DESIGN OF LONG IRIS-LOADED LINACS[*]

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Work of the proton linear accelerator group of the Rutherford Laboratory has been directed towards consideration of the Alvarez structures for acceleration up to energies of the order of 200 Mev and traveling wave structures for use above 200 Mev, where the Alvarez structure becomes inefficient considering the effective shunt impedance per unit length.

The Alvarez Structure

Detailed dimension studies have been done for two tanks serving as a possible extension of the Rutherford Laboratory 50 Mev P.L.A. These studies have been extended up to 110 Mev. The basic dimensions for the P.L.A. extension were suggested by Wilkins (1955) for 405 Mc/s operation and an acceleration rate of 2.3 Mev/m. The drift tube dimensions were set by the requirements for quadrupole focusing and to give maximum rf fields less than 20 Mv/m. A unit cell is given in Fig. 1 and the corresponding dimensions are as follows:

tanks 4 and 5, P.L.A., for energies up to 110 Mev

$D/_\lambda = 0.5319$; $d/_\lambda = 0.2042$; $d_1/_\lambda = 0.0429$

$r_1/_\lambda = 0.0172$; $r_2/_\lambda = 0.0515$; $d_s/_\lambda = 0.0343$

l_d (no supports) $= L\ (0.88242 - 0.8030\beta + 0.25888\beta^2)$

l_d (two supports) $= L\ (0.89904 - 0.85961\beta + 0.32911\beta^2)$

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[*] Report of work done by A. Carne and A.P. Banford

These last two equations have been obtained by the use of a model cavity for 810 Mc/s (corrected for air-to-vacuum, but not for temperature), and by the use of fixed cavities to determine choke joint corrections. These equations are correct to 0.05% at 810 Mc/s.

Above 110 Mev, the outer diameter D is reduced to $D/_\lambda = 0.4975$, to maintain the acceleration rate (by improving the transit time factor). All other dimensions are as before, but the drift tube lengths l_d are now given by the equations:

$$l_d \text{ (no supports)} = L\,(0.81532 - 0.32944\beta - 0.27140\beta^2)$$

$$l_d \text{ (two supports)} = L\,(0.81803 - 0.31388\beta - 0.27140\beta^2)$$

These last two equations are provisional, but should be accurate to within approximately 0.1%.

Estimates have also been obtained for values of effective shunt impedance, (including the transit time factor and assuming a phase stable angle $\phi_s = 30^o$); these values are, at 55 Mev: $R_{s\ eff} = 21.4$ meg/m; at 100 Mev: $R_{s\ eff} = 17.2$ meg/m; at 120 Mev: $R_{s\ eff} = 15.4$ meg/m; at 140 Mev: $R_{s\ eff} = 13.6$ meg/m. These figures have been calculated from "Design Notes on Resonators for P.L.A.'s", AERE GP/R 1613 (1955). More recent work on the properties of the Alvarez structure has resulted in an accurate computer program to give the resonant frequency, the Q value and the shunt impedance. This program has been checked against experimental results and gives the resonant frequency to within 0.25%. Also $R/_Q = 148$ is obtained, compared with the experimental value of 150.6 (± 3%). The program is now being used in a survey of shunt impedance against cell dimensions in the region of 200 Mev. For the dimensions given above at $L = 41.9$ cm and $g \cong 19$ cm (corresponding to 200 Mev) the effective shunt impedance (including a phase stable angle $\phi_s = 30^o$) is $\cong$ 14 meg/m. This work is continuing.

Traveling Wave Structures

It is clear from the above-mentioned results for shunt impedance that the Alvarez structure becomes inefficient at energies approaching 200 Mev. Above this figure a traveling wave system must be used. In practice the chosen structure would be operated in the resonant π-mode, where field and phase may be treated as lumped effects and may be controlled by single devices. For example, a single frequency tuner would suffice for a resonant tank, but for a traveling wave tank (e.g. $\pi/2$ mode), the tuner would have to act smoothly over the whole length of the structure to prevent phase change between beam and wave, and also to avoid reflections in the power transmitted along the structure.

It has been suggested that at 200 Mev there could also be a change to a higher frequency to improve the acceleration rate. There are now two main possibilities: a 1200 Mc/s disc-loaded waveguide with klystron power sources, or a 400 Mc/s waveguide employing coupling between adjacent cavities, with triode power sources. The final choice depends on economics and the practicability of feeding klystrons into high Q resonant systems. In the special case of Planet, the second case only applies since the frequency is determined by the refrigeration plant.

In the first case, the disc-loaded waveguide is clearly the best choice. It has an acceptable shunt impedance (= 37 meg/m at v = c including all transit time factors), and is calculable. In the second case, the disk-loaded structure has an effective shunt impedance of approximately 22 meg/m at v = c. Reduction of the iris diameter, or insertion of drift tubes, can increase this figure, but to overcome the resultant increase in attenuation along the structure some form of coupling must be provided. This can be done magnetically in the cavity end walls, provided the sign at the magnetic coupling is correct. If the magnetic coupling is positive a backward fundamental traveling wave results; if the coupling is negative, the fundamental is forward traveling. A forward traveling wave is desirable for the following reasons: higher shunt impedance, the π-mode frequency is the unperturbed frequency hence frequency tolerance is easier, wide bandwidth with consequent acceptable tolerances.

One example of a structure using negative magnetic coupling is the π-mode structure, where the coupling is achieved by a near resonant loop in the cavity end walls. This structure has an effective shunt impedance of 13.4 meg/m at v = .5c (excluding ϕ_s term).

A second example is the clover-leaf structure shown in Fig. 2. In this structure four projecting wedges are introduced into each cavity. These serve to distort the magnetic field lines into a clover-leaf pattern and so introduce radial components into the field. Each cavity is coupled to its neighbor by 8 equally spaced radial slots, often called negative mutually inductive coupling. By orientation of the adjacent cavities at 45°, the radial components of the magnetic field crossing the holes are arranged to be in opposite directions when the electric field lines and circumferential components of magnetic field are in phase (zero mode). Since the field lines are of nearly equal amplitude, the currents must then flow around each slot. The increased current path results in an increase in inductance so that the resonant frequency is lowered. For the π-mode the currents are in opposite directions on either side of the slot. The slot has then little effect on the current flow, and the resonant frequency in the π-mode is the unperturbed mode.

On the first model of the clover it was intended to bring the nose cones near the beam aperture and put focusing magnets inside them. But it was found that this reduces the effective shunt impedance. Also, with such large penetration, the magnetic field tends to separate from the continuous clover pattern into four separate loops between the nose cones. Reducing the size of the nose cone then gave the required magnetic field pattern.

Measurements at S-band frequencies so far have been done on a fixed nose cone shape and with variations of slot length, cavity length, and beam aperture. From the results it has been possible to obtain a family of curves of phase velocities of ½c to c versus frequency. Typical results are:

for 400 Mc/s, scaled from S-band experimental results

cavity length to give the π-mode; $\beta = 0.37$, $R_{s\ \mathrm{eff}} = 10.08$ meg/m, bandwidth 22%

cavity length to give the π-mode; $\beta = 0.5$, $R_{s\ \mathrm{eff}} = 13.42$ meg/m, bandwidth 19%

Linear scaling of the second case gives $R_{s\ \mathrm{eff}} = 27$ meg/m at $v = c$.

It is possible to improve these values by introducing drift tubes to improve transit time factor and by reducing nose cone penetration. This will have the effect of reducing the surface area, and hence losses. This, however, at the expense of bandwidth. It is to be noted that already the clover-leaf structure is comparable with the π-mode structure and does not suffer from lower breakdown voltages of the coupling loops of the π-mode structure.

A further structure investigated is the Jungle Gym structure described by Mohr (PIBMRI-892-61) and shown in Fig. 3. In this structure the π-mode is described as having a phase change of π between similar support bars. Thus a particle receives acceleration crossing each gap, but bunches can only exist in alternate gaps. S-band models have been made and indicate that the Jungle Gym structure has a backward fundamental wave and has a bandwidth of ≅ 50%. The S-band model was too small to do shunt impedance measurements, so a full-scale 400 Mc/s model is being made, with the following parameters:

1. Outside diameter 14 inches.
2. π-mode at 400 Mc/s, at $\beta = 0.5$.
3. Drift tube profiles initially hemispherical, with the radius determined on the basis of safe breakdown field strength at 400 Mc/s.
4. Beam aperture determined to allow for a drifting beam (in accordance with the proposal of L. Smith) with no internal focusing, the values being scaled from the 50 Mev P.L.A.

This model is being made and tests should start within the next few weeks.

As a concluding remark, it is felt that the resonant structure is preferable over the traveling wave structure. The basic reason is that it is possible to treat a resonant structure in terms of measurement of phase, as a unit, and thereby to tune the cavity as a unit. Considering a traveling wave structure, the phase along the whole length of the structure has to be corrected. Further, the phase velocity has to be correct with respect to the protons over the whole machine. This is a rather difficult problem. Some results obtained by J. Gardner show that the tolerances in terms of phase are quite stringent on a long linac.

Discussion

R. Gluckstern (Yale): Are the results of $R_{s\ \mathrm{eff}}$ for the Alvarez structure obtained at 810 Mc/s?

K. Batchelor (Rutherford): No. These results are based on Wilkins' data at 405 Mc/s.

I. Polk (BNL): Is the first tank of the P.L.A. still operated with grids in the drift tubes?

K. Batchelor (Rutherford): That is correct, yes.

I. Polk (BNL): Are you redesigning to fit in quadrupoles?

K. Batchelor (Rutherford): The redesign is to fit in dc quadrupoles. The earlier work was based on the principle that we would keep the rf structure the same as it is and fit quadrupoles into the present drift tubes. Later it was decided to make the drift tube diameters larger, requiring about 18% more in rf power, which is available. This provides more room for quadrupole magnets and water cooling. Fortunately, a lot of the design work was already done for us, since this turns out to be a scaled-down Nimrod injector. Also this turns out to be very near the original Alvarez machine.

References

"Design notes on resonator for proton linear accelerators", J.J. Wilkins, AERE GP/R1613 (1955)

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"Finite difference computation of parameters of electromagnetic resonant cavities relevant to proton linear accelerators", R. Taylor and P. Kitching, NIRL/M/37, July 1962

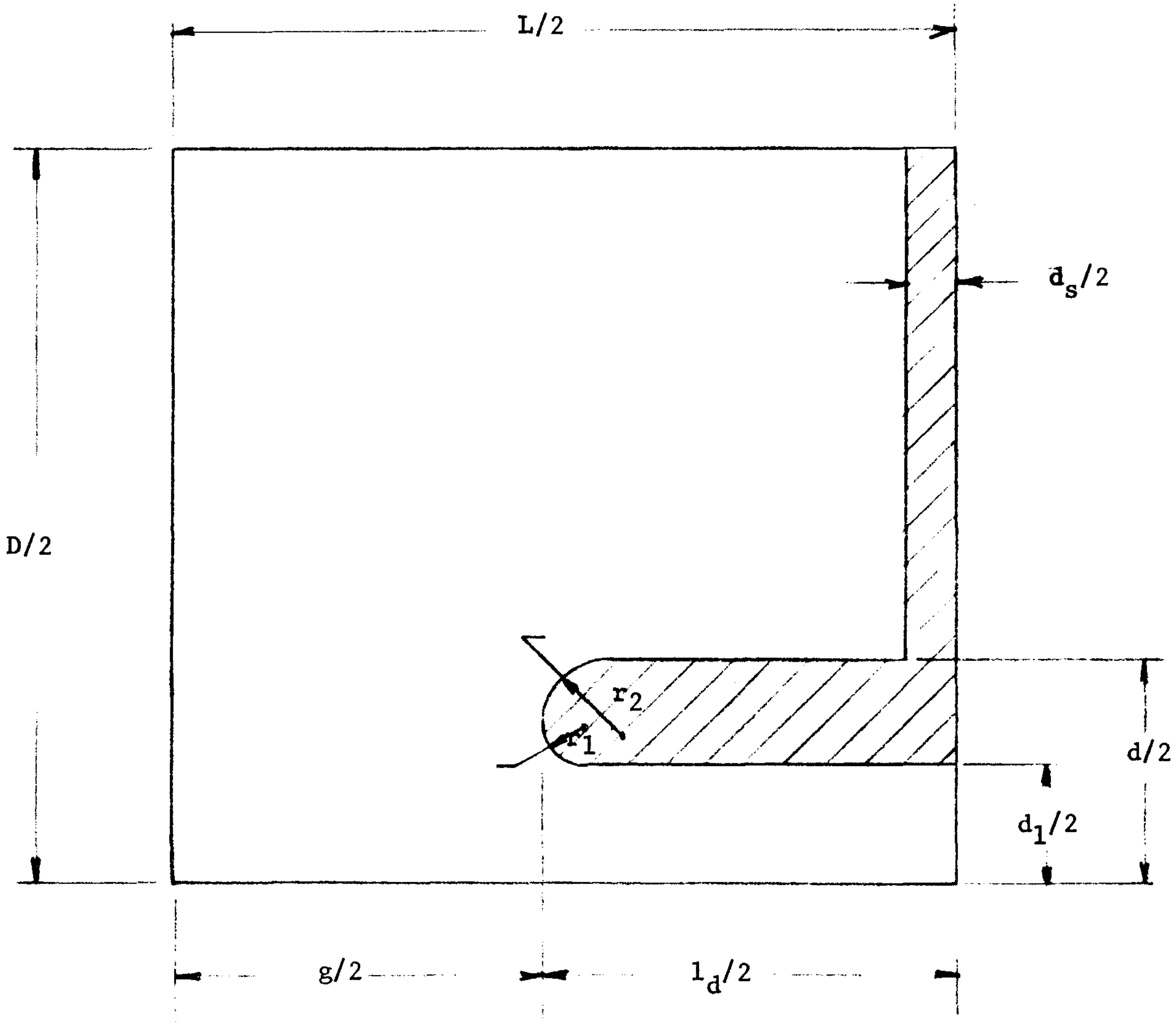

Fig. 1

Unit cell

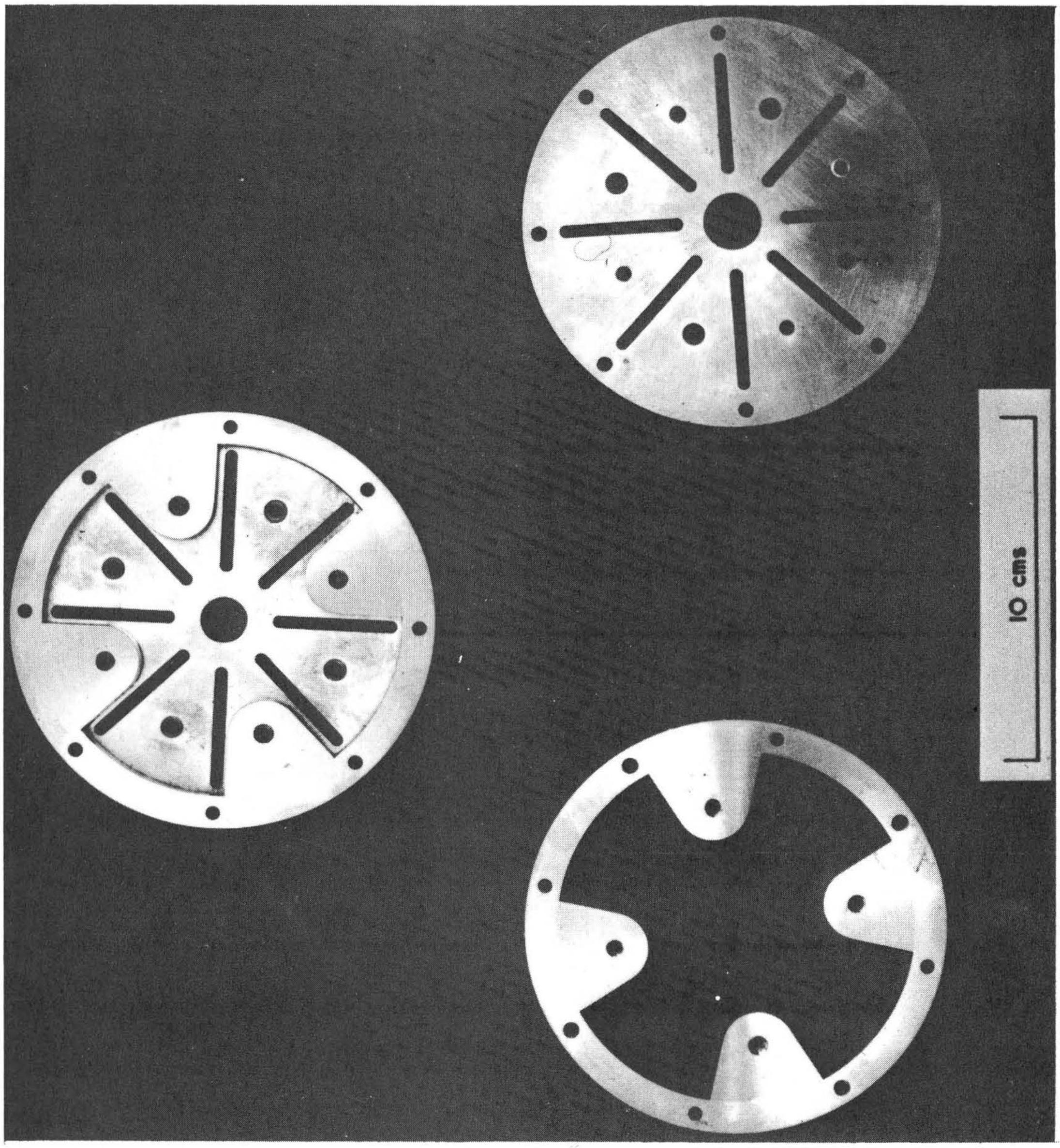

Fig. 2

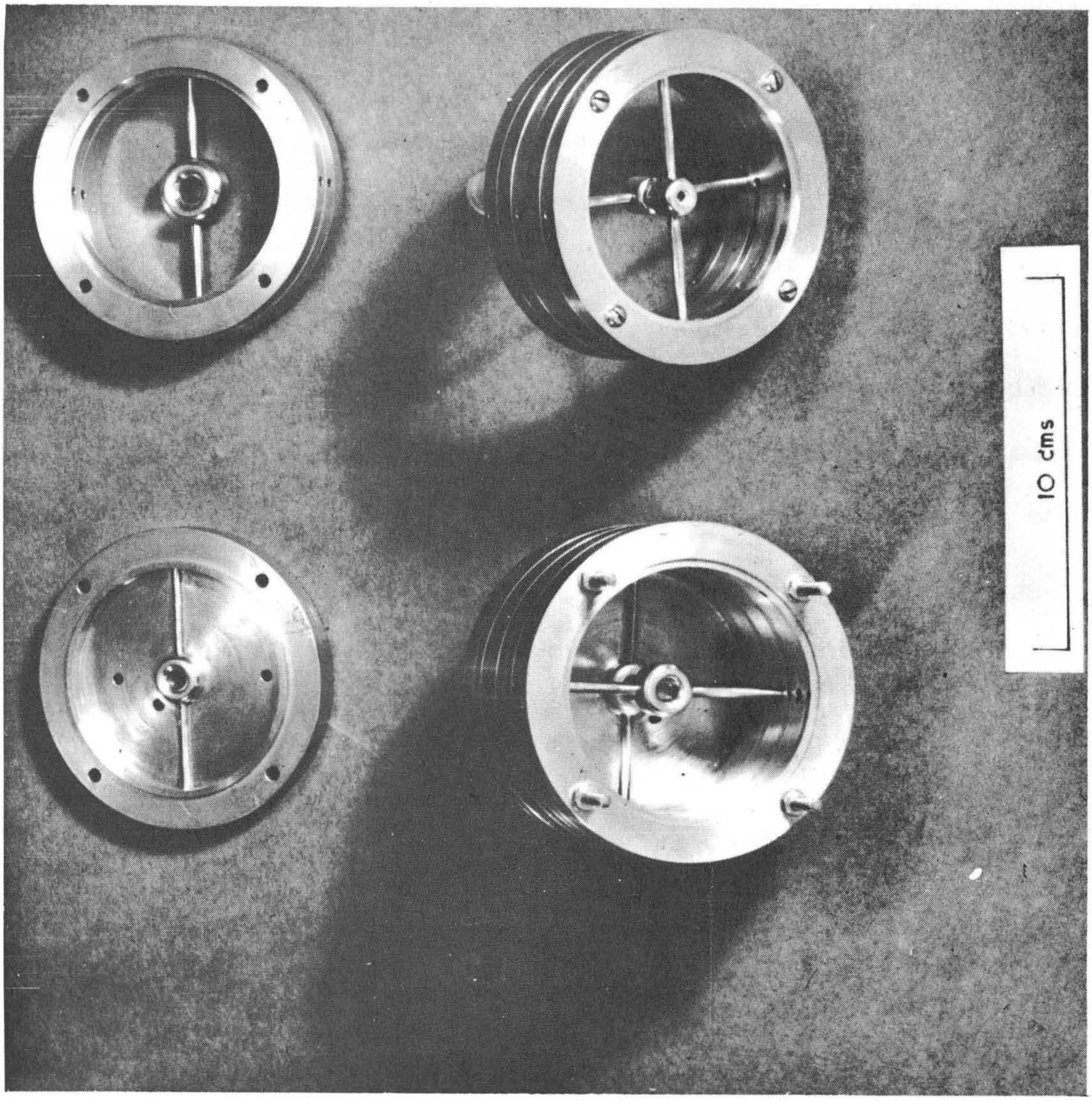

Fig. 3