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**Accelerator Power Concepts
Using Isolated Transmission Lines**

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ACCELERATOR POWER CONCEPTS USING ISOLATED TRANSMISSION LINES

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ABSTRACT

This report outlines the rationale and the advantages of using multiple transmission-line sections isolated by transit time and inductance in accelerating high-current (≈ 10 -kA), short-pulse (≤ 100 -ns) particle beams to the multimegavolt level. The main advantages of this system include reducing the number of output switches required per output pulse by nearly an order of magnitude over conventional systems and increasing the system capability for repetition-rate operation. The isolated transmission-line concept is developed, and possible modes of operation are outlined. In addition, a point design of a 10-kA short-pulse accelerator is presented.

I. INTRODUCTION

The accelerator power schemes currently used in directed energy systems such as the experimental test accelerator (ETA)¹ and the advanced test accelerator (ATA)¹ require many high-quality (high-voltage, low-inductance, low-jitter, and high-repetition rate) switches to accelerate single pulses in sequence. These switches must be high quality because they play a primary role in the acceleration scheme.

The isolated transmission-line accelerator (ITLA) power scheme presented here uses high-power switches in a secondary role that requires lower quality units. ETA/ATA-type acceleration power schemes use the switching action of one switch only one time, whereas the ITLA scheme uses one switch many times through transit-time isolation. The ITLA power scheme can reduce by 10 times the number of switches required by an ETA/ATA system or can provide acceleration power for up to 10 simultaneous ETA/ATA-type pulses with the same number of switches. Another advantage of the ITLA power scheme is that because the system is not limited by ferrite size as is the ETA/ATA system, it can use

the higher saturation flux density and slower frequency response of tape-wound iron cores.

II. ETA/ATA ACCELERATOR POWER SYSTEM

The ETA/ATA accelerator power system uses many pulse generator units that are transformer-coupled sequentially to the pulse being accelerated. A simplified schematic of a one-pulse generator system, which consists of a Blumlein line, a large ferrite toroid, and a high-quality switch, is shown in Fig. 1. The Blumlein line initially is charged to voltage V_0 . The main switch is closed at time $t = 0$ to start the propagation of a shorting wave toward the load from A to B. One-line transit time T_L later, the wave appears at B. If the beam pulse leading edge is at C, the beam pulse duration is $T_p = 2T_L$, and the beam pulse amplitude is $I_p = V_0/2Z_L$, the Blumlein line wave experiences a matched load because of the transformer-coupled beam current. The beam pulse is accelerated through a potential of V_0 for a time equal to $2T_L = T_p$. This method of system operation places severe requirements on the operation of the main switch.

Fig. 1. ETA/ATA-type induction accelerator module.

First, the switch must be triggered with low jitter so the Blumlein line wave arrival at B is synchronized with the beam pulse arrival. Second, the switch must close in a time T_C , much less than the one-way line transit time T_L . The switch closure time T_C is determined by the switch inductance L_S and the line impedance Z_L , or $T_C \approx 3L_S/Z_L \ll T_L/10$. Thus, the switch inductance must be low to permit fast-current risetimes in low-impedance circuits. In addition, the switch also must have a high repetition-rate capability because the switch must be triggered one time for each pulse to be accelerated.

III. ITLA POWER SYSTEM

The ITLA power concept will be developed with a progression of circuits and applications. A basic charged transmission-line accelerator is shown in Fig. 2. This transmission line with impedance Z_L is charged to voltage V_0 and will accelerate a matched beam current pulse of $I_B = V_0/2Z_L$ and pulse length of $T_p = 2T_L$ to an additional potential of $V_0/2$ (assuming the beam initially is relativistic). This system can be expanded so a similar beam pulse with twice the peak current is accelerated by $V_0/2$ by two identical parallel strip lines, as shown in Fig. 3. The two transmission-line accelerator schemes in Figs. 2 and 3 do not require a switch to control the interaction of the transmission line and beam pulse. However, the change in beam potential is only one-half of the charging potential for these matched systems.

Fig. 2. Charged transmission-line accelerator.

The single Blumlein transmission-line generator on the left side of Fig. 4 is a standard method of achieving a voltage or potential output equal to the charging voltage. The Blumlein line does have a higher source impedance; therefore, the peak current is reduced to $I_p = V_0/4Z_L$ for matched operation. Also, a switch S is required to control the interaction of the accelerator with the beam pulse, as in the ETA/ATA system of Fig. 1. When switch S is closed, a shorting wave travels to the other end of the transmission line in a time T_L . Then a matched beam pulse is accelerated by a potential V_0 for a time $T_p = 2T_L$ as shown in Fig. 4. This circuit also can be paralleled as indicated by the dashed lines of Fig. 4. The peak current I_p , accelerated by potential V_0 , can be doubled or $I_p = V_0/2Z_L$. The two Blumlein lines can be activated by a single switch or by separate switches closed simultaneously.

Fig. 3. Parallel charged transmission-line accelerator.

Fig. 4. Blumlein transmission-line accelerators.

Operation of a Blumlein line can be characterized as voltage-vector inversion. The sum of the voltage vectors from A to C in the generalized Blumlein line of Fig. 5a is zero before the switch is closed at time $t = 0$. If the Blumlein line is not loaded across A and C and the switch is closed at $t = 0$, a voltage shorting wave propagates down the transmission line to the open circuit at terminals AB and inverts the voltage vector in the bottom transmission line of Fig. 5a. When the transient wave returns to the switch at $t_0 = 2T_L$, the voltage vector in the bottom line is inverted everywhere as shown in Fig. 5b. At time $t = 2T_L$, the voltage potential available across A and C for the entire line is $2V_0$. If an accelerator structure were connected to A and C, the inversion switch were opened, and a matched beam pulse were injected ($I_p = V_0/4Z_L$, $T_p = 2T_L$) at $t = 2T_L$, the pulse would be accelerated through a potential of V_0 for a period of $2T_L$ until $t = 3T_L$. Note that the perfect switch was opened in this example to make the accelerator operation compatible with transmission-line operation.

Fig. 5. Vector inversion of long transmission line.

This example is used only to illustrate the principle of voltage-vector inversion and its use in an accelerator system.

If the transmission lines of Fig. 5 are much longer than the pulse to be accelerated and, in particular, an integral number of pulse lengths, $T_L = mT_p$, several pulses can be accelerated in parallel by the same set of transmission lines as shown in Fig. 6, where $m = 3$. Note that this arrangement consists of three dual Blumlein line accelerators (previously illustrated in Fig. 4) connected in series, but with only one switch used for voltage inversion.

Operation of the system in Fig. 6 can be made consistent with transmission-line operation (no switch opening required) in the following manner. The two transmission lines are charged initially to voltage V_0 . The switch is closed at $t = 0$, and the voltage inversion takes place as noted for the system in Fig. 5. The accelerator structures in Fig. 6 must be designed to cause minimal discontinuities and, therefore, reflections of the inversion transients. Also, the accelerator structures must not be loaded (no beam pulse present) during the inversion process. After the inversion wave has reached the open end and returned to A ($t = 5.5T_p$), matched beam pulses ($I_p = V_0/4Z_L$, $T_p = T_L/3$) are simultaneously injected at A, B, and C. These pulses are accelerated by a potential V_0 for a period of $T_p = T_L/3$. The individual accelerator structures at A, B, and C are isolated from each other by the transit time of the transmission line.

This particular arrangement offers several advantages. First, only one switch is used to accelerate three beam pulses. Second, the switch used only to invert the long transmission-line potential vectors does not have to be as high quality as a switch that is involved directly in coupling the accelerator to the beam. A third advantage, which is not immediately obvious, is the repetition-rate advantages of this pulse system. The bottom transmission-line section in Fig. 6 from input A to the switch can be lengthened and a transmission-line fan-out can be added to multiplex several switches, one in each leg of the fan-out. This arrangement permits higher rate operation through easy switch multiplexing. The short-duration transients caused by

Fig. 9. Parallel ITLA.

IV. POINT DESIGNS

To evaluate these concepts, a study of strip transmission-line parameters and other accelerator electrical concerns was undertaken for a series system similar to ETA/ATA. Basic strip transmission-line parameters are illustrated in Fig. 10. For a peak beam current I_p and a stage acceleration voltage V_0 , the source impedance Z_s must be

$$Z_s = V_0 / 2I_p \quad (1)$$

Because the ITLA system drives the beam from two sides or with two strip lines in parallel, the transmission-line impedance must be

$$L = \mu_0 \mu_r \frac{d}{w} \ell \quad Z = \left(\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r} \right)^{1/2} \frac{d}{w}$$

$$C = \epsilon_0 \epsilon_r \frac{w}{d} \ell$$

Fig. 10. Strip transmission-line fundamentals.

$$Z_L = 2Z_s = \frac{V_0}{I_p} = \frac{d}{w} \left(\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r} \right)^{1/2} \quad (2)$$

where d is the line separation, w is the transmission-line width, μ_r is the effective permeability of the core, μ_0 is the permeability of free space, ϵ_0 is the permittivity of free space, and ϵ_r is the dielectric relative permittivity.

The line separation is determined by the dielectric strength K_s of the medium between the conductors or

$$d \geq \frac{V_0}{K_s} \quad (3)$$

From Eqs. (2) and (3) the transmission line width is given by

$$w \geq \frac{I_p}{K_s} \left(\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r} \right)^{1/2} \quad (4)$$

To minimize the difference in the transmission-line transit time between the inside and the outside radii, the major helix radius R_h is chosen such that

$$R_h \geq 10 w \quad (5)$$

In addition, the number of pulses m to be accelerated and the helix radius R_h are iterated to obtain an integer value for m in the equation relating the turn transit time T_L to the beam pulse width T_p , or

$$T_L = mT_p = \frac{2\pi R_h \epsilon_r^{1/2}}{C} \quad (6)$$

where C is the speed of light in vacuum.

Next, the erection or total line-inversion time T_i is limited by the loss characteristics of the system. The first constraint on T_i and thus on the number of helix turns is the resistive decay time T_{rc} or

$$T_i \leq 0.1 T_{rc} \quad (7)$$

The line capacitance per unit length is

$$C_L = \frac{\epsilon_0 \epsilon_r W}{d} \quad (8)$$

and the line shunt resistance per unit length is

$$R_L = \frac{\rho d}{W} \quad (9)$$

such that

$$T_{rc} = R_L C_L = \frac{\rho \epsilon_0 \epsilon_r}{d} \quad (10)$$

The inductance of one turn is

$$L_T = \mu_0 \left(\frac{\mu_r A_c}{\ell_c} + \frac{A_s}{\ell_s} \right) n^2 \quad (11)$$

where A_c is the core area, ℓ_c is the core path length, and μ_r is the effective permeability of the core. The term A_s/ℓ_s represents the stray inductance and n is the number of turns through the core. For the series system $n = 1$ and $\mu_r A_c/\ell_c \gg A_s/\ell_s$,

$$L_T \approx \frac{\mu_0 \mu_{rc} A_c}{\ell_c} \quad (12)$$

where μ_0 is the permeability of free space and μ_{rc} is the relative permeability of the core.

The minimum core area must be such that

$$2A_c B_s = 2V_0 T_i \quad (13)$$

where B_s is the magnetic material saturation flux density or

$$A_c \geq \frac{V_0 T_i}{B_s} \quad (14)$$

To minimize inductive loading, the product of core area and relative permeability, $\mu_r A_c$, is chosen to permit the number of helical turns desired. The turn inductance through the core is now

$$L_T = \frac{\mu_c \mu_{rc} V_0 T_i}{\ell_c B_s} \alpha \quad (15)$$

where α is the increase in the $\mu_{rc} A_c$ product required to obtain the desired number of helical turns n . The magnetic length of the core can be approximated by

$$\ell_c = \left(\frac{OD + ID}{2} \right) \pi \quad (16)$$

where OD is the core outside diameter and ID is the core inside diameter. The LC resonant time is finally

$$T_{LC} = \pi(L_T C_T)^{1/2} = \left[\frac{4\pi \mu_0 \mu_{rc} V_0 R_h \epsilon_0 \epsilon_r W \alpha}{(OD + ID) B_s d} \right]^{1/2} \quad (17)$$

where C_T is the capacitance of one helical turn.

The inversion time T_i is related to the number of helical turns and to the structure parameters by

$$T_i = 2n T_L = \frac{4n\pi R_h \epsilon_r}{C}^{1/2} \quad (18)$$

The inversion time must be such that

$$T_i \leq 0.1 T_{rc} \quad (19)$$

or

$$n \leq \frac{0.1 C \rho \epsilon_0 \epsilon_r^{1/2}}{4 \pi R_h} \quad (20)$$

to avoid resistive loading during erection. The reduction of inductive loading is determined by

$$T_i \leq 0.1 T_{LC} \quad (21)$$

From Eqs. (17), (18), and (21),

$$T_i \leq (0.1 \pi)^2 \left[\frac{4 \pi \mu_0 \mu_{rc} \epsilon_0 \epsilon_r^{1/2} V_0 W R_h}{(OD + ID) d B_s} \right] \quad (22)$$

thus,

$$n \leq 2(0.1 \pi)^2 \left[\frac{\mu_0 \mu_{rc} \epsilon_0 \epsilon_r^{1/2} V_0 W \alpha}{(OD + ID) d B_s} \right] \quad (23)$$

or

$$\alpha \geq \frac{n(OD + ID) d B_s}{2(0.1 \pi)^2 \mu_0 \mu_{rc} \epsilon_0 \epsilon_r^{1/2} V_0 W} \quad (24)$$

If a reasonable value of n , the number of helical turns and half the number of switches to be replaced is chosen, the value of α and the erection time can be determined.

Thus, all the parameters for a series ITLA structure can be determined. The values for an oil-insulated, 10-kA accelerator are listed in Table I.

V. CIRCUIT SIMULATION

The operation of a three-turn ITLA was simulated using the NET-2 circuit analysis program.³ The circuit model is shown in Fig. 11, where the rectangular boxes represent transmission-line sections, V1 is the 250-kV charging supply, and S1 is the erection switch. Inductors L19, L20, and L21 represent the turn-isolation inductance associated with the steel cores. Inductors L7, L9, L11, L24,

TABLE I

PARAMETERS FOR OIL-INSULATED SERIES ITLA MODULE

Line-charge voltage	(V)	= 2.5 E + 05
Beam current	(A)	= 1.0 E + 04
beam pulse width	(s)	= 5.0 E - 08
Line separation	(m)	= 3.1 E - 02
Line width	(m)	= 3.1 E - 01
Helix radius	(m)	= 3.1 E + 00
Line impedance	(Ω)	= 2.5 E - 01
Dielectric strength	(V/m)	= 6.0 E + 06
Relative dielectric constant		= 2.3 E + 00
Number of parallel pulses		= 2
Multiple of minimum flux		= 1.2 E + 00
Erection time	(s)	= 1.0 E - 06
Resistive decay time	(s)	= 2.0 E - 01
Core area	(m ²)	= 2.0 E - 01
Core width along beam	(m)	= 2.9 E - 01
RC limit of number of turns		= 1.0 E + 05
LC limit of number of turns		= 5.0 E + 00
Maximum number of turns		= 5.0 E + 00
Acceleration per module	(V)	= 2.5 E + 06

L26, and L28 represent the beam inductance and associated resistance. (NET-2 requires that each inductor have a specified resistance.) The computer-generated wave form in Fig. 12 illustrates the erection of the three-turn ITLA. The acceleration potential in Fig. 12 is the sum of the voltages across the

Fig. 11. Three-turn series ITLA circuit model.

Fig. 12. Three-turn series ITLA erection and discharge wave forms.

transmission line at each acceleration port. Initially, the sum of the charge voltages equals zero. After the main switch (S1) is closed, the wave transients passing by the beam switches invert the bottom line so that the peak erection voltage is 1500 kV or $2m$ ($m = 3$) times the charge voltage of 250 kV. If the beam switches are closed at peak voltage ($t = 600$ ns), a majority of the transmission-line energy is delivered to the load resistors (associated with load inductances). The effective current through one beam load section is shown in Fig. 13, and the acceleration potential imparted to the beam is shown in Fig. 14. Note that the high-frequency spikes in the circuit simulation are due to the ideal transmission-line sections. The circuit simulation can be considered a first-order approximation. For example, all the beam switches were closed simultaneously, but in reality they should be staggered to represent the beam pulse traveling through the accelerator structures in series.

VI. CONCLUSIONS

Isolated transmission lines can be used to reduce the number, quality, and requirements of high-power switches in pulsed accelerators. The param-

Fig. 13. Three-turn series ITLA effective beam current.

eters in Table I indicate that the number of switches in an ETA/ATA-type system can be reduced 10 times for a symmetrical series ITLA in which the erection switch is in the center of a 10-turn helix. Operation of the switches in a repetition mode is

Fig. 14. Three-turn series ITLA acceleration potential.

facilitated in the ITLA system because timing and switching requirements are reduced. Switch multiplexing also is facilitated by the use of switches in a secondary rather than a primary role.

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