: This is quite good. We have the advantage that we do not have to consider space charge which might necessitate larger voltages in our double buncher system. Was this with a flat tank and a stable phase angle of 30 degrees?

SLUYTERS, BNL: Yes.

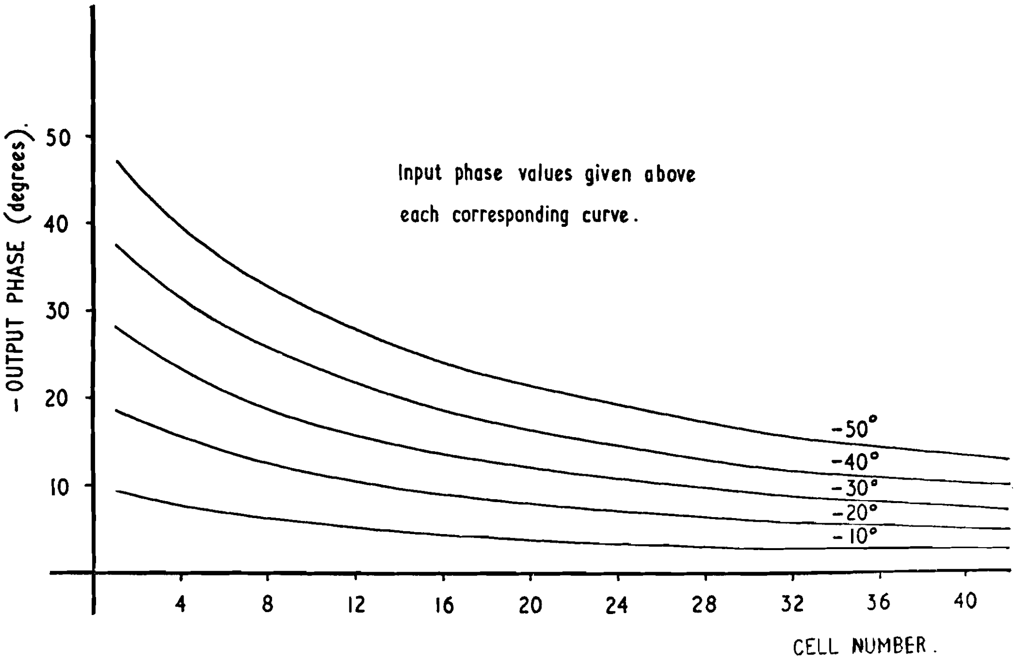

Fig. 1: Reference phase ϕ_R, versus cell number for Tank 1.

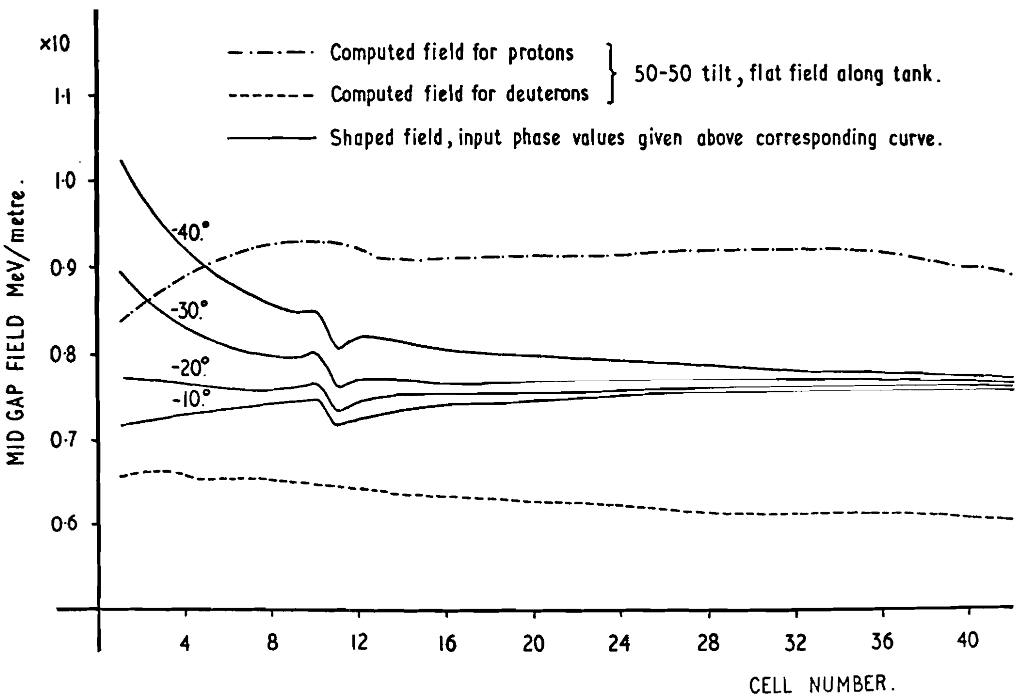

Fig. 2: Field Laws for Tank 1.

Schematic Representation of buncher system.

Diagrammatic Representation of L.E.D.S.

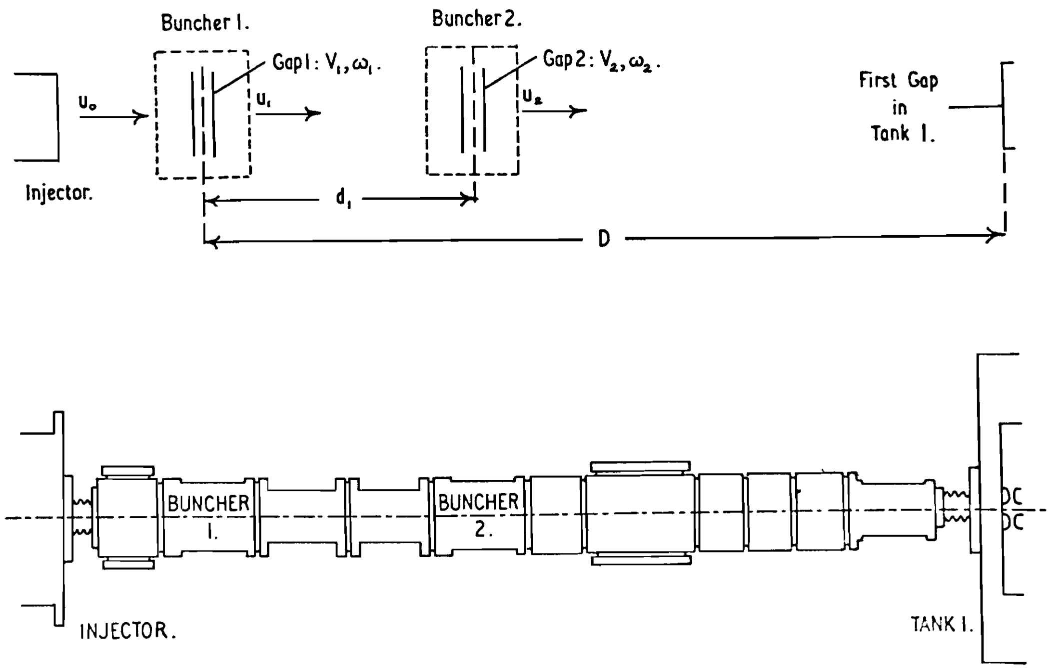

Fig. 3: Double buncher scheme.

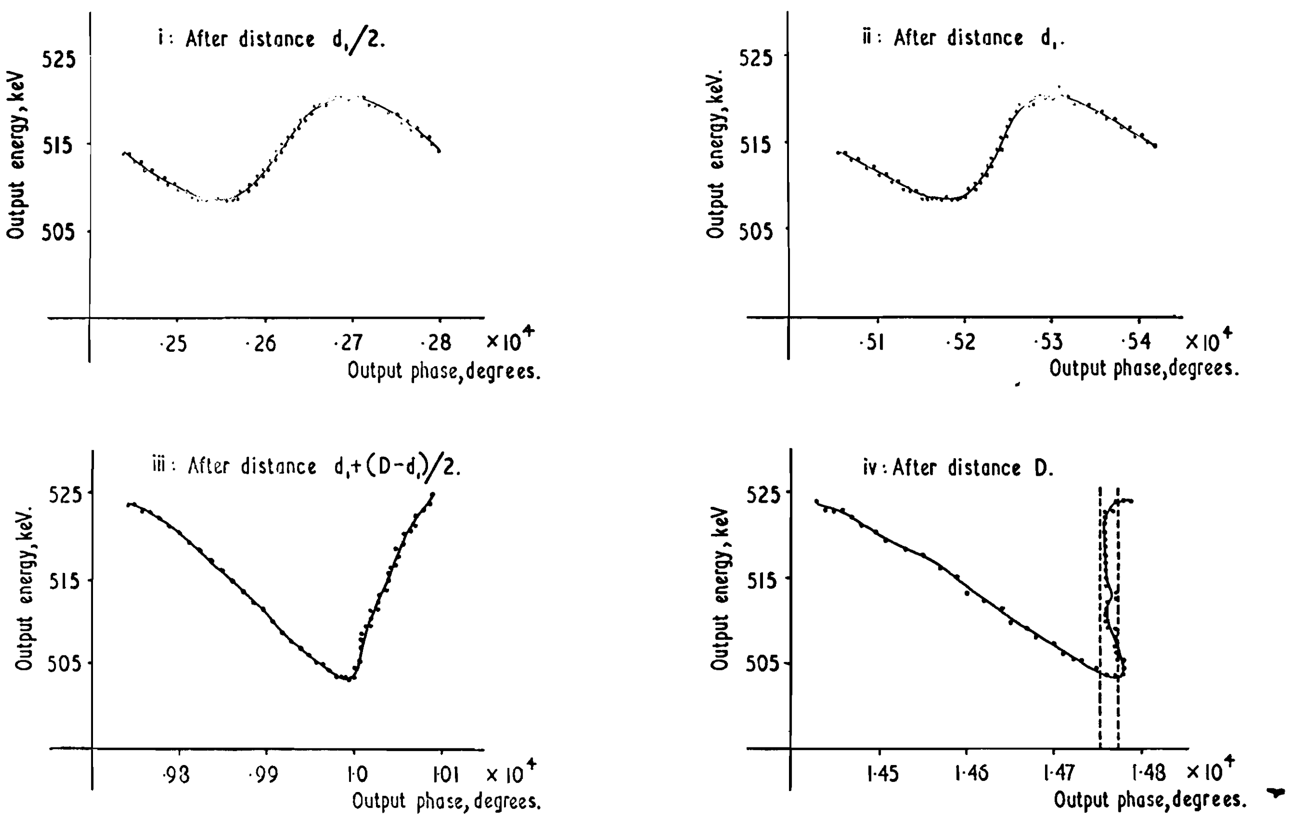

Fig. 4: Output energy versus output phase along the buncher system.

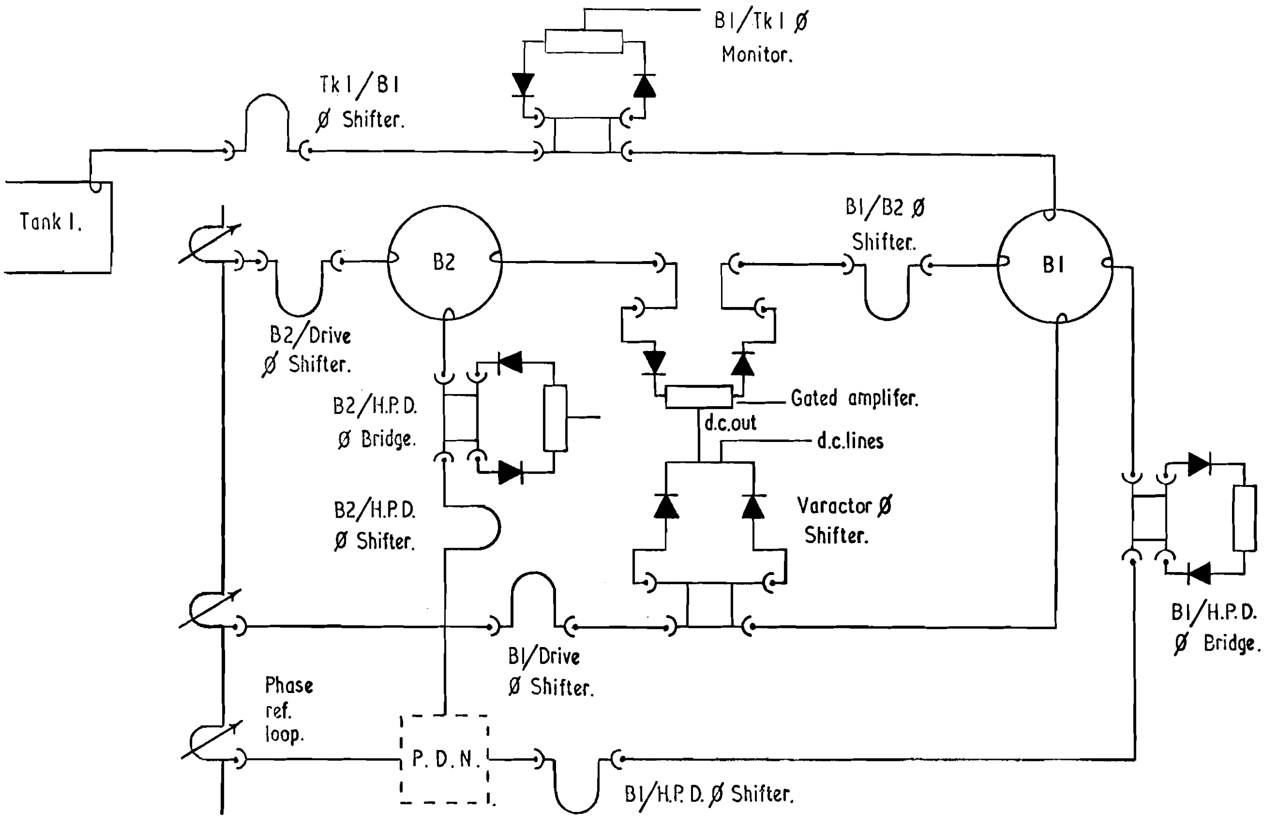

Fig. 5: Simplified R.F. System for the double bunchers.

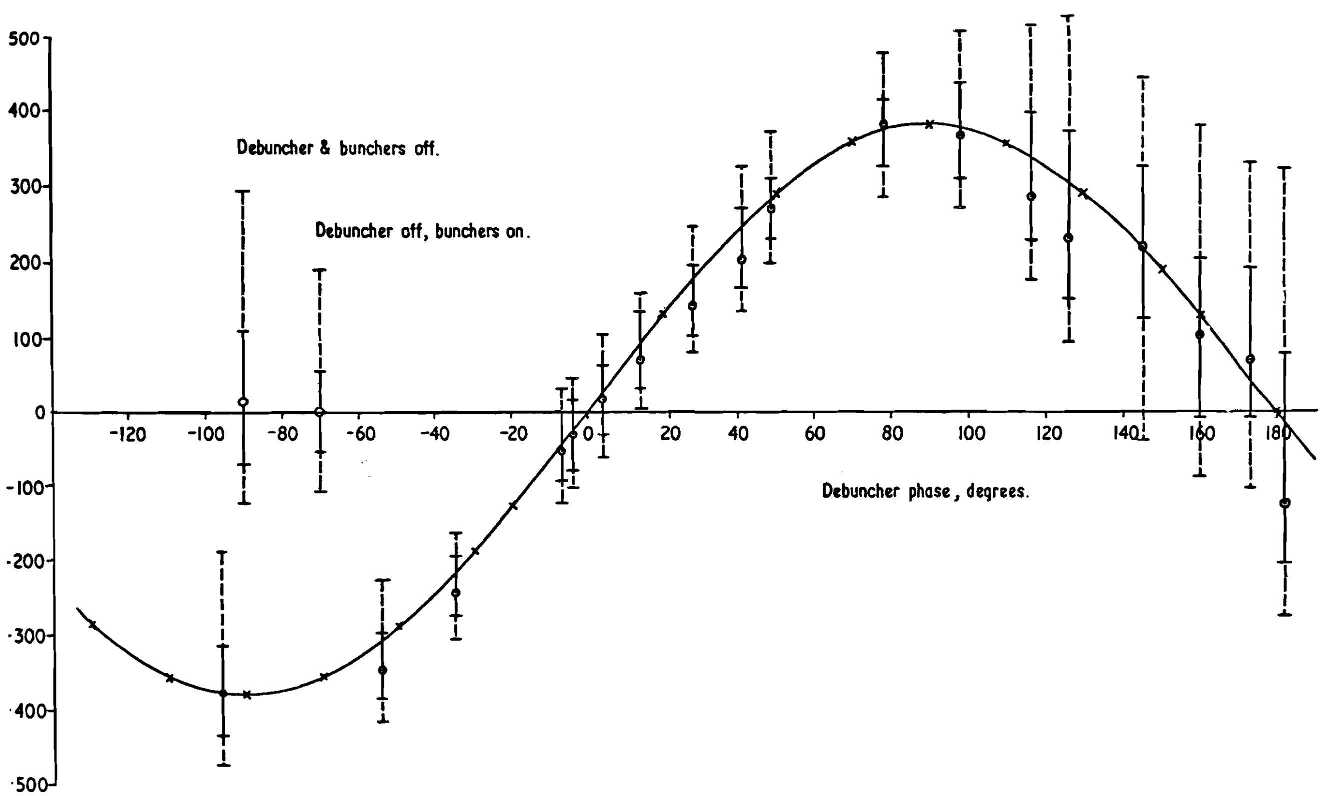

Fig. 6: Output energy spectra, at 50 MeV, as a function of debuncher phase compared with spectra without the debuncher. (The solid lines indicate the spectra width at half height and the dashed lines the width at the base.)

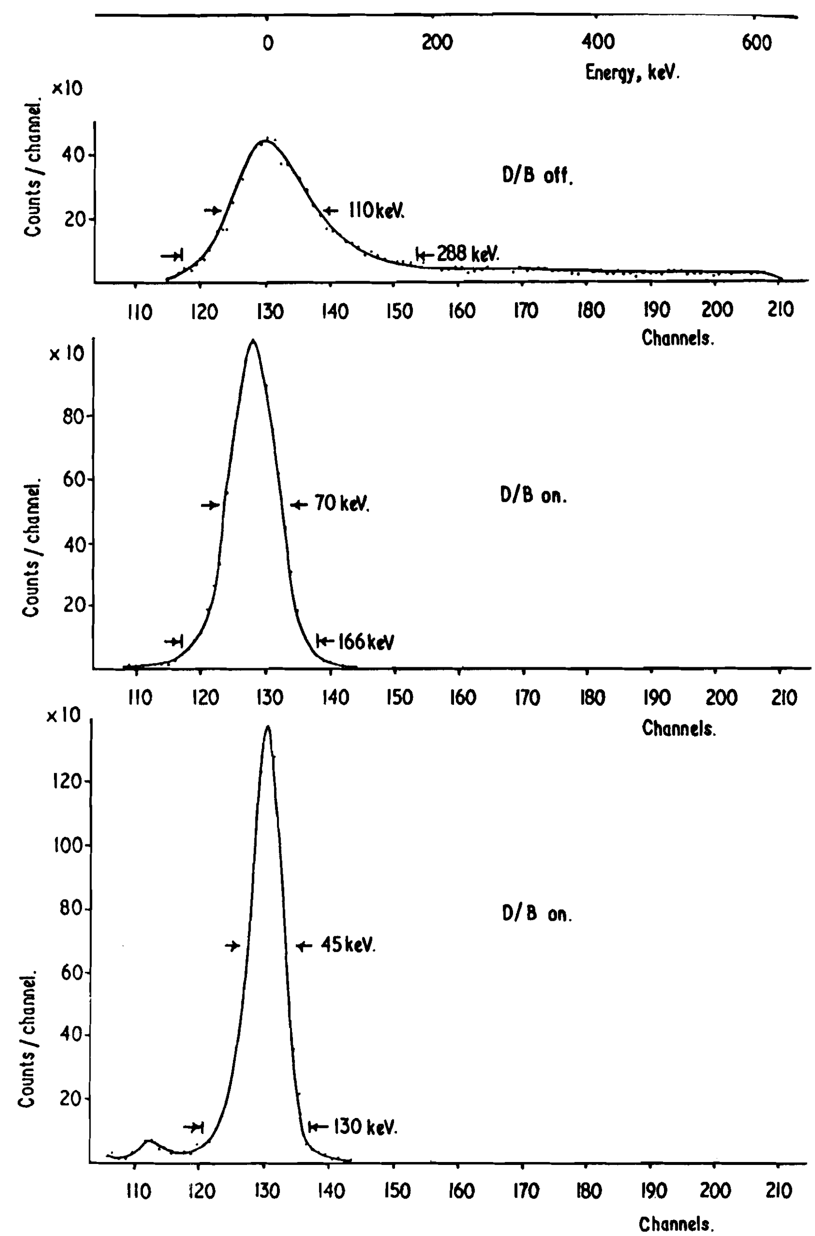

Fig. 7. Energy spectra measured at 50 MeV: a) without the debuncher, b) with the debuncher - full height target - and c) with the debuncher - 0.5 mm target.