IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

TRANSMISSION-LINE CAVITY LINEAR-INDUCTION ACCELERATORS

Donald Eccleshall and Clinton E. Hollandsworth
USA ARRADCOM, Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005

Abstract

High current pulsed electron beams may be accelerated with nominally 100% efficiency using linear induction accelerators based on charged, internally switched, transmission line cavities.[1,2,3,4] Closed form analytical solutions for the accelerating voltage waveforms have been obtained for a general three-line arrangement which permits the switches to be placed in a region of lower electric field than for the two-line systems. It is shown that a set of line impedance ratios exist for which the nominal 100% efficiency is attained and some of these afford voltage gain. Some also give rise to a repeating open circuit gap voltage which might be useful in an efficient recirculating beam accelerator. Experiments with strip and coaxial line cavity models have been performed which validate the theoretical results, allow a comparison with two-line configurations, and identify the degree to which the theoretical assumptions are valid.

The General Three-Line Cavity Analysis

Figures 1a and 1b show schematically two basic geometries for the cavity. They comprise three transmission lines 1, 2 and 3 with impedances Z_1, Z_2 and Z_3 and equal pulse transit times or electrical lengths. In Figure 1a the lines are biconic about a point on the center line along which a pulsed electron beam (shown as a shaded arrow) can propagate within a drift tube. In Figure 1b the lines are coaxial with the beam trajectory. For the coaxial case shown it is indicated that line 3 has a different dielectric from lines 1 and 2 and a separator (shaded) is shown. Clearly it would also be possible to have the structure completely folded; that is, lines 1 and 2 radial to line 3. If the electrode forming the boundary between regions 1 and 2 is charged to a voltage V_0 and switches such as the one shown are closed, voltage pulses of duration $2T\ell$ appear at the end of line 3. Here T is the transit time per unit length of line and ℓ the line length. The end of line 3 farthest from the switch forms a gap in the drift tube across which the beam pulse may be accelerated. The equivalent circuit of this ideal cavity is shown in Figure 2 where we have replaced the switch by a step generator to set up the initial conditions and included a switch impedance. For the work reported here we assume $Z_s = 0$, a situation for which an analytical solution to the circuit equations is possible. The Laplace transform of the open circuit voltage at the gap is:

$$\overline{V} = \frac{2 V_0 \tau_{23} \sinh^2 sT\ell}{s(\cosh 3sT\ell + \rho \cosh sT\ell)} .$$

Here s is the Laplace transform variable and

$$\rho = \rho_{12} + \rho_{23} + \rho_{12}\rho_{23} = \tau_{12}\tau_{23} - 1$$

is given in terms of the reflection and transmission coefficients:

$$\rho_{ij} = \frac{Z_j - Z_i}{Z_j + Z_i} ; \tau_{ij} = (1 + \rho_{ij}) .$$

The inverse transform is a series of voltage pulses of duration $2T\ell$ and the k^{th} pulse $[(2k+1)T\ell < t < (2k+3)T\ell]$ is given by:

$$V^{(k)} = \frac{V_0 \tau_{23}}{1 + \cos\theta} [\cos k\pi + \cos (k+1)\theta]$$

where $\cos\theta = (1-\rho)/2$. This expression gives the same results for $V^{(0)}$ and $V^{(1)}$ as had been derived earlier and reported in Reference 2.

In the presence of a beam pulse of current I duration $2T\ell$ arriving at the gap in the interval defined by k we have a gap voltage $V_g^{(k)}$ and

$$V_g^{(k)} = V^{(k)} - I Z_3 .$$

In a manner similar to that used in Reference 3 it can be shown that the conditions for unit efficiency for transfer of the energy initially stored electrostatically in lines 1 and 2 to the beam on the k^{th} pulse is given by:

$$I = \frac{V^{(k)}}{2 Z_3}$$

$$\text{k odd:} \quad \theta = \frac{(2m + 1)\pi}{k + 1} ; m = 0, 1, 2 \ldots \frac{k-1}{2}$$

$$\text{k even,>0:} \theta = \frac{2m}{k+1} ; m = 1, 2 \ldots \frac{k}{2}$$

and $\tau_{23} = \frac{3 - \cos\theta}{2} = \frac{5 + \rho}{4}$.

In analogy with the situation for two line systems,[2,3] we expect in principle to transfer energy efficiently to a beam which is circulated through the cavity when the open circuit waveform repeats. This happens whenever θ is a rational fraction of π or

$$\theta = \frac{p}{q}\pi; \quad p < q \text{ are integers.}$$

The period of repetition is $2q$ $(2T\ell)$.

Specific Cavity Configurations

Some unit efficiency cases corresponding to a matched beam applied during the k^{th} interval, $I = V_g/Z_3 = V^{(k)}/2Z_3$, are given by:

k	θ	Z_2/Z_1	Z_3/Z_1	$\lvert V_g/V_0 \rvert$
1	π/2	2	6	1.5
2	2π/3	6	42	3.5
3	π/4	0.343	0.461	0.672
3	3π/4	11.6	147.0	6.33

The open circuit waveforms for the first three cases are shown in Figure 3. These waveforms of course repeat with periods $2(k+1)(2T\ell)$ as is shown. The first case has been described before[2] and has the most practical interest since it affords some voltage gain and involves impedance ratios that can be readily attained. In contrast the fourth case, corresponding to $k = 3$, $\theta = 3\pi/4$, is probably impractical. The second case, $k = 2$, $\theta = 2\pi/3$, should be achievable in a folded coaxial configuration and affords substantial voltage gain. Case 3, $k = 3$, $\theta = \pi/4$ is of interest because it corresponds to having the switch across a region of relatively high impedance. Analysis and experiments on two-line models show that the glitches in the output waveform due to current reversals in the switches are less severe in this situation. The case of $k = 2$, $\theta = \pi/3$ is also shown in Figure 3. It is repetitive but cannot be 100% efficient for single pass acceleration. In contrast to the two-line configurations it is not possible to have a waveform that rises to a peak in a succession of pulse periods, $2T\ell$. In the three-line case successive pulses must alternate in polarity.

Model Experiments

The foregoing principle mode analysis provides first order results to define overall performance. We have omitted any discussion of, for example, beam stability and voltage breakdown which must be considered in the context of a specific beam current and application. Generally, however, a flat topped accelerating voltage V_g is required and, for a recirculating device, the waveform should maintain its integrity for several repetitive periods. To determine the severity of waveform deterioration a number of experiments have been performed using coaxial cables with mercury switches and parallel-plate lines with both mechanical and avalanche transistor switches.

The output from a 50 Ω array ($Z_1:Z_2:Z_3 = 1:1:1$) of RG-254/U cables controlled by a mercury switch is shown in Figure 4. The shields of lines 1 and 2 are charged. The coupling to line 3 requires cross-connection of a shield of line 3 to the center pin of line 1 and introduces non-coaxial regions which produce some ringing. Nonetheless the repetitive nature of this configuration is clearly indicated. The output from a 1:2:6 parallel-plate line switched mechanically is shown in Figure 5. The signal was obtained from a capacitive pickoff near the end of line 3 and is in general agreement with the waveform of Figure 1 for these impedance ratios. However a sizeable glitch appears in the output at approximately $6T\ell$ and by the occurence of the second negative swing severe waveform distortion is evident. This glitch, apparently associated with current reversals in the switch, occurs in all geometries and with all switches used in our model experiments. Another example is given in Figure 6 which shows the output from a 1:1:2 line switched by an avalanche transistor circuit.

Conclusions

A number of three-line cavity arrangements have been found which may be attractive for efficient acceleration in a single beam pass. The cavities offer the prime advantage of placing the switch in a region away from the accelerating gap where the electric field can be lower. Experimentally we have been unable to reproduce the predicted waveform using the simple experimental models for more than 6 pulse periods. This, together with the fact of adjacent pulse polarity reversals, suggests that three-line cavities will be unattractive for a recirculating accelerator to achieve high gradients. This is in contrast to the two-line system where waveforms have been observed to repeat for 8 repetitive periods or 24 pulse periods. Experiments on a full-scale three-line folded cylindrical cavity are in progress.

Acknowledgements

We wish to acknowledge the many contributions made by Joe Correri to the model experiments.

References

1. A.I. Pavlovskii, et al., Sov. Phys. Dokl. 20, 441 (1975).

2. D. Eccleshall, et al., IEEE Trans. in NS 26, 4245 (1979).

3. J.K. Temperley and D. Eccleshall, "Analysis of Transmission-Line Accelerator Concepts," USA ARRADCOM, Technical Report ARBRL-TR-02067, May 1978.

4. I.D. Smith, Rev. Sci. Instrum. 50, 714 (1979).

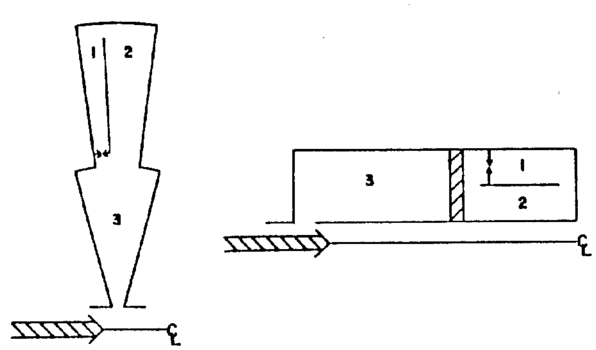

Figure 1. Three-line cavity configurations.

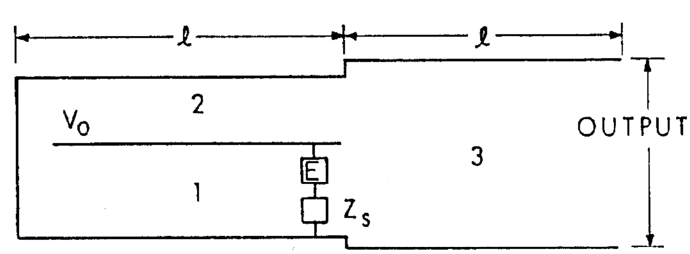

Figure 2. Equivalent circuit of the three-line system.

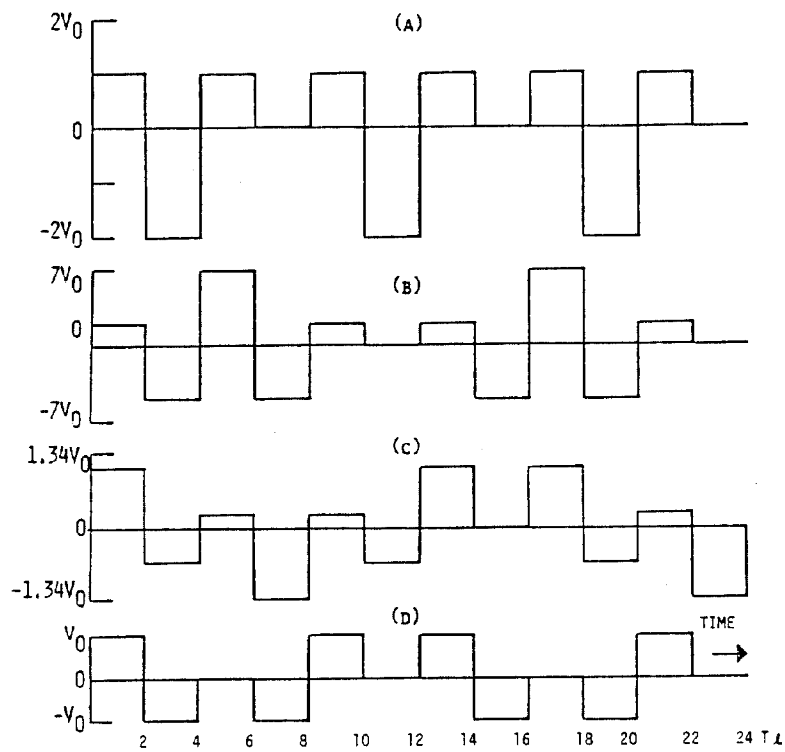

Figure 3. Open-circuit waveforms with $Z_1:Z_2:Z_3$ equal: (a) 1:2:6, (b) 1:6:42, (c) 1:0.343:0.431, (d) 1:1:1.

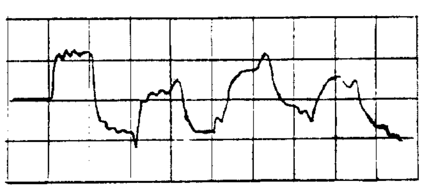

Figure 4. Output voltage waveform of a coaxial cable array ($Z_1=Z_2=Z_3/50\Omega$). The time calibration is 50 ns per division.

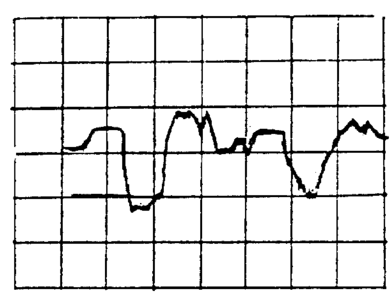

Figure 5. The output voltage waveform for parallel-plate lines ($Z_1:Z_2:Z_3=1:2:6$) which are mechanically switched. The time calibration is 20 ns per division.

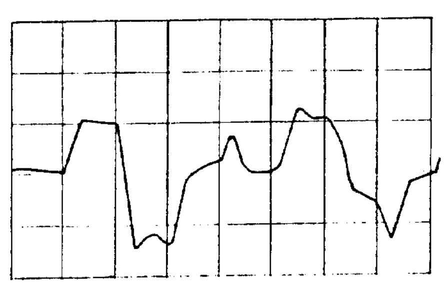

Figure 6. The output voltage waveform for a parallel-plate line system ($Z_1:Z_2:Z_3=1:1:2$) which is switched electrically. The time calibration is 10 ns per division.