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CHARGED, INTERNALLY SWITCHED TRANSMISSION LINE CONFIGURATIONS FOR ELECTRON ACCELERATION

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Abstract

High current pulsed electron beams may be accelerated with nominally 100% efficiency using induction accelerators based on stages of charged internally-switched constant-impedance transmission lines.[1-4] Under certain conditions one obtains a repeating open circuit voltage waveform which can, in principle, be used to transfer 100% of stored energy to a beam which is recirculated and this would permit a higher overall acceleration gradient. We have also identified some efficient three line arrangements which could be exploited in the single pass mode. Some of the fundamental practical limitations to these concepts, such as the pulse distortion at line discontinuities and coupling to the beam, have been addressed.

Two-Line, Single Pass Acceleration

Simple two-line configurations of single cavities are shown schematically in figures 1a and 1b. The cavity impedances are determined by the angles α, β, γ in the biconic case of figure 1a and by the radii a, b, c in the cylindrical case of figure 1b. The two lines, with impedance Z_1 and Z_2, have equal length, ℓ. Line 1 is switched with a set of switches, S, circumferentially positioned close to the accelerating gap in the beam tube. When the center electrode separating lines 1 and 2 is charged to a voltage V_0 and the switch is closed a series of voltage pulses appear at the gap as an output of line 2. If the transit time per unit length of line is T, the duration of the pulses is $2T\ell$. In the absence of a beam, the equivalent circuit shown in figure 1c may be used to deduce that the m^{th} voltage pulse, $V^{(m)}$, is given by:

$$V^{(m)} = (-1)^m V_0 \frac{\sin (2m+1) \frac{x}{2}}{\sin \frac{x}{2}} \quad . \tag{1}$$

Here $x = \arccos \rho$ and ρ is the reflection coefficient going from line 1 to line 2; $\rho = (Z_2-Z_1)(Z_1+Z_2)^{-1}$.

Recurring voltage waveforms are obtained if x is a rational multiple of π. Examples of such repeating waveforms are shown in figure 2 for $\rho = 0$ $(Z_1=Z_2)$, $\rho = \frac{1}{2}$ $(Z_2=3Z_1)$ and $\rho = -\frac{1}{2}$ $(Z_1 = 3Z_2)$.

When a beam with current I and duration $2T\ell$ is applied during the m^{th} voltage pulse the gap voltage becomes, in a principal mode approximation,

$$V_g = V^{(m)} - IZ_2. \tag{2}$$

Using equations (1) and (2) it has been shown[2,3] that a nominal 100% of the stored energy in the cavity is transferred to the beam on the m^{th} voltage pulse if

$$x = \frac{2j+1}{2m+1}\pi, \; j = 1,2,3 \; ..... \; (m-1), \; m > 1 \; , \tag{3}$$

$$\text{and } I = V^{(m)}/2Z_2 \quad . \tag{4}$$

It is instructive to note that that for m = 1, $V_g = V^{(0)} = V_0$; that is, there is a symmetric bipolar pulse at the gap. In the $\rho = 0$ case beams of duration $4T\ell$ must be used to achieve 100% efficiency for which $V_g = V_0/2$. For $\rho = 0$ the pulse amplitude preceeding the arrival of the beam is $2V_g$.

Two-Line Cavity, Recirculating Beam Acceleration

If with the two-line cavities described in the previous section a lower beam current is used, energy remains in the cavity and voltage pulses of duration $2T\ell$ but reduced amplitude continue to appear at the gap. These voltages may be obtained by superposing the open circuit voltage, $V^{(m)}$, and the voltage at the gap generated by the passage of the beam pulse. In the principal mode and lossless line approximation, the latter is given by $V^{(k)}$ where

$$V^{(k)} = Z_2 I, \; k = 0; \; V^{(k)} = 2(-1)^k Z_2 I \cos kx, \; k>0 \; . \tag{5}$$

Here k counts the intervals since the beam passed the gap. This equation together with the conditions necessary for a repeating waveform may be used to show that, if a beam is recirculated to arrive at the gap during some integer multiple of the repetition period, the voltage gain on the s^{th} pass is

$$V_g^{(s)} = V^{(m)} - Z_2 I \; (2s-1) \quad . \tag{6}$$

The cumulative voltage gain after κ passes is therefore

$$V_R^{(\kappa)} = \kappa(V^{(m)} - \kappa \, Z_2 I) \quad . \tag{7}$$

The condition for unit efficiency corresponds to $I = V^{(m)}/2\kappa Z_2$, and to values of the impedance ratio parameter, x, given by equation (3). The results may be summarized as follows: To accelerate a beam with current I in the recirculating mode with nominally 100% efficiency after κ passes we match the cavity to a current κI. In this case the overall beam voltage gain is $\kappa V^{(m)}/2$. Because of losses in the cavity, waveform deterioration and the fact that the voltage gain per pass decreases in each successive pass, it is neither practical nor profitable to recirculate κ times. If the beam is recirculated only λ times the total voltage gain, V_{acc}, and efficiency, η, become

$$V_{acc} = \frac{1}{2} \lambda V^{(m)} \left(2 - \frac{\lambda}{\kappa}\right) \; . \tag{8}$$

$$\eta = \frac{\lambda}{\kappa}\left(2 - \frac{\lambda}{\kappa}\right) \quad . \tag{9}$$

Thus, if $\lambda = \kappa/2$, the total voltage gain and efficiency are reduced by only 25%. As an example, if $\rho = ½$ and $V_0 = 1$ MV, $Z_2 = 50\ \Omega$, a 2 kA beam could be accelerated to 7.5 MV with 75% nominal efficiency after five passes. The beam would have to arrive at the gap at intervals of 3τ (or 6τ, or 9τ) where $\tau = 2T\ell$ is the beam pulse width. An arrangement for recirculating in a multigap system with constant magnetic field magnets is shown very schematically in figure 3.

Three-Line Cavity Configuration

Figures 4a and 4b show schematically two basic geometries comprising three transmission lines of equal length, ℓ, with impedances of Z_1, Z_2, Z_3. To illustrate some design options figure 4a shows biconic lines in which a single dielectric is used and the line impedances are determined by the angles the

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the conical surfaces make with the axis. In figure 4b coaxial geometry is shown in which regions 1 and 2 have a different dielectric from that in region 3. If the electrode forming the boundary between regions 1 and 2 is charged to a voltage V_0 and the switches are closed, voltage pulses of duration $2T\ell$ again appear at the gap. The first two voltage swings, $V^{(0)}$ and $V^{(1)}$, in the absence of a beam are

$$V^{(0)} = 2V_0 Z_3(Z_2+Z_3)^{-1}, \quad T\ell < t < 3T\ell \qquad (10)$$

$$V^{(1)} = -8V_0 Z_2 Z_3^2 (Z_2+Z_3)^{-2}(Z_1+Z_2)^{-1}, \quad 3T\ell<t<5T\ell. \qquad (11)$$

As before the gap voltage, V_g, in the presence of a beam applied during the second period and with current I and duration $2T\ell$ is approximated by $V_g = V^{(1)} - IZ_3$. The efficiency, η, for transfer of the initially stored electrostatic energy to the beam is given by

$$\eta = \frac{4(V^{(1)}-IZ_3)IZ_1Z_2}{V_0^2(Z_1+Z_2)} \quad . \qquad (12)$$

Many possible impedance ratios have been identified with some practical interest. We here restrict ourselves to two cases; one because of the design simplicity and the other because it yields 100% efficiency. These are:

(a) $Z_3=2Z_2=2Z_1$, $I=V_g/Z_2$, $V_g=8V_0/9$, $V^{(0)}=-4V_0/3, \eta=(8/9)^2$

(b) $Z_3=3Z_2=6Z_1$, $I=V_g/Z_2$, $V_g=V^{(0)}=1.5V_0$, $\eta=1$.

Case (a) was identified briefly in reference 2. We note that the undesirable feature from the point of view of voltage breakdown at the gap of having $V^{(0)}>V_g$ may be avoided by halving the beam current. This gives $V_g = V^{(0)} = 4V_0/3$ at the expense of a reduced efficiency, ($\eta \approx 0.6$). Case (b) is of particular interest not only because of the high efficiency but also because it affords some voltage gain and provides a symmetric bipolar gap voltage. When efficiency is not at a premium low current beams could be accelerated through voltages up to three times the charging voltage. For completeness we note that Ian Smith (private communication) has identified an alternative three line arrangement which also moves the switches to a lower field region and yields 100% efficiency.

Acceleration Gradients

Simple expressions for the single pass acceleration gradient can be obtained in cases of practical interest. For matched beam currents, I, pulse lengths, τ, provided $I/\tau << 10^{14}$ A/s, we can write the single-pass acceleration gradients, which are independent of cavity dielectric, as

$$E_{SP} = \frac{I}{\tau c} r\, z \;;\; c = \text{velocity of light in vacuum.} \qquad (13)$$

The parameter r depends on the line geometry. In the case of biconic lines in which $\beta = 90°$ and α-β, β-γ are small angles, r = 1 (figure 1a). If α-β, β-γ are large angles we can have $r \approx 1.8$. For a coaxial geometry in which gap distances, d, are neglected, $r = \ln(c/a)$ (figure 1b). The parameter z depends on the line impedance ratio; for two-line systems in which $Z_2 = Z_1 (\rho=0)$ and $Z_2 = 3Z_1 (\rho=\frac{1}{2})$, z = 120 Ω and 90 Ω, respectively. In the three-line cases the same values of r may be used but we find 80 Ω ≤ z ≤ 120 Ω depending on the specific geometry with the higher value corresponding to the unit efficiency case, $Z_3 = 3Z_2 = 6Z_1$. Higher gradients can of course be obtained by reducing the nominal efficiency: if efficiency is reduced from 100% to 75% a three-fold increase in gradient is achieved.

More dramatic increases in acceleration gradient may be obtained for relatively low-current beams by recirculating the beam through the accelerator. This is due to the increase in the total voltage gain, and the fact that the cavity is designed for a higher current. Using equation (8) and (13), for recirculating beam currents I<20 kA, the gradient E_R is given by

$$E_R = \lambda\kappa(2 - \frac{\lambda}{\kappa})\, E_{SP} \;, \qquad (14)$$

where E_{SP} is the gradient associated with the beam current I in a design giving unit efficiency for a single pass. Thus if $\lambda = 3$ and $\kappa = 6$ a twenty-sevenfold improvement in gradient is achieved at a nominal efficiency of 75%. Of course, we have neglected in the analysis any spaces that would be taken up by the magnets used to recirculate the beam.

Gap Waveform Deterioration

Principal mode analysis provides first order results to define overall performance. Thus we omit 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 constant beam energy during the pulse is required and a crucial consideration is the effect of line discontinuities on the voltage waveform at the gap, particularly for a recirculating mode. Therefore we have performed a number of equivalent circuit and computer simulation analyses of the output waveform and several experimental tests at low voltages.

The waveforms predicted by equation (1) are easily demonstrated with a mercury switch and pairs of coaxial cable arrays, each array consisting of cables in parallel as required to achieve the desired impedance ratios. Several ratios were studied including those of figure 2. Figure 5 shows the oscilloscope trace obtained for $\rho = -\frac{1}{2}$.

To study discontinuity effects experimentally, avalanche transistors were used to switch charged strip transmission-line pairs ($\rho = 0$ and $\rho = \frac{1}{2}$). In practice the discontinuity d (figure 1) need only be large enough to satisfy voltage stand-off requirements, i.e., d = h, the smallest line spacing. In figure 6 results for two extreme cases are shown. The longer rise times and more rapid deterioration in overall quality of the pulse in the large-discontinuity configuration are evident. The output signals were derived from a capacitive pickoff and the associated RC time constant is responsible for the exponential envelope of the pulse train.

More detail on risetime deterioration is provided in figure 7. The superimposed traces are for d = h and d = 12 h. The upper and lower traces show the regions around $\tau = 2T\ell$ and $\tau = 6T\ell$ respectively. For the strip lines reasonably good agreement is obtained between experiment and analysis which uses published equivalent circuit parameters. Present experimental work includes refinement of the work described above using mechanically improved strip-lines and construction of a practical cylindrical cavity ($\rho = \frac{1}{2}$ and air dielectric) for detailed studies of the effect of switch configuration on output waveform.

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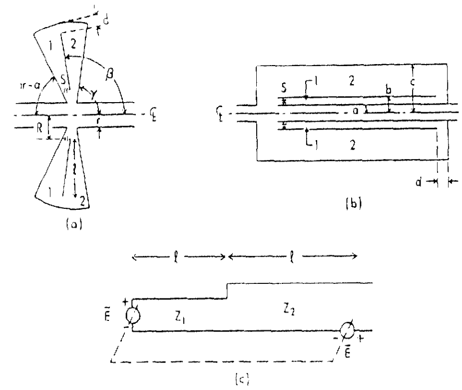

Figure 1. Asymmetric Pulse-Line Configurations.

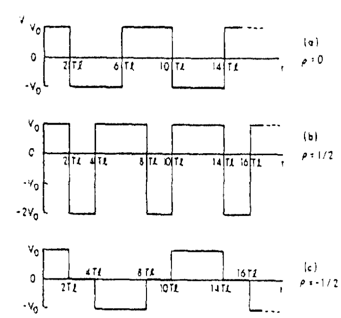

Figure 2. Recurring Open-Circuit Voltage Waveforms.

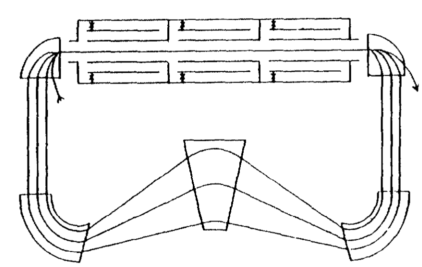

Figure 3. Schematic Diagram of Recirculating Accelerator with Constant Field Magnets.

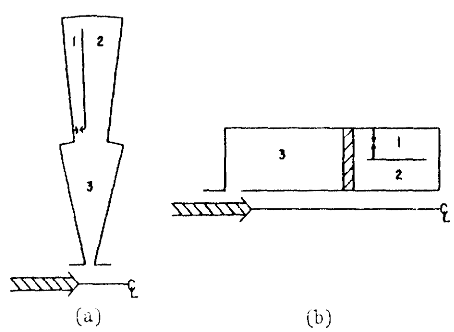

Figure 4. Three-Line Configurations.

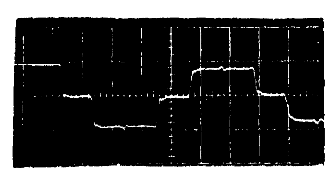

Figure 5. Oscilloscope Trace for $\rho = -\frac{1}{2}$, $\ell = 7.3$ M.

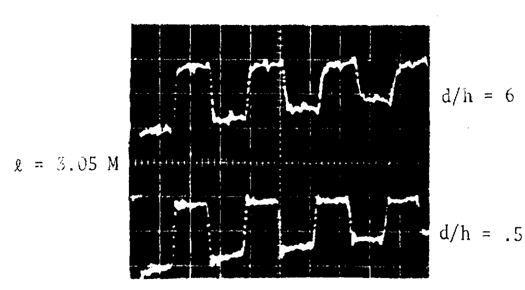

Figure 6. Output of $Z_1 = Z_2 = 47\ \Omega$ Strip-Line.

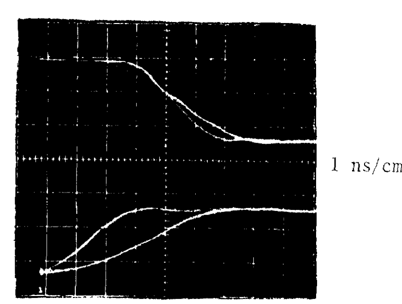

Figure 7. Output of 47 Ω Strip-Line (see text).