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Accelerator Applications of Photoconductive Power Switches

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ACCELERATOR APPLICATIONS OF PHOTOCONDUCTIVE POWER SWITCHES

by

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ABSTRACT

This report discusses the application of photoconductive power switches in high-power, high-current, pulsed accelerators. Two state-of-the-art, high-current, pulsed-accelerator applications are discussed, and advantages of the photoconductive power switch are compared briefly with those of other switches. A new power-conditioning system using a photoconductive power switch is described and compared with present technology for short (<1-μs) high-power (MW-TW) electrical pulse applications.

I. INTRODUCTION

The photoconductive power switches being developed at Los Alamos[1] have many advantages in high-current, pulsed-accelerator applications with gradients up to 10 MV/m. They permit the efficient use of very high voltages and currents at high rates of circuit response with precise timing control, benefits impossible to achieve with any other technology. Precisely controlled photoconductive power switches make the use of distributed power conditioning for high-current, pulsed, multistage accelerators possible. The closure rate, the precise control and isolation, and the scalability of photoconductive power switches will make accelerator systems much simpler and more efficient. Development of high permittivity and solid dielectric energy storage materials in concert with the photoconductive switches can be expected to reduce the size of accelerator systems at least an order of magnitude.

II. ACCELERATOR POWER CONDITIONING

A. Applications

The first application is the very high current electron beam accelerator, similar to that used in nuclear-weapon-effect simulations. The diode load requires 1-MV voltage and 4-MA current pulse of 40-ns duration. The pulse repetition rate for this system is low, approximately one pulse per day. Figure 1 shows the power-conditioning technology being used for this type of system. A Marx circuit multiplies voltage from the dc charge level (∿100 kV) to the megavolt level. This circuit charges intermediate capacitive energy storage, usually using water as a dielectric, in about 10 μs. A triggered high-pressure gas switch discharges the intermediate energy storage into a water-insulated transmission line section. The transmission line is charged in several microseconds, and sequential-series self-closing water switches and transmission line sections form a narrow pulse that is applied to the diode load. The electron beam formed by the diode load is accelerated through a thin foil to produce an intense electron beam that is used to generate weapons-like radiation. Commonly, several of these generators are built in parallel, and the output pulses combine at a single load. The parallel generators are synchronized by triggering the individual high-voltage spark gaps simultaneously and then relying on repeatable self-closures of the series water switch to deliver individual pulses to the common load at the same time. However, the jitter of the gas switches and the water switches makes synchronizing these generators an unsolved problem, and total-load-current reliability has not been achieved.

The second accelerator application is for a directed-energy, charged-particle beam, in which a series of high-voltage gaps accelerate high-current beam pulses along the beam path. The power conditioning for each accelerating section uses the same general power-conditioning system as that shown in Fig. 1; Fig. 2 illustrates the same system in more detail. This type of accelerator is termed a foilless system[2,3] because the beam pulse does not pass through a foil, but through multiple, sequential accelerating sections.

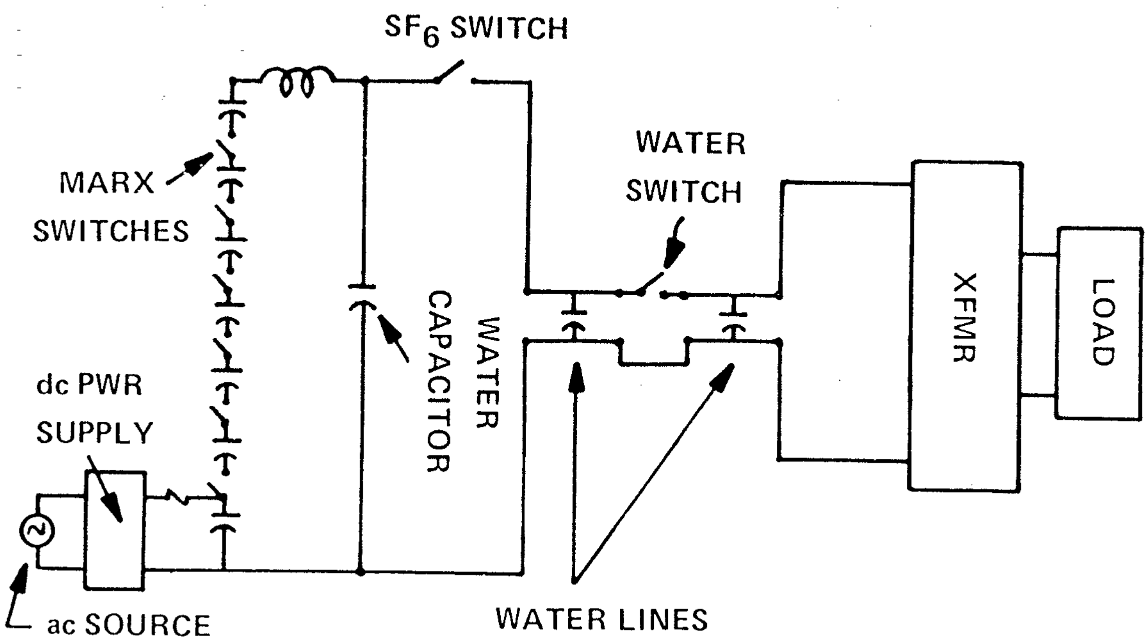

Fig. 1. Conventional power conditioning in a very high current electron beam accelerator.

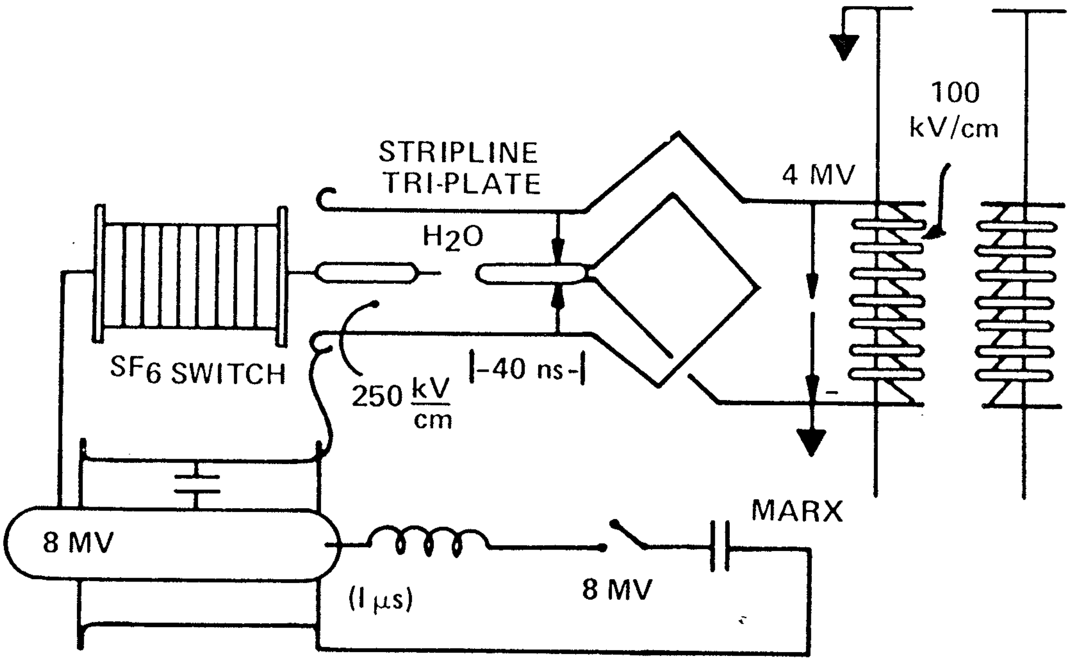

Fig. 2. Power conditioning for each accelerating section: 4 MV, 100 kA, 40 ns (16 kJ).

B. Power-Conditioning System Operation

The conventional generating and conditioning of high-power (1-TW), short-duration (<1-μs) electrical pulses illustrated in Fig. 1 are a three-step process. (1) The required voltage is obtained with a megavolt Marx circuit that multiples the initial charge voltage and charges an intermediate energy storage capacitor, usually with water as the dielectric. (2) The energy stored in the water capacitor at several megavolts is transferred into a water transmission line section with a triggered gas switch, producing a longer pulse than desired with slower than optimum risetime. The triggered gas switch is responsible for the output pulse timing and synchronization and must be controlled precisely. (3) The pulse risetime is sharpened and the pulse compressed as the energy is switched through additional, sequential, water-insulated transmission line sections with self-closing water switches. Finally, the pulse is delivered to the load through a transmission line system.

C. Deficiencies of Conventional Technology

Conventional power-conditioning systems have several deficiencies. The gas spark-gap timing is the only control point in the pulse generation and shaping sequence. The water switches must close reliably and sequentially, as well as repeatably and precisely. The control of a megavolt gas switch with subnanosecond precision is difficult; and the successive water switch closures, which depend on many variables, lead to a relatively large jitter in the arrival of the output pulse at the load. Thus, to synchronizing several generators with subnanosecond precision is very difficult.[2]

Much input energy is dissipated in the system switches and left in the various energy storage devices because of repeated handling of large energies at large currents during pulse forming and shaping. The closure time (resistive phase time) of the gas switch and the water switches (∿10 ns) compares with the desired output pulse length, resulting in energy loss during switch closure and a limit on the minimum output pulse risetime. Also the finite number of parallel conducting paths in water switches limits the output pulse risetime because of switch inductance. Therefore, system efficiency is low and the minimum output pulse risetime is limited, especially in low-impedance systems.

Water is the commonly used energy storage medium because it has large relative permittivity (81), because large high-voltage geometries can be easily fabricated and insulated to give the smallest inductance, and because it is a self-healing dielectric. However, the water dielectric system is commonly charged in <10 μs to avoid resistive energy loss, and large dimensions are required for high-voltage isolation. Thus, conventional systems occupy large volumes and require a high-power (short-charge-time) charging system.

III. COMPARISON OF PHOTOCONDUCTIVE AND CONVENTIONAL SWITCH TECHNOLOGY

A. Photoconductive Switch Description

General photoconductive device geometry used in high-power switches is illustrated in Fig. 3, where a block of photoconductive material such as silicon, GaAs, or InP is shown with electrodes deposited on the ends. The operating voltage determines and the surface breakdown of the electric field limits the distance between electrodes or contacts. The controlling source then illuminates the entire region between the electrodes to change the conductivity uniformly between the electrodes.

B. Scalability

The bulk nature of photoconductive device operation, which separates device size or power from device speed, permits scaling a single-switch device to nearly any set of operating parameters. Scalability of the photoconductive device is an important advantage in switching applications. These advantages result from a linear first-order scaling of voltage with length and inverse scaling of inductance, current, and average power with width.

1. Voltage Scaling with Length. The relatively large electrical strength of common semiconductor materials (≥100 kV/cm) implies that a compact, high-voltage device is possible. Closure or increasing conductivity takes place uniformly over the length of this device, so its length can be scaled to the desired operating voltage. Thus, a megavolt switch may be only 10 cm long.

Photoconductive technology can provide a single switch for nearly any operating voltage so that large-series-parallel arrays need not be used. As a result, triggering and switch application are simpler, and the switch operates at its designed parameters rather than at derated parameters.

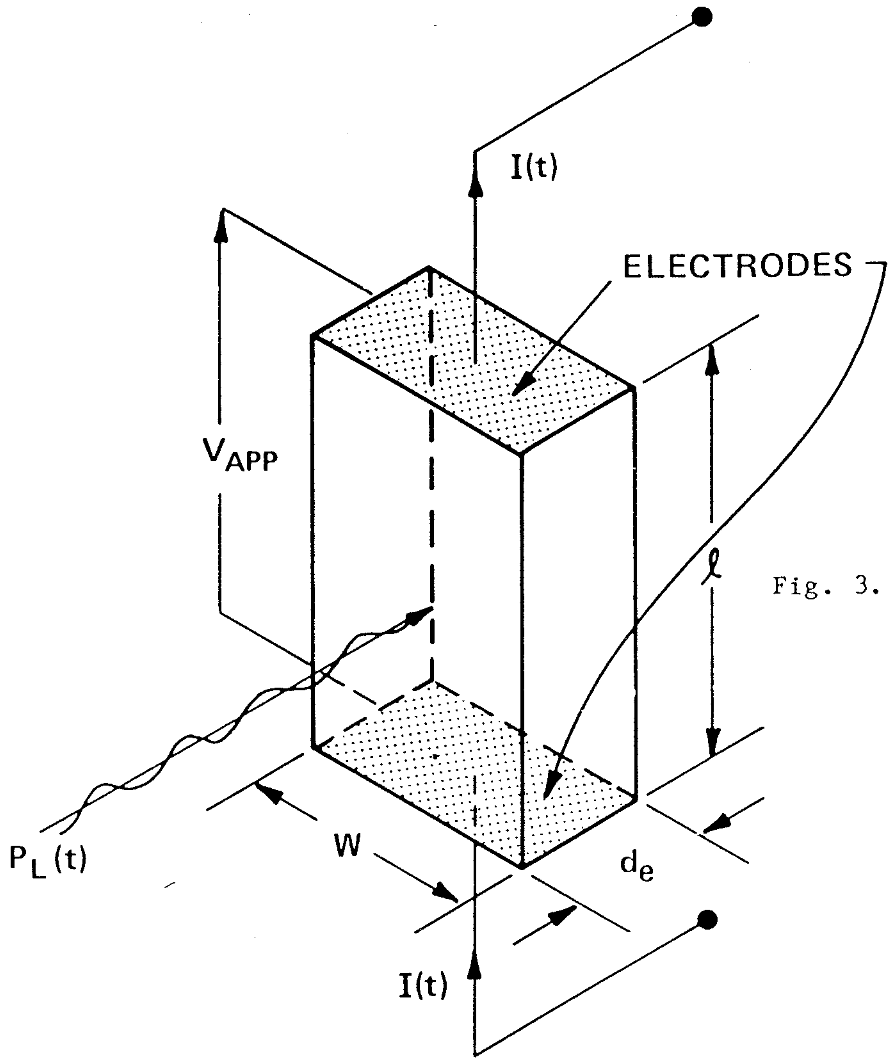

Fig. 3. Basic photoconductive switch geometry.

2. Current Scaling with Width. In the first-order case, the amount of thermal energy deposited in the switch limits the current-carrying capability of a photoconductive device. This thermal energy increases the device temperature to a level that causes damage. The quantity I^2t describes the amount of energy deposited and is a function of the current level and the duration of the current flow. The energy deposited in the switch per unit volume depends on the switch width for a given current. The resistance of the photoconductive device is independent of width for a given optical energy incident on the surface. The same number of carriers is generated independent of the device width so that the total resistance between the electrodes is a constant. Increasing device width reduces the current density and the energy dissipated

per unit volume, and it enables the device to operate at a higher total current. Therefore, increasing the device width for a given current duration can scale the required operating current.

a. Power Scaling with Width. The area available for heat removal from the conducting switch increases as the device width increases. Therefore, the amount of heat removed continuously (quantity is derived later in this report) determines the average power at which the switch can be operated. Reducing energy dissipation per unit volume and increasing the area available for heat removal combine as the device width increases so that the average switch power scales with width.

b. Inductance Scaling with Width. Switch inductance, an important parameter in very fast systems where the desired pulse risetime is small, is inversely proportional to the number of parallel current paths through the switch. Current conduction uniformly across the entire switch width makes the photoconductive switch inductance much lower than possible with any other technology. In addition, because switch resistance is independent of switch width, any inductance value can be specified without changing the switch resistance.

The photoconductive switch has a unique inductance advantage compared with conventional switching devices. High-pressure gas or liquid spark gaps are commonly used for very high power applications. Spark gaps conduct current through gaseous arc channels that are very inductive because of very small arc diameters. Multichannel spark-gap devices have been devised to reduce the switch inductance, but the arc channel spacing is limited to several centimeters. Thus, one advantage unique to the photoconductive power switch is the extremely low inductance possible.

C. Optical Control

Using a photoconductive element as a switch has several advantages as a result of the optical or external control characteristic. These advantages include complete electrical isolation, very low relative jitter in the closure of multiple devices or simultaneous closure of all areas of a large device, and the extremely small closure time possible with high-power lasers.

1. Control System Isolation. Controlling a switch from a completely isolated source offers many advantages in system operation. Using these

switches for very high voltage applications is much simpler than using conventional devices. The isolation also permits the use of many different switches with one control source scanning or multiplexing individual switches in parallel, thereby increasing the frequency of operation or selecting switches in parallel that have different characteristics, depending on the system requirement. The isolation of the control source and the mobility of the controlling light beam from the source will permit many sources to be applied to a single source or a single source to be applied to multiple loads.

2. Low Jitter. Energy used for optical control in the form of very high power light pulses from lasers permits a fraction of the optical pulse energy to be applied to many different devices simultaneously or in a well-timed sequence, depending on the difference in beam transit time between devices. Similarly, a short laser pulse can spread over a large surface area causing conduction in the entire switch surface in subnanoseconds. This result contrasts with the conventional array system in which the individual devices operate at parameter levels much lower than those possible with a single device.

Jitter in conventional switching systems results from the jitter of the electrical systems generating the trigger pulses and from the difference in closure times of the individual switches, which are dependent on the switch environment and history. Time delay between trigger pulse arrival and the closure process initiation is part of a statistical process that depends on the availability of a free electron. The faster the risetime of the electrical trigger pulse, the less the jitter ranges from the average value. Thus, very low jitter, electrically triggered systems must use a very fast rising trigger pulse that is generated from another switch also with jitter. In addition, the larger the total number of switches to be closed, the larger the scatter in the jitter of the entire system.

The photoconductive switch technology combines very fast closure with subnanosecond delay, independent of the circuit conditions because of the very low jitter in the arrival time of the optical trigger pulse to the switch. These switch characteristics provide a method of synchronizing many switches with very low jitter, a synchronization previously impossible.

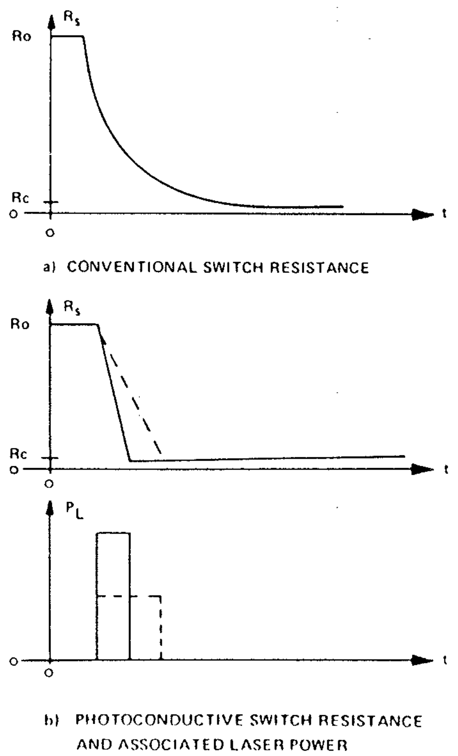

Fig. 4. Closure rate in (1/e) time.

3. Closure Rate Control. Conventional switches change from the open state to the closed state with a characteristic (1/e) time (Fig. 4a) because carrier generation in the switch depends on the electric field across the switch, which decreases as the switch resistance drops. For spark gaps, the (1/e) time is termed the resistive phase time because switch resistance is still approximately equal to load resistance for this time after switch closure initiation. This process occurs in gas, liquid, and vacuum switches, where the carriers are generated by electric fields in the switch.

Other solid-state switches such as the silicon-controlled rectifiers (SCRs) can be turned on in a small area at the gate. For the device to conduct large amperages, the conduction region must spread laterally throughout the junction region, which is a very slow process because of the very low electric field after initial conduction. Closure time for standard SCRs is long compared with that of photoconductive switches and has an exponential resistance decay characteristic. The light-activated silicon switch (LASS),[4,5] developed at Westinghouse and Lawrence Livermore National Laboratory (LLNL), uses the SCR structure with three-series-PN junctions. A laser simultaneously and entirely changes conductivity at the gate so that the entire LASS also can be turned on in nanoseconds. However, because of the SCR structure, the device voltage is limited to <10 kV, and arrays must be used to operate at voltages and currents greater than those possible with a single device. In addition, transporting the controlling optical pulse to the gate structure is much more difficult than illuminating the surface of a photoconductive switch.

The rate at which the conductivity of a uniformly illuminated photoconductive element increases is equal to the rate at which the desired optical energy is delivered to the element surface (Fig. 4b). A single photon in the standard photoconductive device generates a single-hole-electron pair, so the number of photons and thus the total optical energy required to turn on the switch can be determined. The time in which the conductivity will change or the switch will close is the time in which the optical energy is delivered. The photoconductive switch can be completely closed or the resistance changed from the high OFF state to the low-resistance conducting state in less than a nanosecond with a high-power laser pulse. Switch size or power does not affect the time rate of resistance change because the optical control source and not the circuit conditions determines the closure rate. Therefore a photoconductive device designed to operate at 10 kV operates the same whether the applied voltage is 1 V or 10 kV.

The capability to close the switch in a very short time means that the energy resistively deposited in the switch is reduced, that the system itself can be more efficient, and that the risetime or the current rise rate in the load can increase. When conventional switches are used in systems requiring very high powers in time scales comparable to the resistive phase time, much of the energy is deposited in the switch, and switch closure time limits the pulse risetime. However, photoconductive power switches make possible, for the first time, very high power pulses in the nanosecond region, generated with high efficiency.

IV. BLUMLEIN LINE PULSE GENERATORS

A. Blumlein Line Description and Operation

The Blumlein line[6] consists of two transmission line sections of equal length (Fig. 5). A common source charges the transmission line sections to the same potential so that the electric field vectors in the two lines cancel

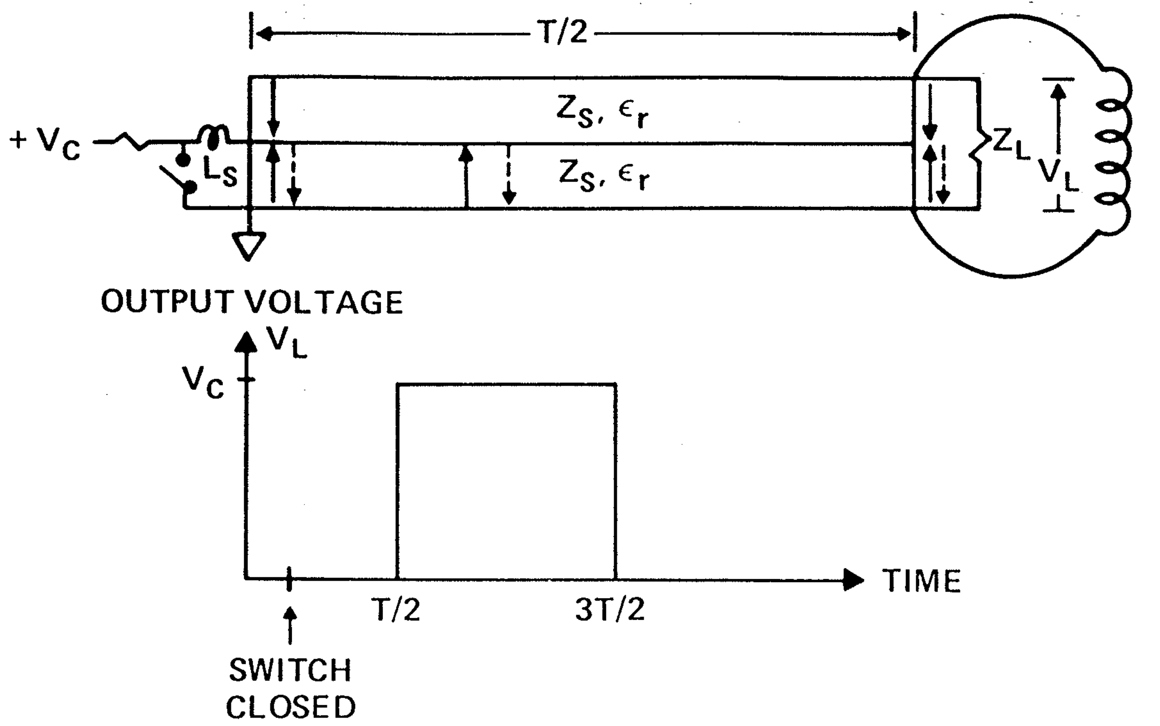

Fig. 5. Blumlein line description.

across the load. The bottom line in Fig. 5 charges to ground, and therefore the current charging the upper line must flow through the load or charge by pass inductor. The pulse generation process is initiated when a switch at the input end of the lower transmission line is closed. Closing this switch reverses the electric field polarity on the bottom transmission line in a transient manner. The inverted electric field pulse travels to the output end of the lower line, where the lower line impedance sees the load impedance and the upper line impedance. If load impedance is matched to twice the single-line impedance (a reflection coefficient of 0.5), additional transients in the electric field in the transmission lines travel to the input ends of the upper and lower lines. An electric field transient equal to one-half the electric field charge travels from the load end to the input end. When the input end of the transmission line sections is reached, the lower electric field transient is reflected, not inverted with a reflection coefficient of +1, and the electric field transient in the upper line is reflected, not inverted with a reflection coefficient of -1. These reflections then travel back to the load end, where the sum of all electric field transients and the initially charged electric field have been canceled; the load pulse is terminated, as shown in Fig. 5. At the end of the load pulse, all energy stored originally in the transmission lines has been transferred to the load impedance for the matched case.

The Blumlein line is an impedance transformer between the input switch and the load. The input switch, which initiates the pulse generation sequence, operates at intended pulse-output voltage for a matched load system and at twice the load current. This sequence differs from the conventional pulse-line sequence in which the switch connects a charged line to a matched load and must operate at twice the intended pulse-output voltage with current equal to the output current.

B. Blumlein Line Operation with Conventional Switches

The Blumlein line configuration and spark-gap switches with either water or gas dielectric are commonly used in high-power pulsed systems, but they have several deficiencies. First, the closure time (the time in which conventional switch resistance decreases to a small fraction of the source and load impedance) is finite, usually tens of nanoseconds. The resistive phase time depends on several factors and will change with changes in the switch geometry, gas pressure, trigger method, applied voltage, etc. If the resistive phase time is comparable to the desired pulse length, much energy that was stored in the lower transmission section is deposited in the switch, making the system inefficient and the load pulse voltage less than the charging voltage. The resistive phase problem increases when the source and load impedances are very low ($<1\ \Omega$). The second problem associated with Blumlein operation is the switch inductance on the lower line in Fig. 5. Without dispersion in the transmission lines, the voltage falltime of the input switch is the risetime of the output pulse. Thus, if the inductive time constant of the system (the ratio of switch inductance to line impedance) compares with the desired pulse length, the frequency response of the system lengthens the output pulse, resulting in a much slower risetime than that preferred. This problem is enhanced in very low impedance systems. Problems are formidable in triggering a single switch to obtain low jitter, small resistive phase time, and multiple arcs to minimize inductance. Triggering multiple spark gaps with these desired characteristics and low relative jitter has been impractical and appears only remotely possible.

C. Strip Blumlein Line Analysis

Analysis of Blumlein line design will proceed with the strip transmission line configuration (Fig. 6). The impedance of each of the transmission line sections is

$$Z_s = (\mu_o/\varepsilon_o)^{1/2} d/(\varepsilon_r^{1/2}\, w) \quad , \tag{1}$$

where μ_o and ε_o are the permeability and permittivity of free space, respectively, d is the line conductor separation, w is the line width, and ε_r is the relative permittivity of the dielectric between the line conductors. The impedance of free space is defined as

$$Z_o = (\mu_o/\varepsilon_o)^{1/2} \tag{2}$$

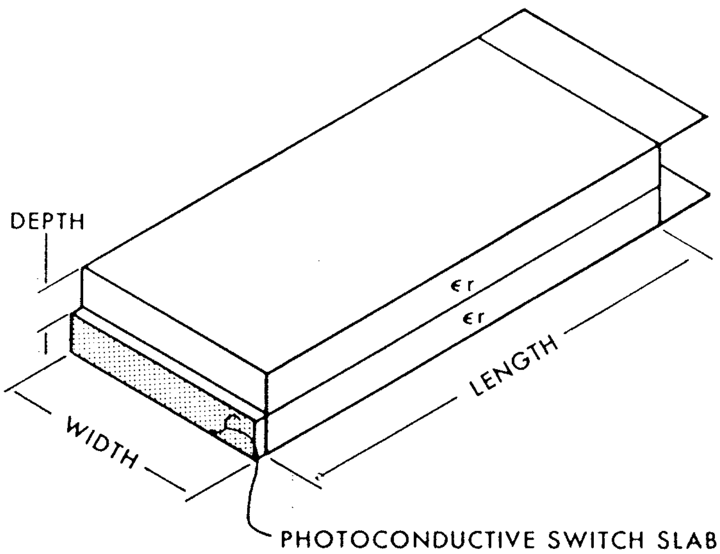

Fig. 6. Strip transmission line configuration.

or 377 Ω. The speed of light in the line dielectric determines output pulse duration, which is equal to the two-way transit time of the electric field transients produced by switch closure.

$$t_p = 2\,\ell\,\epsilon_r^{1/2}/c \quad , \tag{3}$$

where c is the speed of light in a vacuum and ℓ is the length of the transmission line. The dielectric strength of the transmission insulation determines the minimum separation of the transmission line conductors

$$d = V_c/E_m \quad , \tag{4}$$

where V_c is the line charge voltage and E_m is the dielectric strength of the line insulation. Energy stored in the Blumlein transmission line sections equals the energy deposited in a matched load during the two-way transit of the lines and can be determined by

$$E_B = V_L^2\,t_p/Z_L = V_c^2\,t_p/(2\,Z_s) \quad , \tag{5}$$

where Z_L is the matched load resistance equal to twice the individual line impedance or $Z_L = 2\,Z_s = Z_B$, and the matched load voltage is equal to the line charge voltage or $V_L = V_c$. Thus, energy stored in the Blumlein becomes

$$E_B = E_m^2\,\epsilon_r\,w\,\ell\,d/(Z_o\,c) \quad . \tag{6}$$

The energy stored in the Blumlein lines per unit volume is then

$$E_{B/v} = E_B/(w\,\ell\,d) = E_m^2\,\epsilon_r/(2\,Z_o\,c) \quad . \tag{7}$$

As an example, if $E_m = 10^7$ MV/m and $\varepsilon_r = 900$, the energy stored per unit volume is about $E_{B/v} = 0.4$ MJ/m^3 or 0.4 J/cm^3.

Power to the load interface or output power per unit area is determined from the load power or

$$P_L = V_c^2/Z_L \quad . \tag{8}$$

For a matched system $Z_L = 2\ Z_s$, the power delivered to the cross-sectional area at the end of the Blumlein structure is

$$P_{L/a} = P_L/(2\ w\ d) = E_m^2\ \varepsilon_r^{1/2}/(4\ Z_o) \quad . \tag{9}$$

For example, $E_m = 10$ MV/m, $\varepsilon_r = 900$ so that the value for P becomes ~ 2 TW/m^2 or 200 MW/cm^2.

Choosing the optimum pulse risetime will approximate the switch inductance requirements. The inductive time constant of the circuit should be one-third of the desired risetime, which assumes an instant switch closure or

$$L_s/Z_s = T_r/3 \quad , \tag{10}$$

where L_s is the switch inductance. For example, if $Z_s = 1\ \Omega$ and $T_r = 1$ ns, then L_s must be less than 0.3 nH, which is the upper limit that does not include the switch closing time. This example points out the problem with using conventional switches in low-impedance circuits when fast risetimes are required.

The dimensions and the relative dielectric constant of the transmission line can be determined for the above equations. Transmission line length is determined from Eq. (3) or

$$\ell = t_p \, c/(2 \, \varepsilon_r^{1/2}) \quad , \tag{11}$$

and the ratio of transmission line width to separation is

$$w/d = Z_o/(Z \, \varepsilon_r^{1/2}) \quad . \tag{12}$$

Both equations depend on the relative dielectric constant of the transmission line. Photoconductive switch requirements affect transmission line design when the switch width is equal to the transmission line width and the switch length is equal to the transmission line separation. To avoid current filamentation because of negative-slope photoconductor resistivity with increasing temperature, the switch carrier density in silicon must be such that $n_c \leq 5 \times 10^{23}\ m^{-3}$. This density corresponds to a switch resistance in silicon of

$$R_s \geq d/(n_c \, \mu \, e \, d_e \, w) = 0.1 \, d/w \quad , \tag{13}$$

where d_e is the effective absorption depth of the optical wavelength, μ is the sum of the carrier mobilities, and e is the electron charge. In addition, when the switch is closed, resistance should be a small portion of the circuit impedance, and for the Blumlein circuit,

$$R_s \leq 0.01 \, Z_s \quad . \tag{14}$$

The switch resistance R_s must be in the range

$$0.01 \, Z_s \geq R_s \geq 0.1 \, Z_s \, \varepsilon_r^{1/2} \, / \, Z_o \tag{15}$$

to switch efficiently and to avoid current filamentation. Equation (15) also gives an upper limit on the value of the dielectric constant for the energy storage line, or

$$\varepsilon_r \leq (0.01\ Z_o\ n_c\ e\ \mu\ d_e)^2 \quad , \qquad (16)$$

which for silicon and $n_c = 5 \times 10^{23}\ m^{-3}$ is about 1600. Thus, the parameters for the transmission line section and the photoconductive switch are determined.

The switch line current density is determined by

$$I/w = V_c/(Z_s\ w) = E_m\ \varepsilon_r^{1/2}/Z_o \quad , \qquad (17)$$

and the switch current density is

$$\acute{J} = I/(w\ d_e) = E_m\ \varepsilon_r^{1/2}/(Z_o\ d_e) \quad . \qquad (18)$$

These basic relations determine the capabilities and requirements of the Blumlein line configuration of transmission line sections and photoconductive switches.

D. Blumlein Line Module

In stacked-transmission-line pulse generators,[7] the smallest independent module consists of a single Blumlein line (Fig. 6). This module uses a solid dielectric in the transmission lines and a photoconductive switch across the width of the bottom transmission line section. The basic Blumlein line module specifications are representative of many applications and are listed in Table I.

TABLE I

BLUMLEIN LINE MODULE SPECIFICATIONS

Electrical Characteristics	
Charge voltage (kV)	100
Output voltage (kV)	100
Output current (kA)	100
Line impedance (Ω)	0.5
Blumlein impedance (Ω)	1
Output pulse length (ns)	40
Line length (cm)	20
Line width (cm)	25
Line separation (cm)	1
Blumlein height (cm)	2
Dielectric Parameters	
Relative dielectric constant	900
Dielectric strength (kV/cm)	100
Photoconductive Switch Parameters	
Width (cm)	25
Height (cm)	1
Inductance (nH)	<1
Line current density (kA/cm)	4
Current density (kA/cm^2)	40
Conduction resistance (Ω)	0.01
Optical energy required (mJ)	100

Switch and module specifications do not exceed the expected or demonstrated parameters for solid dielectrics or photoconductive switches. The dielectric constant for the energy storage line is 900, a factor of 10 higher than water but a factor of 10 lower than some dielectrics. This value was chosen so that the size of the energy storage system could be reduced and so that an acceptable line current density could be obtained in the photoconductive switches. In addition, we wanted a uniform dielectric constant for frequencies up to the gigahertz region, and reducing the maximum value of the dielectric constant permits maintaining the dielectric permittivity at a constant value over a wider bandwidth.

The switch resistance is 1% of the Blumlein output impedance, and the inductance gives a risetime of 1 ns. The optical energy required for switch closure (0.1 J) is a minimum for the electric field (100 kV/cm) used in calculating the switch length. If switch height or length was increased by a factor of 2 (50 kV/cm) to reduce the electric field stress, the optical energy requirements would increase by a factor of 4 to ∿0.4 J per Blumlein module.

V. APPLICATIONS OF STACKED-LINE PULSE ENERGY SOURCES

The modular approach, based on solid dielectric transmission sections and photoconductive switches, permits tailoring the energy delivery system to the load. In some cases, modular approach application can alter the present load configurations. A schematic of a stacked-line module is shown in Fig. 7.

The first typical application involves an electron beam accelerator in a single-foil diode configuration, where very high currents (4 MA) and moderate voltages (1 MV) are required for nuclear-weapons-effect simulation. The modular approach would use the basic Blumlein configuration. Each Blumlein module would have a photoconductive switch as wide as the strip transmission lines. The individual Blumlein modules would form a stacked-line module in series. Ten Blumlein series modules, described in Table I, would form the stacked-line module (Fig. 8), providing a 1-MV pulse into a matched load of 10 Ω at a 100-kA current. The stacked-line modules would be placed in parallel around the edges of a pair of large disks to provide the desired current [40 modules in parallel (Fig. 9)]. For 20-cm-wide modules, the disk diameter is ∿2.6 m and the disk separation is 20 cm. To match module impedance to load, the dielectric between the disk plates must be a material comparable to the energy storage dielectric in the modules. Note that the design is compact and water is not used as an energy storage medium. In addition, the simultaneous arrival of the energy pulses to the load can be well synchronized.

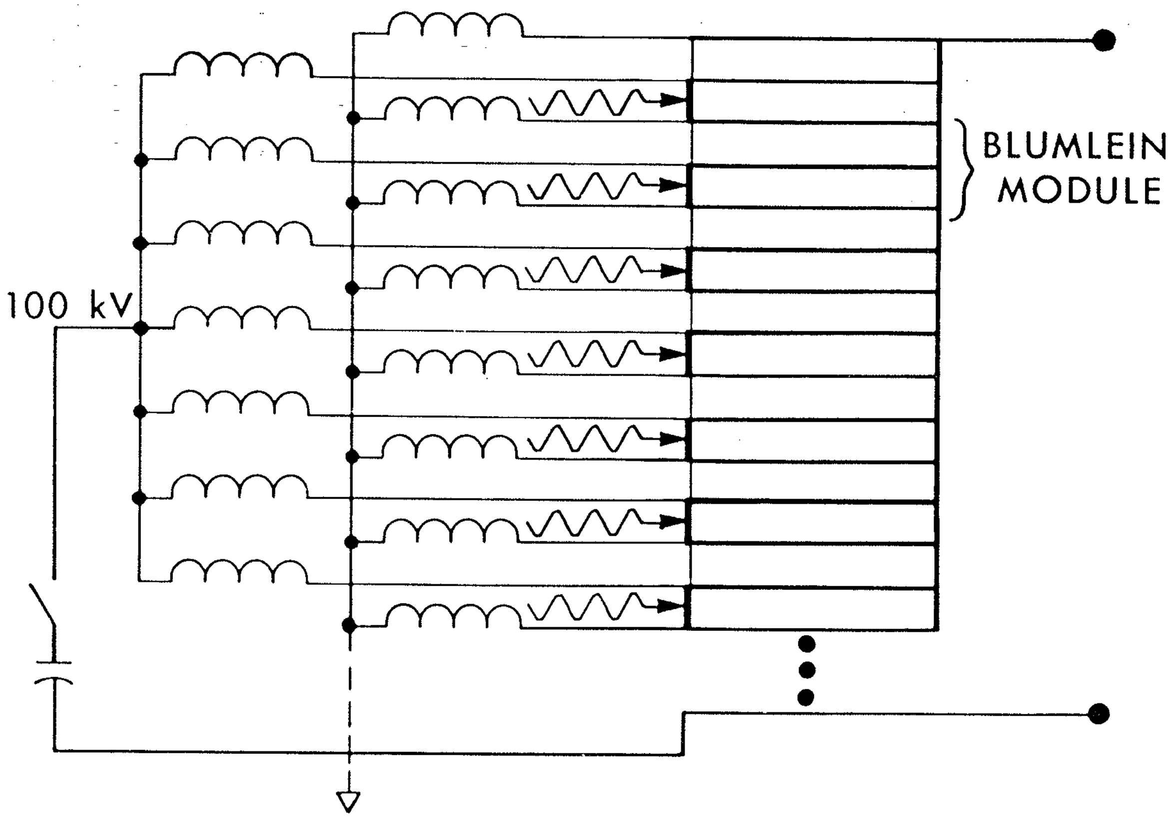

Fig. 7. Stacked-line schematic for multiple Blumlein transmission line sections.

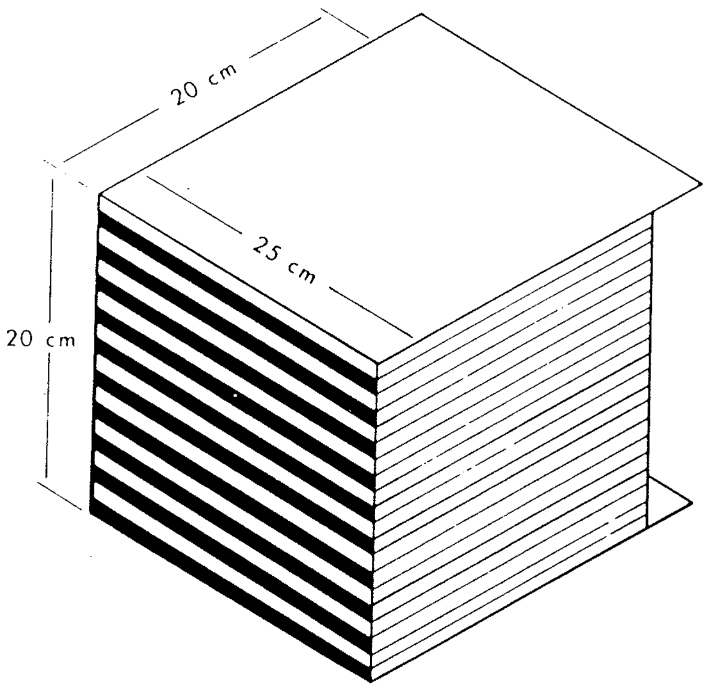

Fig. 8. Stacked-line module, 1 MV, 100 kA.

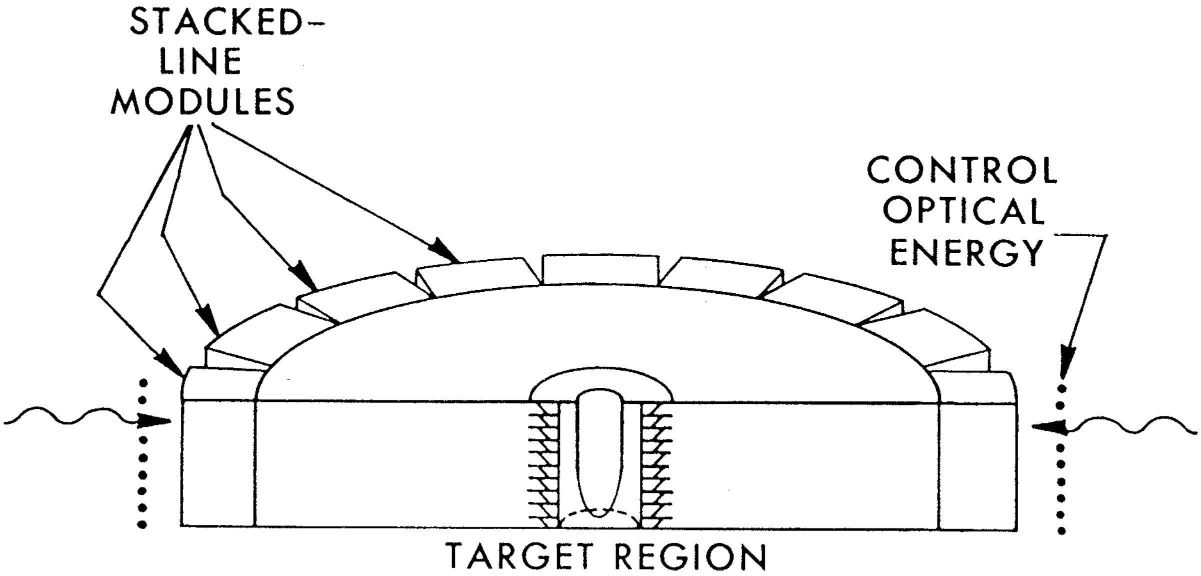

Fig. 9. Cross section of high-current weapons-effect simulator.

The second typical application involves a linear accelerator in which many foilless diodes[2,3] couple energy to an electron beam pulse that is traveling through the accelerator sections in sequence. With the modular approach, the accelerator gap, which is separated by a graded insulator stack (Fig. 10), can generate a 4-MV pulse at a 100-kA current into a matched 40-Ω load. These modules, based on the Blumlein module of Table I, can be used in the two arrangements illustrated in Fig. 11. The insulator stack is usually operated at an electric field of 100 kV/cm. The energy is stored in the Blumlein modules at the same electric field, but because the output voltage of the Blumlein configuration into a matched load equals the charge voltage (or only one-half of the open-circuit value of twice the charge voltage), the Blumlein height is twice that of the accelerating column. Two stacked modules applied from opposite sides of the beam tube can be used in series to obtain the maximum accelerating gradient. The maximum accelerating potential is

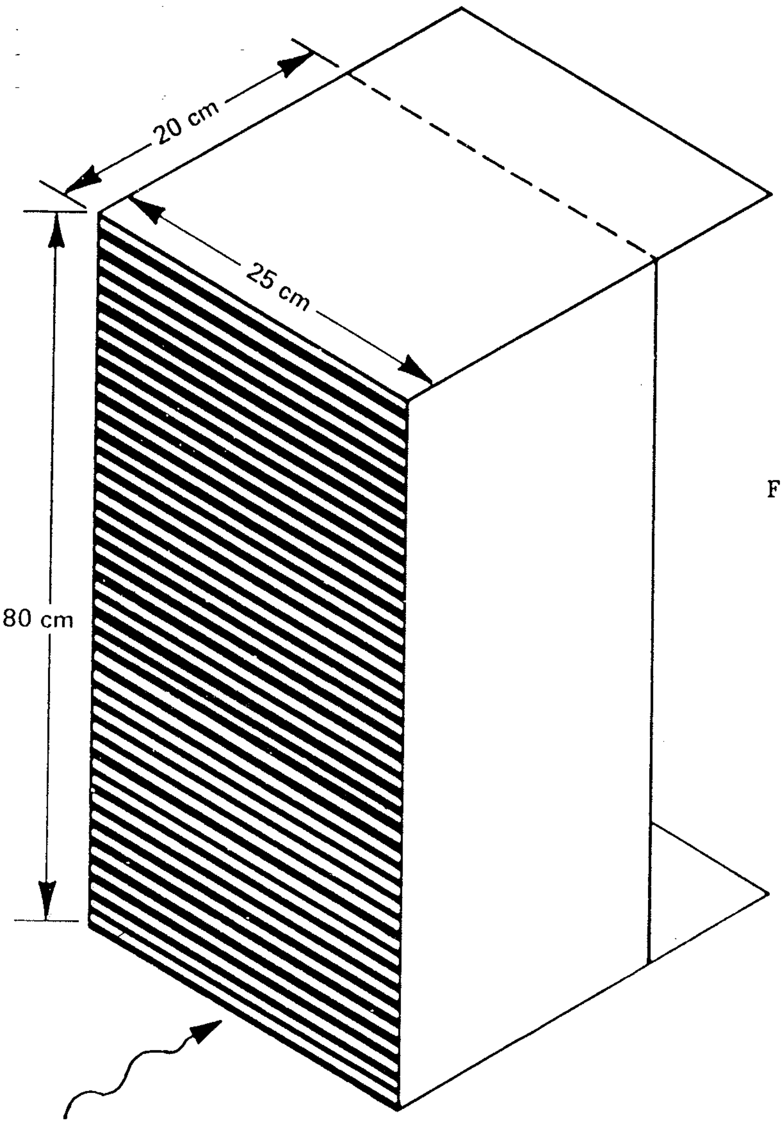

Fig. 10. 4-MV, 100-kA stacked-line module.

~8 MV/m for the arrangement shown in Fig. 11b. If higher current is required, the modules can be placed in parallel at each stack or the number of accelerating columns can be reduced. If two stacked-line modules are placed in parallel (Fig. 11a) and two are placed in series (Fig. 11b), the accelerator power per meter using the modules from Table I is 200 kA at 10 MV/m or 2 TW/m, which corresponds to an energy of 80 kJ in a 40-ns pulse. The precise timing of the photoconductive switches permits distributing the accelerating column and power supply so that the arrangement in Fig. 12 can be used and individual switches can be timed to phase the application of the accelerating potential. Note that as the beam pulse becomes relativistic, the optical control beam will proceed at the same speed as the accelerated beam.

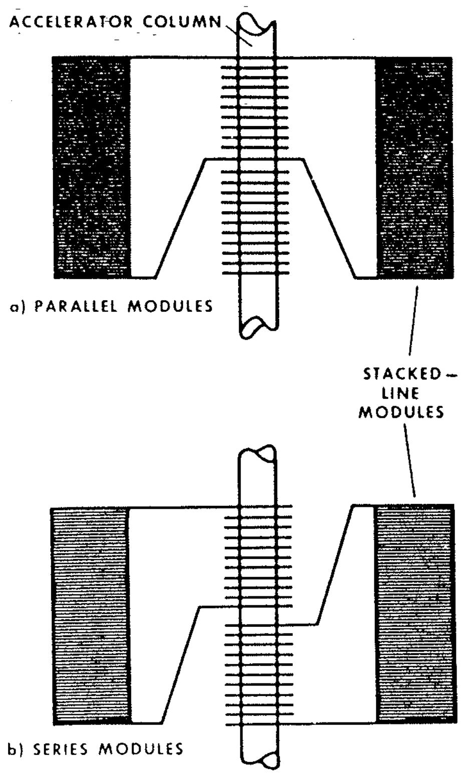

Fig. 11. Two applications of basic Blumlein modules.

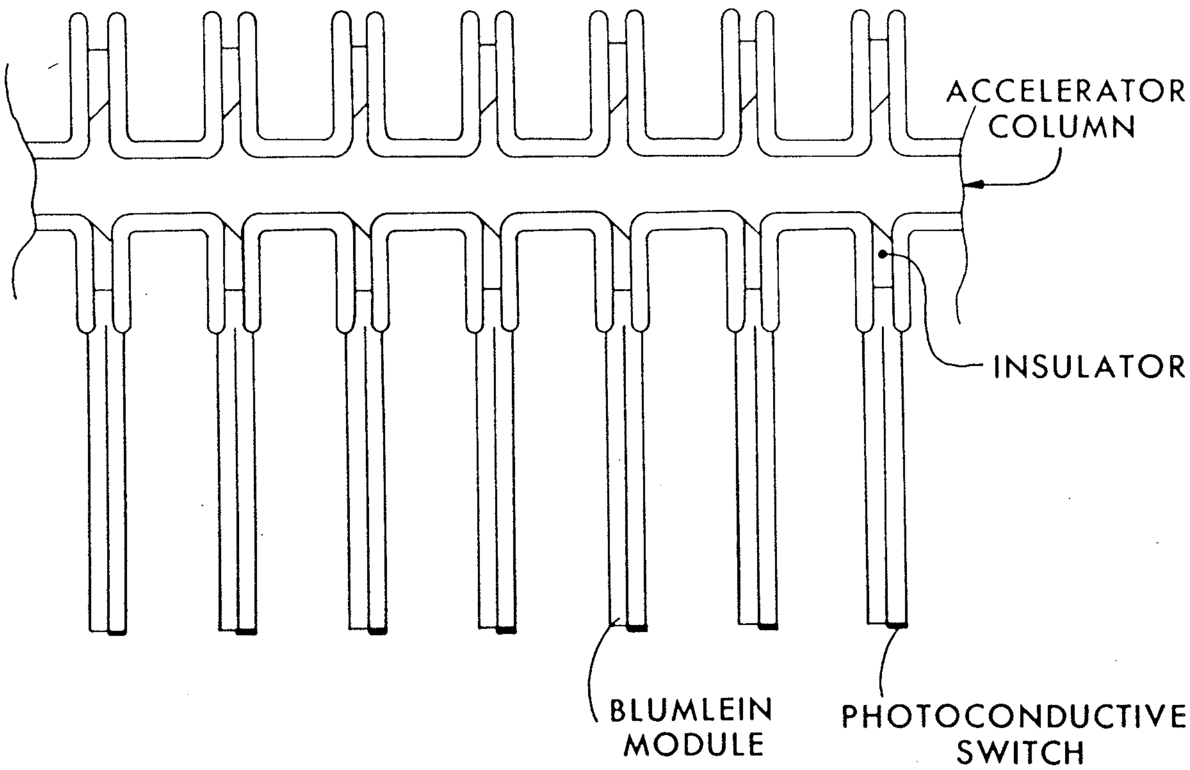

Fig. 12. Distributed accelerator using distributed Blumlein modules.

VI. ALTERNATE POWER-CONDITIONING SCHEMES

The development of photoconductive power switches will greatly reduce the complexity, size, and weight of the accelerator power-conditioning system.

Such switches, with their low inductance and precise closure, will enhance the closed-cavity transmission line accelerators now being developed.[2,3,8] The power-conditioning schematic (Fig. 13) can be used with the stacked-line modules or the individual Blumlein modules in a distributed system because of the photoconductive power switches. Note the simplicity of this system compared with Fig. 1, which represents the conventional approach. Also, note that the maximum voltage in the system is 100 kV for the distributed system for the systems external to the stacked-line modules. The efficiency of the system also reduces the requirements on the power-conditioning system. Energy is generated by a prime power source such as a rotary flux compressor and stepped up in voltage with a standard transformer as in Fig. 13. This pulse, which is approximately 1 ms long, charges the Blumlein modules, either separately or in the stacked-line configuration. At peak charge on the Blumlein modules, energy is transferred to the electron beam pulse being accelerated in

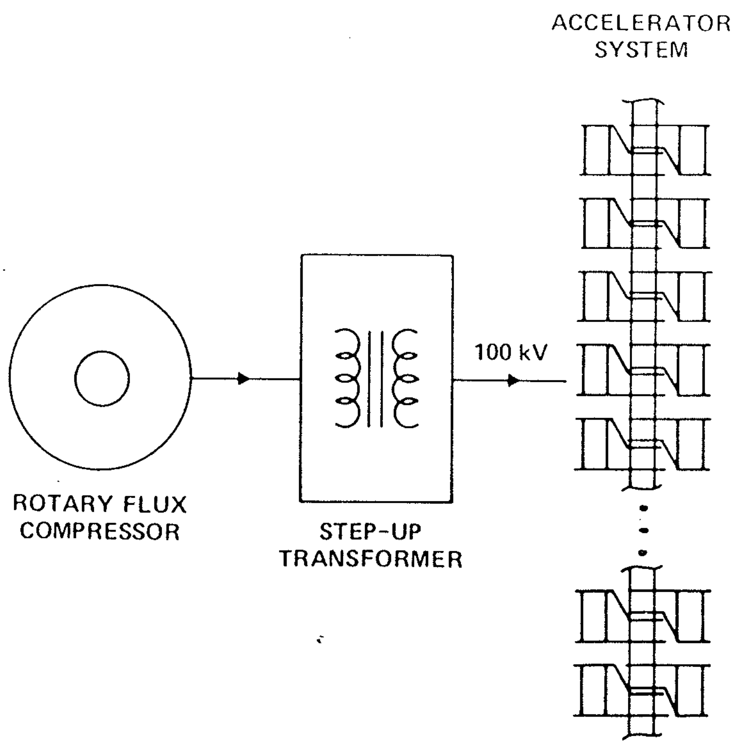

Fig. 13. Simplified power conditioning.

a laser-controlled sequence. Fewer components and a smaller energy storage system, brought about by the solid dielectric transmission line systems, have reduced the size and weight of the power supply.

Moving the optical control beam between switches during the interpulse interval makes possible other modes of operation, such as multiplexing multiple sources to a single load or multiple loads to a single source. Multiple sources and a single accelerator column are illustrated in Fig. 14.

The simplicity and size reduction possible with photoconductive power-conditioning systems also permit other accelerator schemes to be developed for directed-energy weapons. The electron-beam-pulse duration and current intensity, as well as the interpulse spacing, all affect pulse propagation in the atmosphere. Several propagation modes have been proposed that select both a

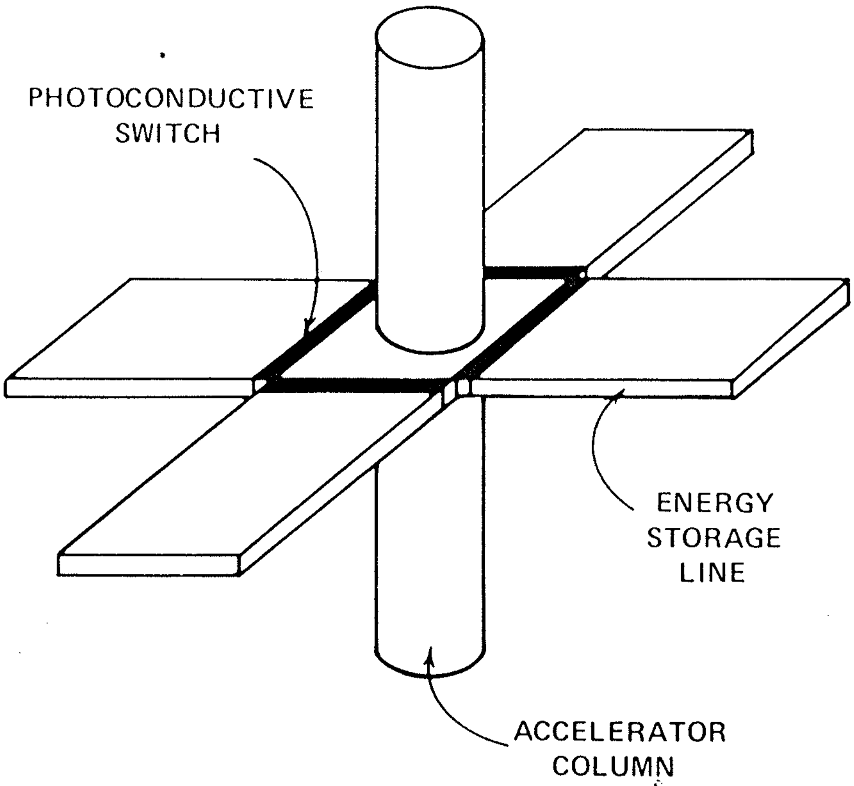

Fig. 14. Multiple sources with one load arrangement.

ratio of pulse duration to pulse separation and a specific pulse current. However, each proposed system has been limited, generally, to a fixed ratio of pulse duration to pulse separation, determined by the power-conditioning system. For some applications, photoconductive power switches will permit choosing pulse duration and pulse separation independently of the power-conditioning system. Size reduction in the power-conditioning system and the precise control possible with lasers make this choice possible.

A high-current accelerator system can be designed, as illustrated in Fig. 15, to deliver a variety of pulse durations and a variety of pulse spacings, to tailor the current during the pulse, or to chirp the pulse train in transit to the target. Reducing size and complexity in the conventional accelerator permits fabrication of multiple accelerator columns in the same volume as that used with a conventional system. The number of accelerator columns determines the number of pulses to be accelerated in a burst, or it reduces the duty cycle of a single accelerator column so that previously impossible combinations of pulse intensities and pulse spacing become possible. The impedance of the Blumlein modules in each accelerator determines beam pulse length for that accelerator. For example, a 100-kA pulse with a 10-ns duration will be accelerated by 100 kV using the module shown in Fig. 16. Many of these modules are placed along the accelerator column, and the optical control energy is channeled to the photoconductive power switches with fiber-optic bundles (Fig. 17). In this way, during a burst, shape and duration of the individual electron beam pulses can be tailored to obtain the optimum propagation mode. Figure 18 shows two modes of tailoring individual beam pulses. This power-conditioning method is the most easily controlled, the most efficient, most straightforward--and possibly the only--method of accelerating a burst of individually tailored beam pulses. In addition, delaying the controlling laser pulse can change the interpulse spacing in real time. This method is the most efficient way to use the continuous pulse train (CPT) mode of propagation.

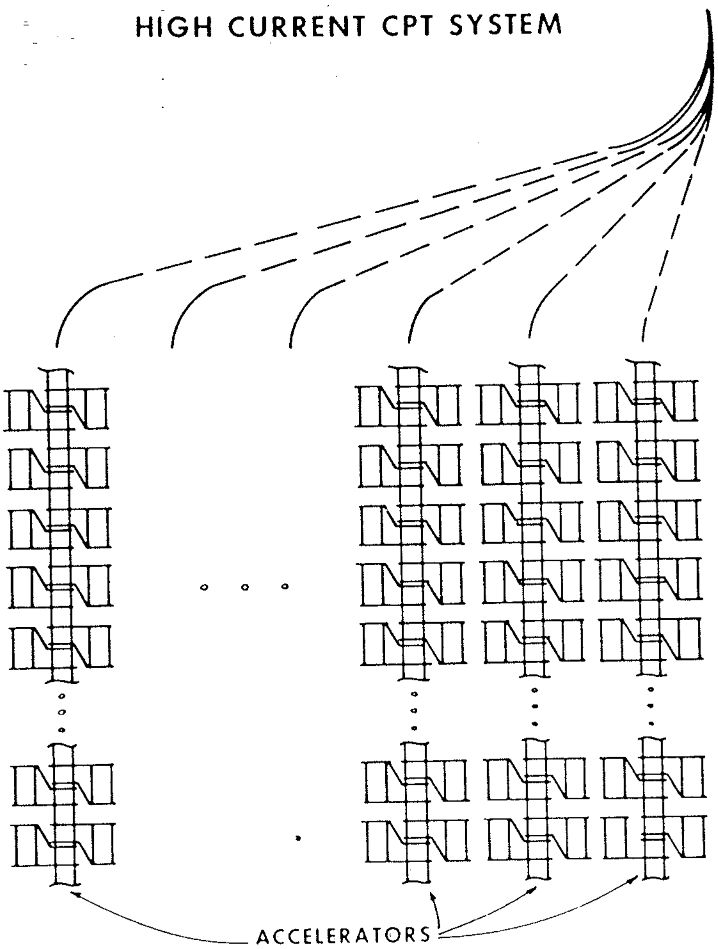

Fig. 15. High-current accelerator systems.

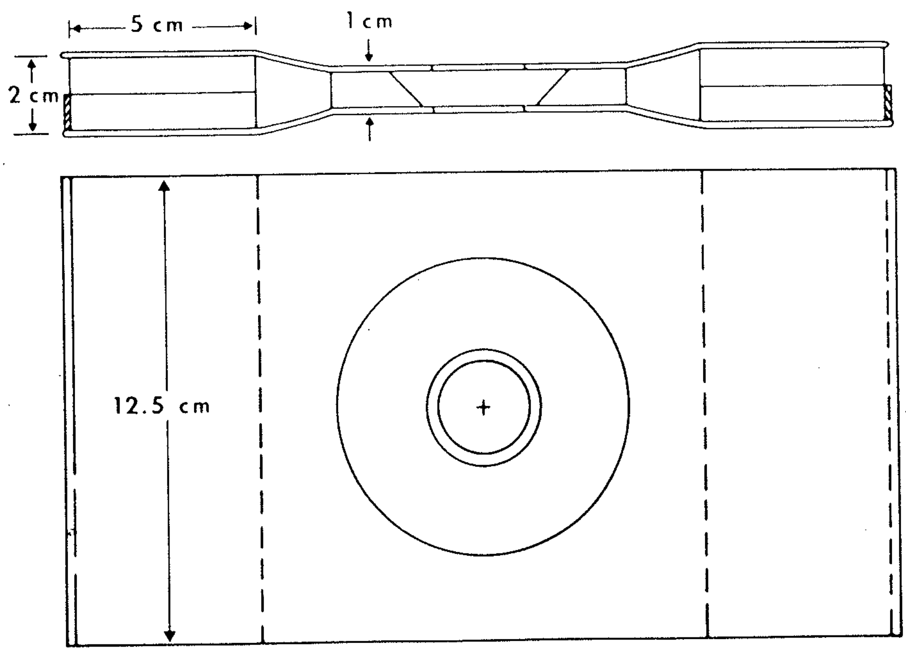

Fig. 16. 100-kV, 100-kA, 10-ns module.

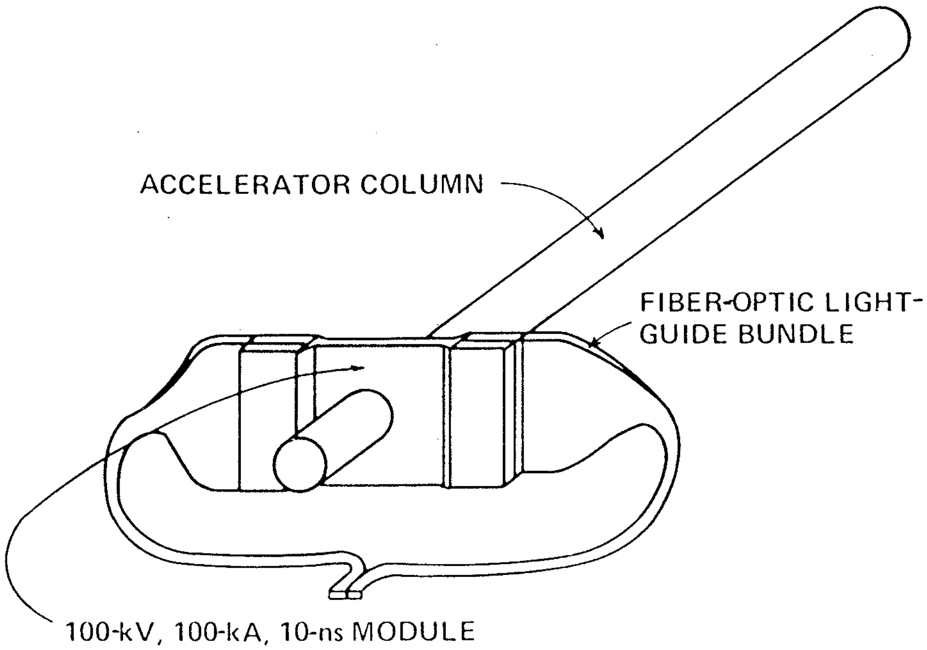

Fig. 17. Many modules are positioned along the accelerator column, and optical control energy is channeled into photoconductive power switches with fiber-optic bundles.

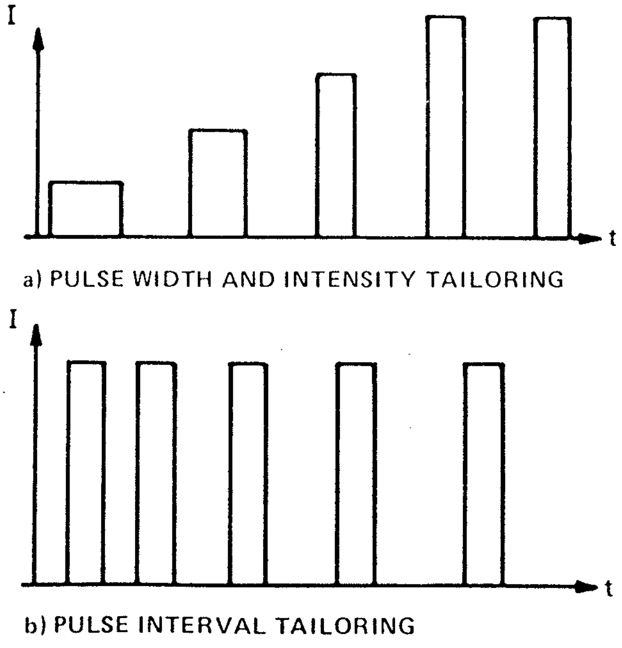

Fig. 18. Pulsed-train tailoring of individual beam pulses.

VII. SUMMARY

Photoconductive power switches can control very high pulse currents and voltages efficiently with a precision that is impossible with any other technology. The precise control and the fast circuit response possible with photoconductive power switches permit the development of accelerator power-conditioning systems that are more efficient, simpler, and more flexible than other technologies. Combining solid dielectric, energy storage systems and photoconductive power switches reduces the size and weight of conventional power-conditioning systems by at least an order of magnitude, a reduction brought about by less complexity in the power-handling and the power control systems. Conventional weapons-effect-simulation accelerator systems operate in parallel, so synchronizing of multiple generators at the load with nanosecond precision is very difficult using conventional controls and switches. However, photoconductive power switches provide precision timing and control that can synchronize many parallel pulsers. Similarly, directed-energy particle beam accelerators require precise control of the many series stages that apply very high power to each accelerated beam pulse. With conventional technology, sychronizing sequential power pulses with the beam pulse is very difficult. Also, the switching action is lossy, and energy in the individual power systems must be handled repeatedly to obtain the desired pulse shape. Again, photoconductive power switches can generate the very high power pulses required for sequential acceleration of a beam pulse with precise control and an efficiency much greater than that now possible. Photoconductive switches permit distribution of the power modules while maintaining precise control so that much lower stage voltages can be used. In addition, energy storage systems using solid dielectric are smaller so that multiple accelerators or multiplexed sources on a single accelerator can feasibly generate a tailored burst of electron beam pulses designed for optimum propagation. These advantages all suggest that photoconductive power switches and solid dielectric energy storage systems must be developed if reliable, high-energy accelerator systems are to be achieved, especially for directed-energy particle beam weapons systems.

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