DESIGN OF PROTON LINEAR ACCELERATORS FOR ENERGIES UP TO 300 MeV (*)

D.E. Young, R.S. Christian, T.W. Edwards,
F.E. Mills, D.A. Swenson, and J. van Bladel

Midwestern Universities Research Association,
Madison

(Presented by D.E. Young)

Proton linear accelerators of the Alvarez type are limited in energy because the efficiency of the conventional 2π structure for particle acceleration becomes small at higher energies. Many problems in the transition from this structure to another type of accelerating device can be minimized if the transition is made at sufficiently high energy. This is true when it is desired to continue the acceleration with either a traveling wave linear accelerator or a circular magnetic accelerator.

In order to extend the conventional structure to higher energies, 200 MeV or higher, it is necessary to minimize power losses by making a proper choice of cavity and drift-tube parameters. Computational methods have been developed[1] for calculating the resonant frequencies and fields of cavities with drift tubes which are arbitrary figures of revolution. Using these methods, an optimization of the cavity drift-tube dimensions have been made at 200 Mc/s and at energies of 50, 100, 150, and 200 MeV to give minimum power losses for cylindrical drift tubes. Drift tubes of other shapes are now under investigation to determine whether it is possible to further reduce the power losses at the higher energies. Ellipsoidal drift tubes have shown that a small improvement is possible.

Computational Method

For φ-independent transverse magnetic modes, Maxwell's equations reduce to

$$\frac{\partial^2 F}{\partial r^2} - \frac{1}{r}\frac{\partial F}{\partial r} + \frac{\partial^2 F}{\partial z^2} + k^2 F = 0$$

where $F = rH_\varphi$, and $k = \omega/c$. F is chosen so that the boundary conditions are simple. The solution of this equation is written in terms of an eigen-function expansion; the eigenvalue is calculated from a variational principle. A convergent iterative process is possible with each new eigenvalue giving a better value of F. For digital computation, these equations are reduced to finite difference relations and the calculation carried out over a mesh defined by the linear accelerator unit cell.

Fig. 1 illustrates the type of geometry considered in the calculation (by symmetry only one quadrant need be considered). If the resonant frequency is specified,

(*) Supported by the U.S. Atomic Energy Commission.

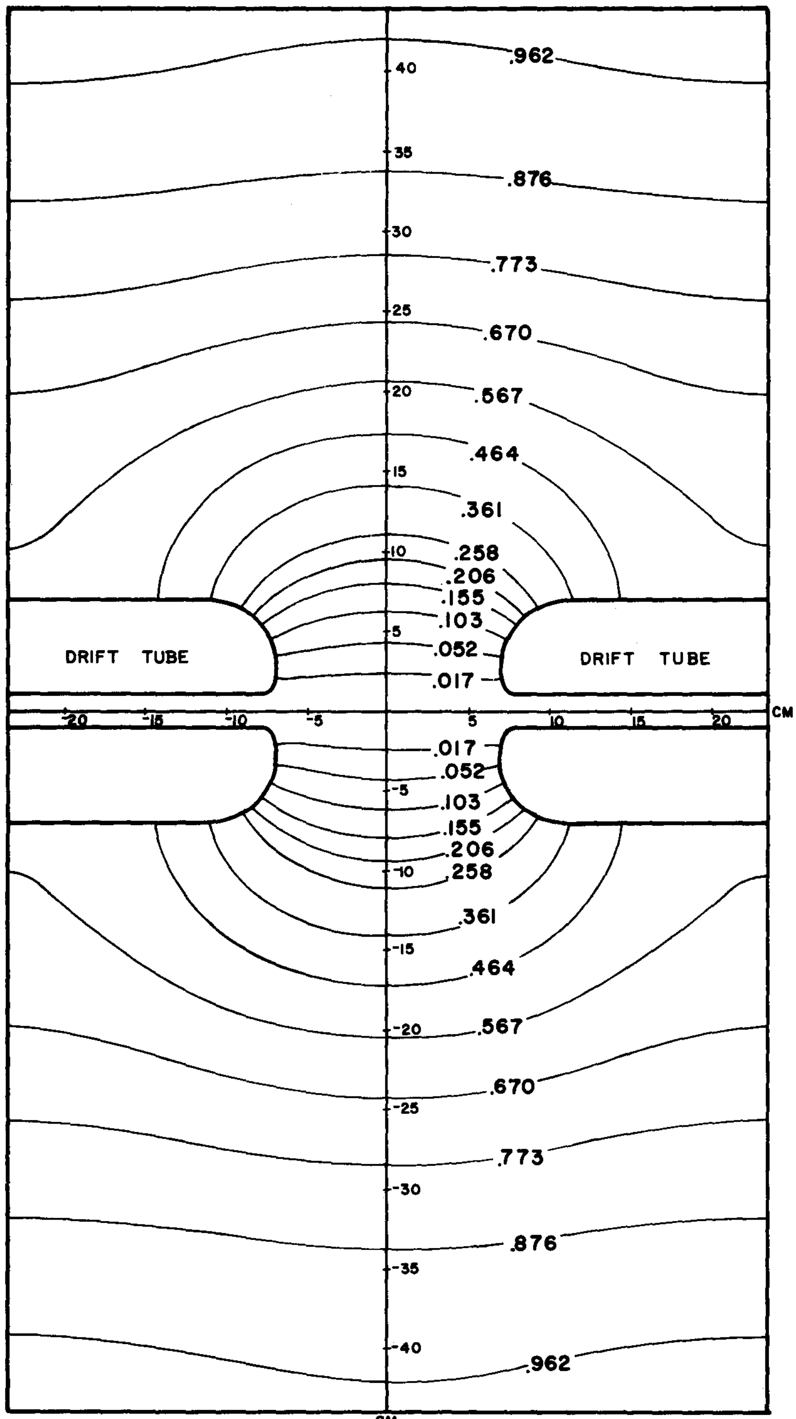

Fig. 1 F plot of a 50 MeV linac unit cell. F = rH (normalized to 5.06×10^{-6} J/m^3) f = 200.8 Mc/s; Q = 76,900; β = 0.313 (49.6 MeV); T = 0.8 (Transit time factor) ZT^2 = 55.2 MΩ/m (Effective shunt impedance).

five geometrical parameters must be considered for cylindrical drift tubes: (1) the drift-tube diameters, (2) the gap length, (3) the cell diameter, (4) the cell length, which is determined by the energy, and (5) the radius on the drift-tube corner. The usual practice is to choose these parameters so as to maintain resonance at the desired frequency (in this case 200 Mc/s), and in order to achieve the highest accelerating efficiency. The efficiency of the structure is based on achieving a maximum value of the "effective" shunt impedance ZT^2, where T is the transit-time factor and Z is the usual shunt impedance defined as the ratio of the square of the maximum axial accelerating voltage across the gap to the total power loss in the cell. The curves are lines of constant F and have the same direction as the electric field lines. With the F values known throughout the cell, it is fairly simple to calculate field strengths, power losses on the cell, the cavity "Q", the shunt impedance, transit-time factor, or other factors important for cavity design.

Results

Resonance curves at 200 Mc/s have been developed for cylindrical drift tubes over a range of the geometrical parameters by a large number of computer runs. At the particular energies of 50, 100, 150, and 200 MeV, a sufficient number of runs have been taken to allow a selection of the maximum value of the "effective" shunt impedance. At other energies out to 400 MeV runs have been made for a geometry which would be expected to give high values for the shunt impedance. These maximum values are shown in Fig. 2 where it is seen how the efficiency of the conventional 2π structure deteriorates at higher energies.

The problem of the decreasing efficiency of the structure at higher energies is illustrated by the unit cell at 200 MeV shown in Fig. 3. The drift tube has become so long that the desirable electric accelerating mode looks very different from that in Fig. 1. If one investigates the iso-H lines (lines drawn through points of equal H at equal intervals in H), it is observed that a great deal of H flux occurs along the surface of the drift tube indicating large current flow in the drift-tube surface. These currents cause large power losses and result in the decreasing value of the shunt

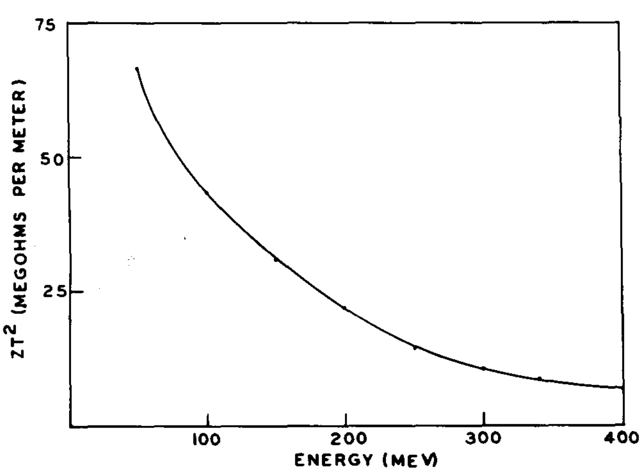

Fig. 2 Plot of maximum efficiency of cylindrically shaped drift tube versus energy.

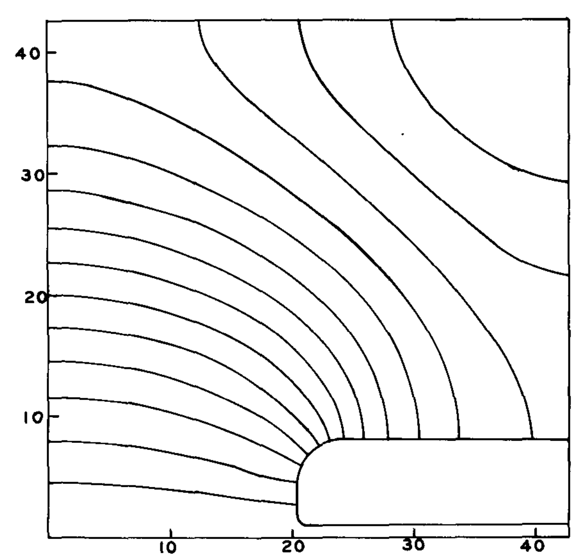

Fig. 3 200 MeV cylindrical drift tube F plot.

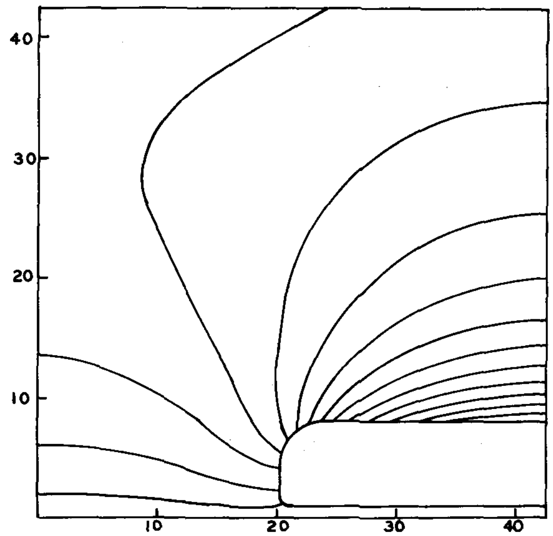

Fig. 4 200 MeV cylindrical drift tube iso-H plot.

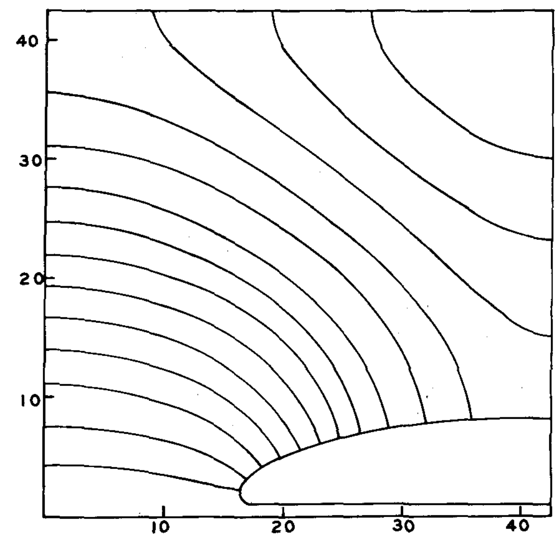

Fig. 5 200 MeV ellipsoidal drift tube F plot.

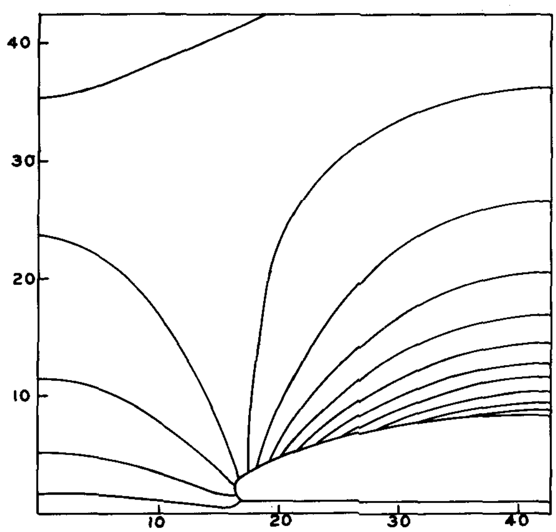

Fig. 6 200 MeV ellipsoidal drift tube iso-H plot.

impedance at higher energies. This is shown in Fig. 4.

To improve this situation, we are now investigating drift tubes of other shapes. The computer program has been modified to handle drift tubes of arbitrary shape provided the outside curvature does not change sign. Ellipsoidal drift tubes show an improvement in efficiency over the cylindrical shape. This is shown in Fig. 5 for an ellipsoidal shaped drift tube of the same diameter as the cylindrical drift tube of Fig. 3 and 4. The fewer number of F lines terminating on the drift-tube surface is indicative of smaller power losses on the drift-tube surface. This is also shown on the iso-H plot, Fig. 6, where it can be seen that some of the field has been restored to the gap. The "effective" shunt impedance has been improved from 15.6 MΩ per meter for the cylindrical drift-tube geometry to 18.7 MΩ for the ellipsoidal drift tube.

It is not certain at this time whether the increased efficiency of the ellipsoidal drift tubes can be realized in practice. Since the efficiency is strongly dependent upon the transit-time factor, the greatest efficiency is obtained for very small diameters of the drift tube and where the gap between drift tubes is also smallest. At these small diameters and at high energy there is little difference in the efficiency for various drift tube shapes. Furthermore, the ellipsoidal shape results in higher voltage gradients in the cavity. This fact, plus the added fabrication cost may rule out the more complicated shapes. On the other hand, if increased diameters are required to insert radial focusing devices, the ellipsoidal shape may be worthwhile.

References

1. T.W. Edwards, MURA Report No. 622 (unpublished, 1961).
2. R. Taylor, J. Nuc. Energy, Part C, Vol. 3, p. 128 (1961).

DISCUSSION

WHEELER : Although the methods used by the MURA and Yale programs for shaped drift tubes are quite different, they do in fact lead to quite similar results. The apparent difference in the numbers for shunt impedance which I quoted for Yale as compared to the MURA figures comes about because we have reduced our values by about 20% to account for losses (such as drift-tube stems and coupling loops) which are not included in the theoretical calculations.

YOUNG : Yes. I might also indicate that the computer program has been checked out experimentally not only by comparing with other results both for existing linacs and with the Yale program, but also on a precision frequency cavity. We find that we can calculate essentially everything that we can measure.