

## A NEW SWITCHED POWER LINAC STRUCTURE

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### INTRODUCTION

In the last few years, many ideas, suggestions and proposals have been presented on the subject of linear colliders and related technologies. The common denominator of this activity points to the need for machines that stretch present capabilities to a level that would have been considered impractical or useless in the not-too-distant past. For example, an accelerator delivering low repetition rate electron bunches 100 fs ( $10^{-13}$  sec) long would not have generated great interest in the high energy physics community fifteen years ago; these bunch lengths (and shorter) are now essential for  $e^+e^-$  colliders in the quantum beamstrahlung energy regime. Similar considerations apply to another basic parameter of a linac, i.e., the gradient: at a few tens of GeV final energy, and a gradient of 20–40 MV/m, the accelerator length is kept within "reasonable" limits. But at 40 MV/m, a 1 TeV machine will be 25 km long. In other words, the need for high-duty cycle, the fact that moderate gradients were satisfactory and the availability of high-power RF sources all have controlled the development of linear accelerators. The needs have now changed, hence the attempt to find alternative solutions for short bunches and higher gradients.

One could catalog the various proposals submitted in broad categories: inverse effects, collective acceleration, wakefield mechanisms, pulse (switched) power, conventional and unconventional RF sources, laser acceleration supported by microscopic structures, and combinations thereof of one or more of these. This catalog (of the available literature, by no means complete) contains thirty-five rather distinguishable machines, according to our count. Of these, only two are in the pulse power category.

Pulse power differs from RF only to the extent that the power compression stage of a resonant cavity is replaced by fast (ultrafast) switching. The two approaches are, in essence, the same: a potential difference between two conducting planes increases the energy of

the charged bunch traversing the planes. Pulse power eliminates the very expensive and complicated conversion from wall plug to RF energy, and lends itself quite naturally to the acceleration of very short bunches. On the other hand, there are "proven" techniques to generate high peak power RF while subnanosecond switching is at a stage far from the needs of a linear accelerator. This paper is devoted to the description of a new pulse power structure, and to the proposal for a switching technique that appears to fill the requirements of future high-gradient machines.

A switched power linac structure has been suggested by Willis.<sup>1</sup> The structure consists of a set of parallel disks of radius  $R$ , with a hole in the center, where an electron beam is accelerated by EM wave injected uniformly at the disk's periphery, with the appropriate phase. The wave is spatially compressed while travelling towards the center; starting with an electric field  $E_0$ , the energy gained by a charge  $q$  crossing the gap  $g$  between two disks will be  $qGE_0g$ . Analytical calculations have shown that<sup>2</sup>

$$G = 2 \sqrt{\frac{2R}{\tau_R c + g}},$$

where  $R$  is the radius of the disks,  $\tau_R c$  is the product of the risetime of the pulse times the speed of light (the "space rise" of the pulse). This expression is rigorously correct if the plates have no hole in the center: a case of little interest if an electron beam has to be accelerated. However, it can be shown that this expression is a good approximation if the diameter of the hole is smaller than the gap between the plates. The value of  $G$  has been experimentally verified by Aronson *et al.*<sup>3</sup> by varying  $\tau_R$  and by measuring the  $E$  field at different radii.

A good approximation for  $G$  that includes the effect of the center hole on the accelerating field is:

$$G \cong 2 \sqrt{\frac{R}{\tau_R c + g}}.$$

The reduction factor of  $\sqrt{2}$  is close to the experimentally measured value,<sup>3</sup> when the hole diameter is equal to the gap  $g$ .

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Invited talk presented at the 4th Workshop: Pulse Power Techniques for Future Accelerators, Erice, Trapani, Sicily, March 4–9, 1988; and also presented at the Switched Power Workshop, Shelter Island, New York, U.S.A., October 16–21, 1988.

The electron bunch length required by future colliders must be very short, in order to achieve useful values of luminosity. Typical bunch lengths are of the order of 1-2 mm or less in the "classical" beamstrahlung regime, and down to a few tens of microns in the "quantum" beamstrahlung regime.<sup>4</sup> This implies that gap lengths in a pulse power structure should be small, i.e., of the order of a few millimeters; and since  $\tau_{RC}$  appears as  $g$  in the gain formula, a serious restriction is imposed on the pulse risetime, if reasonable efficiency is expected. The impedance seen from the periphery of a pair of disks is given by ( $Z_0 = 377 \Omega$ ;  $R \gg g$ ):

$$Z = Z_0 \frac{g}{2\pi R}$$

or  $Z = 1 \Omega$  for  $g = .1 \text{ cm}$ ,  $R = 6 \text{ cm}$ . The gain  $G$  for 3.3 ps risetime will be 15.5. A gradient of 200 MV/m will be obtained with  $\sim 13 \text{ kV}$  pulse injected. Therefore, one needs 1000 switches/meter, each capable of 3.3 ps risetime with a current of 13 kA. Although the total energy switched per meter of structure is small (.56 Joules), the peak power is  $1.7 \times 10^{11}$  watts!

In conclusion, the plurality of switches, the fast risetime needed, high peak power and the required uniformity in switching (the wavefront injected must be uniform around the radius, or else transverse fields will be seen by the accelerated bunch) appear to be rather difficult goals to achieve simultaneously.

The new accelerating structure removes some of the difficulties of the radial line structure: first of all, the new structure does not need an extremely fast risetime to achieve high gradients efficiently.

Furthermore, the switch configuration of the radial line structure is circular (around the periphery of the disks); the switch of this new structure is rectilinear. This makes the optical setup necessary to drive the switch (with laser light) simpler and cheaper. The new structure has two other advantages over the radial line: it offers the possibility of implementing energy recovery schemes without interfering with the switch; and for equal gradient, the energy/unit length needed by the radial line is higher (for practical values of  $\tau_{RC}$ ).

### DESCRIPTION OF THE STRUCTURE

Consider a flat plate transmission line (Fig. 1), of width  $L$ , with initial interelectrode distance  $g_1$ , filled by a dielectric (relative dielectric constant  $\epsilon_r$ ). The two plates (anode

and cathode) forming the line are not exactly parallel, but slightly converging, i.e., the interelectrode distance decreases at a shallow angle. A pulse of duration  $\tau$  is injected in the side shown as  $AA'$  in Fig. 1. The wavefront of the pulse is parallel to the direction  $AA'$ , the electric field has the direction indicated. The pulse travels towards  $BB'$ , which forms an angle  $\theta$  with  $AA'$  given by:

$$\theta = \sin^{-1} \frac{1}{\sqrt{\epsilon_r}} \quad (1)$$

The flat plate transmission line is cut into ribbons of width  $w_1$ , each starting at  $BB'$ . The initial ribbon thickness is  $g < g_1$  (remember that the two plates are not parallel). Continuing from left to right, both width and thickness of the ribbons are reduced continuously, while the ribbon is twisted  $90^\circ$ . After the twist, a bend of an angle  $\theta$  aligns the  $E$  field of every ribbon in a straight path. The  $E$  field in the regions will be aligned and with the proper phase for accelerating a charge (already) moving the velocity  $c$ , because of the delay inserted in each section by Eq. (1) and because each transition transformer has the same delay. Figure 2 is a shaded drawing of one section (equivalent to Fig. 1).

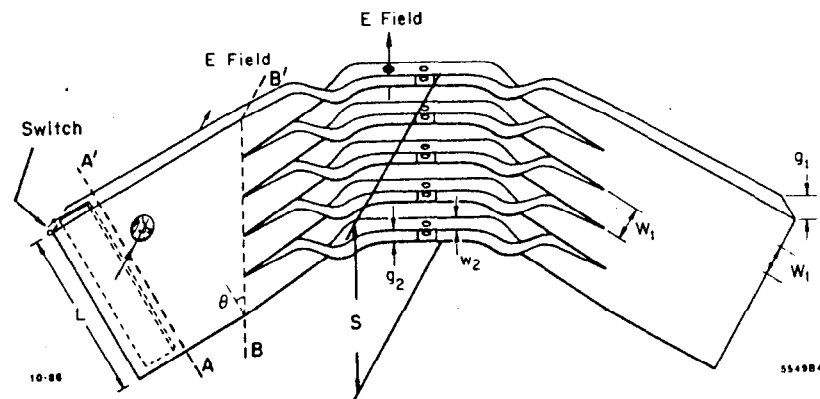


Figure 1: Isometric view of the new pulsed structure. The central electrode on the left hand side is intended to represent schematically a Blumlein-like pulse injection. The switch in this case is symbolically shown only on the upper left corner. In a true structure, the switch will be uniform along the center electrode.

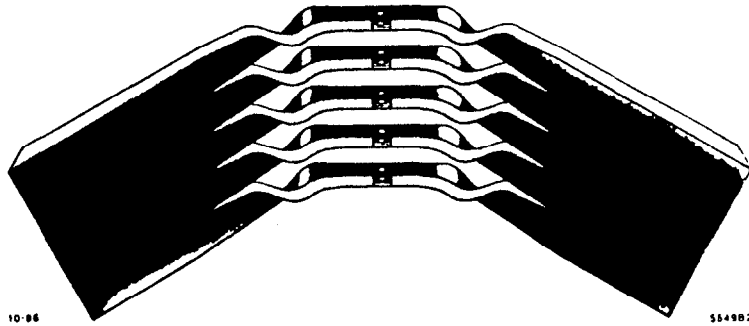


Figure 2: Shaded drawing of Fig. 1 (continuing lines). The beam will be accelerated through the holes in the central region.

During the transition, the value of the dielectric constant  $\epsilon_r$  is lowered: this can be done by changing the dielectric mixture, or by using short sections of dielectric with progressively lower  $\epsilon_r$ . The idea is to change the impedance from the value\*

$$Z_i = \frac{Z_0}{\sqrt{\epsilon_r}} \frac{g_1}{g_1 + w_1} \quad (2)$$

to the value of

$$Z_f = Z_0 \frac{g_2}{g_2 + w_2} \quad (3)$$

as smoothly as possible, in order to minimize the amount of reflected power;  $Z_i$  is the impedance of a section of width  $w_1$  at the beginning of the line,  $Z_f$  is the impedance at the accelerating region. At this point, it is clear that the structure can be described as a set of cables pulsed in parallel and rearranged in series (with appropriate delays) so that starting with a wave of amplitude  $V_0$ , the final accelerating potential will be:

$$V_f = V_0 \cdot \frac{L}{w_1} \cdot \sqrt{\frac{Z_f}{Z_i}} \quad (4)$$

\* Note: The expression is a good approximation to the exact impedance value of a parallel plate transmission line.

Substituting 2, 3 in Eq. (4), we can write the equation for the gradient gain  $G$

$$G = \frac{E_{final}}{E_{initial}} = \frac{V_f \cos \theta}{L} \cdot \frac{g_1}{V_0}$$

as

$$G = \epsilon_r^{\frac{1}{2}} \cos \theta \frac{g_1}{w_1} \sqrt{\frac{g_2(g_1 + w_1)}{g_1(g_2 + w_2)}} \quad (5)$$

The travelling pulse appearing in the accelerating region has an electric field parallel to the direction of motion of the electrons, but also a magnetic field that gives a transverse impulse  $p_{\perp}$  to the electron bunch. This effect can be compensated for by using the following technique. The width of each ribbon  $w_1$  is larger than the gap  $g_2$ , so that there is a spacing between each accelerating region. Suppose that  $w_1 \cong 3g_2$ ; in this case we can interleave two more accelerating structures rotated  $120^\circ$  from each other. If the  $V_0$  amplitude is the same in every triplet of successive accelerating gaps, the transverse momentum gain  $p_{\perp}$  is averaged to zero (see Fig. 3).

The three lines structure is the minimum required for averaging  $p_{\perp}$  to zero, if the striplines are continued after the accelerating region. More generally, neglecting electrode's thickness, the value of  $N$

$$N = \frac{w_1}{g_2 \cos \theta} \quad (6)$$

must be an integer greater than or equal to three. This condition will completely pack the length  $S$  with  $S/g_2$  gaps.

After the accelerating gap, the ribbons are twisted again to form a flat transmission line; in this manner the energy of the electrical pulse left after acceleration can be recovered, or at least removed

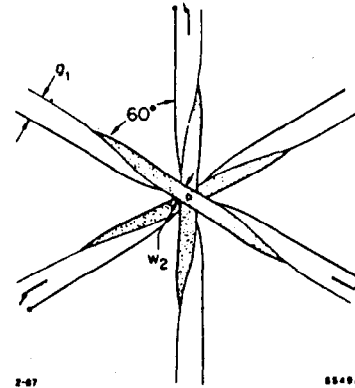


Figure 3: Beam end view of three crossed structures. Again, the Blumlein structure is shown to indicate where the pulse is injected.

from the structure to avoid heating and/or damage to the switch used to inject the pulse.

There are many variants to the structure just described. For example, the use of a dielectric to control the delay of the high voltage pulse is not strictly necessary. The delay can be obtained in vacuum by an appropriate length of the individual ribbons. The geometry will be somewhat different, and one loses the factor  $\epsilon_r^{1/4}$  in the gradient gain ( $\epsilon_r = 1$ ).

Another variant is to interrupt (leave open) the ribbons after the accelerating region (see Fig. 4). In this case the pulse will be reflected back, almost completely;\*\* the electric field will increase by a factor of two, and the magnetic field will be reduced by a large factor. We will interleave at least three structures in this case, to compensate for the small residual magnetic field, and to pack the accelerating region completely. The gradient gain of this configuration (open end lines, completely packed) will be:

$$G = 2\epsilon_r^{1/4} \sqrt{\frac{g_1(g_1 + w_1)}{g_2(g_2 + w_2)}} \quad (7)$$

If  $(w_1/g_1) \cong (w_2/g_2)$  (which implies that  $Z_i \cong Z_f$ ), the gradient gain can be approximated as:

\*\* The reflection coefficient of an open line is frequency dependent.

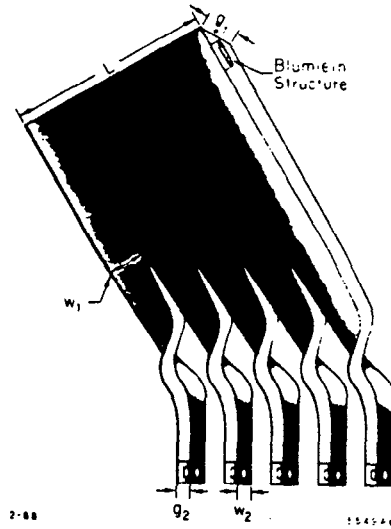


Figure 4: Shaded drawing of the open line structure. The acceleration is now from left to right, through the holes at the end of each line.

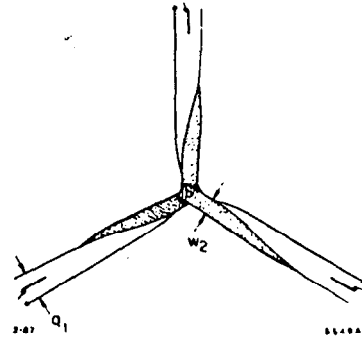


Figure 5: Beam end view of the open line case (analogous to Fig. 3).

$$G \cong 2\epsilon_r^{1/4} \frac{g_1}{g_2} \quad (8)$$

These expressions for the gain do not contain the pulse risetime, or pulse length. The assumption made in Eq. (4) is that the twisted transition region is equivalent to a transformer, with voltage gain given by  $(Z_f/Z_i)^{1/2}$ ; this is correct if the pulse length is much shorter than the length  $l$  of the twisted transition. The pulse length must be longer than  $\sim w_2/c$ , to insure proper reflection from the open end. A beam line end view of this configuration is in Fig. 5 (analogous to Fig. 3). To leave open the end of the twisted sections may be necessary at high energies, since the synchrotron radiation loss goes as  $\gamma^2 B^2$ , and for large values of  $\gamma$  this energy loss can be a substantial fraction of the gradient.

Two effects have been neglected in Eqs. (7) and (8). The first is due to the fact that the "open circuit" reflection coefficient is not exactly +1, but a complicated function of the line geometry and of the frequency components present in the pulse. The second is due to the presence of a hole (iris) in the accelerating region. The effect of the hole is to reduce the field by some 20% when  $g_2$  is equal to the iris diameter (this reduction comes from numerical simulation and from some measurements done on the radial line transformer). A reasonable and conservative guess for the contribution of these losses is to replace the factor of two with  $\sqrt{2}$  in Eqs. (7) and (8). In conclusion:

$$G \cong \sqrt{2} \epsilon_r^{1/4} \sqrt{\frac{g_1(g_1 + w_1)}{g_2(g_2 + w_2)}} \quad (9)$$

For:

$$\frac{w_1}{g_1} \cong \frac{w_2}{g_2}$$

$$G \cong \sqrt{2} \epsilon_r^{1/4} \frac{g_1}{g_2} \quad (10)$$

and, as mentioned before, Eqs. (9) and (10) are good approximations if:

$$\frac{w_2}{c} < \tau < \frac{l}{c}$$

The energy/unit length of accelerator needed to obtain a given gradient can be calculated

as follows: The input impedance of each section as seen from AA' (Fig. 1) is:

$$Z = \frac{Z_0}{\sqrt{\epsilon_r}} \frac{g_1}{g_1 + L} \cong \frac{Z_0}{\sqrt{\epsilon_r}} \frac{g_1}{L} \quad (11)$$

For a voltage  $V_0$  injected in this line, the energy contained in the pulse of duration  $\tau$  is:

$$\mathcal{E}_L = \frac{V_0^2}{Z_0} \sqrt{\epsilon_r} \frac{L}{g_1} \tau \quad (12)$$

On a length  $S = L/\cos\theta$  of accelerator, we have a number of lines given by Eq. (6), so that the total energy needed per unit length will be:

$$\frac{\mathcal{E}_L}{S} = \frac{V_0^2}{Z_0} \sqrt{\epsilon_r} \frac{w_1}{g_1 g_2} \tau \quad (13)$$

Using Eq. (9), we obtain the energy/unit length as a function of the final gradient  $E_f$ :

$$\frac{\mathcal{E}_L}{S} = \frac{E_f^2}{2Z_0} \frac{g_2 + w_2}{g_1 + w_1} w_1 \tau \quad (14)$$

This expression can be simplified by:

1.  $\tau = (2w_2/c)$ , minimum pulse length requirement.
2.  $Z_0 c = \epsilon_0^{-1}$ ,
3.  $w_1 \gg g_1$ ,

so that Eq. (14) can be written as:

$$\frac{\mathcal{E}_L}{S} = E_f^2 \epsilon_0 w_2 (w_2 + g_2) \quad (15)$$

### A NUMERICAL EXAMPLE

The following is an exercise in designing a section of length  $S = 1$  m, to give an idea of the order of magnitude of the parameters involved. A more accurate optimization of the machine requires a detailed knowledge of a few effects which are difficult to calculate: the interference between adjacent lines, the pulse spread while traversing the twisted sections,

the actual reflection coefficient from the open end of the lines, etc. Furthermore, some of the assumptions are somewhat arbitrary: the conditions given in Eq. (16),  $2w_2/c = \tau$ , is just a rule of thumb to avoid improper reflections from the open end. The exact value of the constant "2" depends, among other things, upon the actual pulse shape reaching the open end.

We will use a pulse length already achieved by Fletcher:<sup>9</sup> 100 ps. This pulse length was obtained with a switch working in air at atmospheric pressure. The design gradient (without beam loading) will be 300 MV/m, or about 20 times the present SLAC gradient. We will use a high-frequency dielectric ( $\epsilon_r = 11$ , commercially available) to load the initial section of the lines. The structure will have the open line configuration. The pulse length determines the value of  $w_2$  [Eq. (16)]:  $w_2 = 15$  mm. The value of  $g_2$  is taken as 6 mm, giving a reasonable aspect ratio for the accelerating portion of the lines. The number of sections  $N$ , [Eq. (16)] is chosen, rather than  $w_1$ ; for simplicity, we take  $N = 12$ , which will fix  $w_1 = 70$  mm ( $\cos\theta = 0.953$ ). The last dimension to select is  $g_1$ , the interelectrode distance at the beginning of the sections. This parameter controls the impedance at the beginning of the sections, the detailed structure of the pulse-forming Blumlein structure, the gradient gain and the voltage needed to obtain the desired gradient. For different values of  $g_1$ , we have:

Table 1.

$g_1$ mm	$Z_i$ $\Omega$	$G$	$V_i$ kV	$\mathcal{E}/\text{pulse}$ Joules
6	.68	4.87	370	231
10	1.14	6.44	466	219
15	1.70	8.14	553	206
20	2.27	9.68	620	194

The choice of  $g_1$  will be dictated by the detailed design of the power compressor preceding the switch (probably a magnetic pulse sharpening system), and by the properties of the

switch itself. At any rate, the energy handled by each switch is approximately 20 Joules, or 2 kW at 100 pps rate, quite a modest level for a switch operating in gas.

### COMPARISON BETWEEN THE RADIAL LINE AND THE NEW STRUCTURE

The energy needed by the new structure can be compared to the energy needed  $\mathcal{E}_R$  in a radial line transformer, as a function of the final gradient and risetime of the pulse:

$$\frac{\mathcal{E}_R}{S} = \frac{\pi\tau}{2Z_0} E_f^2 (\tau_{RC} + g) \quad (16)$$

If we specify the pulse length  $\tau$  as  $\tau = 2g/c$ , Eq. (16) becomes:

$$\frac{\mathcal{E}_R}{S} = \epsilon_0 \pi E_f^2 g (\tau_{RC} + g) \quad (17)$$

Comparing this expression to  $\mathcal{E}_L/S$  given by Eq. (14) ( $\tau = 2w_2/c$ ), we obtain, for the same gap  $g_2 = g$ :

$$\frac{\mathcal{E}_R}{\mathcal{E}_L} = \frac{\pi g \left( \frac{\tau_{RC}}{g} + 1 \right) (g_1 + w_1)}{\left( 1 + \frac{w_2}{g} \right) w_1 w_2} \quad (18)$$

Since  $g_1 \ll w_1$ , the two structures will require the same energy when:

$$\frac{\tau_{RC}}{g} = \left( 1 + \frac{w_2}{g} \right) \frac{w_2}{\pi g} - 1 \quad (19)$$

for  $w_2/g = 3$ ,  $\tau_{RC}/g = 2.82$ ; the value of  $\tau_{RC}/g$  drops rapidly: for  $w_2/g = 2$ ,  $\tau_{RC}/g = .91$ .

### COMPARISON WITH AN X BAND LINAC

Recently, P. Wilson<sup>5</sup> has presented a study of a linac working in the X band (11.42 GHz). The value for elastance is quoted as  $s = 10.5 \times 10^{14}$  V/Cm. From Eq. (14) we can write the elastance of the open line structure as (see Appendix):

$$s = \frac{(1 + A_1)}{\epsilon_0 w_2^2 (1 + A_2)} \quad (20)$$

where  $A_1 = g_1/w_1$ , and  $A_2 = g_2/w_2$ . With the geometrical values of the previous example (Table 1), we obtain  $s = 3.89 \times 10^{14}$  V/cm ( $g_1 = 6$  mm) and  $s = 4.61 \times 10^{14}$  V/cm

( $g_1 = 20$  mm). The elastance parameter scales as  $\omega^2$ ; a pulse with a risetime  $\tau$  contains frequencies up to

$$f \cong \frac{1}{2.2\tau}$$

or  $\approx 4.5$  GHz (for  $\tau \approx 100$  ps). We conclude that part of the difference between the two values of elastance is due to the frequency dependance, and that we could obtain a value of  $s$  equal to the X band linac for a pulse of 65 ps (instead of 100 ps) duration.

### TRANSIENT DISPERSION AND ATTENUATION

The skin depth associated to a frequency  $f$  is given by

$$\delta \cong k \sqrt{\frac{\rho}{f}} \text{ cm} ; \quad k = 5 \times 10^3 ; \quad (21)$$

where  $\rho$  is the resistivity of the conductor ( $\Omega \cdot \text{cm}$ ),  $f$  is the frequency (Hertz). For Cu at 4.5 GHz,  $\delta = 1.0 \mu$ . A length  $l$  of conductor with a width  $w$  will present a skin depth resistance of

$$R = \rho \frac{l}{\delta w}$$

This value has to be compared with the impedance of a parallel plate line

$$Z = Z_0 \frac{g}{w}$$

The ratio  $R/Z$  for a 1-m transmission line length is of the order of  $4 \times 10^{-3}$ ; hence, losses due to skin depth are small. The attenuation due to the presence of dielectric can be approximated as

$$A = 9.1 \times 10^{-8} f \text{ tg } \delta \sqrt{\epsilon_r} \text{ db/m} \quad (22)$$

for  $\epsilon_r = 11$ ,  $\text{tg } \delta = 4 \times 10^{-4}$  (a commercial plastic dielectric material)

$$A = 0.6 \text{ db/m } @ 4.5 \text{ GHz}$$

We conclude that losses are small for a line length of 20-30 cm loaded with this dielectric.

Using fused silica ( $\epsilon_r = 4$ , and  $\tan \delta = 2 \times 10^{-4}$ ), the attenuation will be reduced to 0.2 db/m; other dielectrics (like sapphire) are expensive and difficult to fabricate in odd shapes.

The use of a dielectric is probably needed to avoid field perturbations due to randomly fluctuating field emission currents: even at very high electric fields, the short pulse duration does not allow regenerative (avalanche) effects; but current due to field emission should be kept conservatively below  $1/10^6$  of the main current flowing in the lines. Perhaps the dielectric is not needed, or a surface treatment of the cathode may be sufficient.

Finally, there is a small wavefront distortion introduced by the twist transition from the beginning of each strip to the region where the  $E$  field has been rotated by  $90^\circ$ . The center of the transmission line will be shorter than the outer edges. Using the numbers given in the numerical example, if the transition occurs in 20 cm, then the length difference amounts to about 2 mm. If the average value of the dielectric constant during the twist is nine (we started at  $\epsilon_r = 11$ ), the transit time difference is  $\sim 20$  ps, which is small compared to the pulse length.

### GRADIENT LIMITS

Very little is known about vacuum breakdown for short, subnanosecond pulses. We found only one reference in the literature in which nanosecond pulses were used to determine the breakdown strength of small vacuum gaps.<sup>6</sup> The interesting point of this experiment is that field intensifying whiskers were identified visually as the breakdown initiators; furthermore these whiskers were destroyed by short pulses (1 ns or less), and did not form again once destroyed (again, for very short pulse durations). The authors found that for pulses  $< .5$  ns long, the breakdown field between Cu exceeded  $1.4 \times 10^9$  V/m (80 kV on a 57-micron gap); with W electrodes the field was  $3 \times 10^9$  V/m for pulses less than 1 ns (80 kV on 27 microns). Whether the  $3 \times 10^9$  V/m field can be held for a few picoseconds on a much larger area and gap will have to be proven by experimentation. Nevertheless, the values reported are encouraging.

Another limit, probably far from practically achievable gradients, is due to the melting of the structure's surface. We will present here an order of magnitude estimate for a parallel plate structure subject to a pulse of duration  $\tau$ . The energy dissipated by a pulse of duration

$\tau$  is given by  $i^2 R \tau$ , where  $R$  is the resistance due to skin effect. The skin depth  $\delta$  is given by Eq. (21). For a parallel plate line, the volume heated will be  $w \cdot \delta \cdot \ell$ ,  $w$  being the width,  $\ell$  the length of the structure. We can therefore write

$$\frac{V^2}{Z^2} \rho \frac{\ell}{w \delta} \tau = C_p \Delta T w \delta \ell, \quad (23)$$

with  $C_p$  = specific heat of the electrodes (Joules/cc),  $\Delta T$  = increase in temperature ( $^\circ\text{K}$ ). This equation simplifies as  $[\tau f \sim (1/2)]$ :

$$\Delta T = \frac{E^2}{Z_0^2} \frac{1}{2C_p k^2}. \quad (24)$$

All metals have  $C_p \simeq 2.5$  to 3 Joules/cc. The value of  $\Delta T$  goes from  $3200^\circ\text{K}$  for refractory metals (like W or Ta) to  $1000^\circ\text{K}$  for Cu. Equation (24) estimates the temperature increase of a very thin layer of conductor, under the assumptions that there is sufficient heat conduction between two successive pulses to ignore the repetition rate dependence of  $\Delta T$ . The gradient limit calculated according to Eq. (18) for  $\Delta T = 3200^\circ\text{K}$ ,  $C_p = 2.5$  J/cc is  $E = 2.4 \times 10^{10}$  V/m. Notice that the units of  $E$  in Eq. (24) are V/cm.

### ANOTHER EXERCISE

We will repeat the calculations for a very high gradient machine; the measurements of vacuum breakdown reported in the previous chapter (Ref. 6) have shown that 3 GeV/m is a gradient that can be sustained between tungsten electrodes without breakdown. The pulse length will be 10 ps, a factor of 10 shorter than the previous example. This pulse length may be achievable with a gas avalanche switch triggered by a short-pulse UV laser. The accelerating gap will be reduced to 0.5 mm, and consequently, all dimensions will be scaled down. For example, the transformer/transition section in the previous example was of the order of 30 cm, to insure a "smooth" transition between the switch and the accelerating gap. The same smoothness can be obtained by a 10-cm-long transition, when the values of  $w_1$  and  $w_2$  are 1.5 and 0.15 cm, respectively. Therefore, the shorter pulse will propagate without appreciable losses ( $\simeq 1$  db) through the shorter length of transition.

The number of sections for complete packing given by Eq. (6) is  $N = 30$ . For an accelerating gap of 0.5 mm, the electrode's thickness cannot be ignored, and the number of sections must be reduced. Of course, the effective average gradient will be reduced, as well as the energy/unit length. By selecting  $N = 16$ , we allow for electrode thickness and some spacing between each gap, or between a complete set of gaps. The average gradient will be reduced to 1.5 GeV/m. The geometrical dimensions are as follows:

Table 2.

Parameter	Dimension
$g_1$	15 mm
$g_2$	0.5 mm
$w_1$	15 mm
$w_2$	1.5 mm
$N$	16
$\epsilon_r$	11
$\tau = 2w_2/c$	10 ps

From these numbers, we obtain:

$$G = 54.6$$

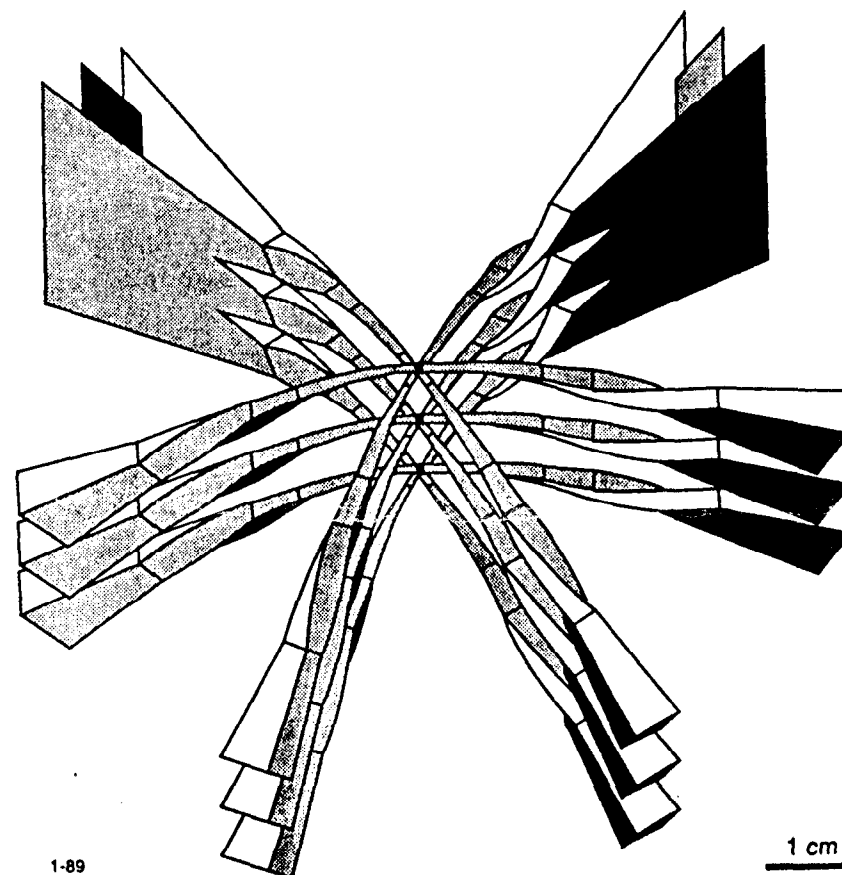
$$V_0 = 824 \text{ kV}$$

$$\mathcal{E}/S = 65 \text{ J/m}$$

Each switch (there are 16 of them) will control 4 J, or 480 watts at 120 pps.

Figure 6 is a very simplified drawing of the structure. Only six (out of sixteen) units are drawn, and of these, only two are complete with the Blumlein structure.

An approximate scale is indicated. Also, the dimension (length) of the Blumlein electrode is greatly exaggerated for clarity. In practice, the electrode length is only 3 mm.



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Figure 6: Sketch of a high-gradient machine. Only six units (out of sixteen). The two top units are complete with the Blumlein structure. Acceleration occurs in the center, where all transition transformers converge.

## SWITCHING

The key ingredient for a pulse power machine is the capability of ultrafast, reliable switching of very large currents, at moderately high voltages. We want to propose a gas avalanche switch (GAS) as a possible candidate; preliminary calculations show that the risetime obtainable is within the range of a few picoseconds, when switching the large current needed to drive a pulse power structure. We will give a description of the switching in a

medium, starting from an elementary, idealized case. For a more detailed study of the problem, see Ref. 13.

Consider a volume enclosed by two electrodes of area  $A$ , a distance  $g$  apart forming a condenser charged at voltage  $V_0$ , and of capacity  $C$ . Let us ionize the medium uniformly in an infinitely short time, with a density of free charges  $d$  (Coulombs/m<sup>3</sup>). The electrons will begin to move with velocity  $v$  towards the anode (ions are ~ stationary), and after a time  $t$  given by

$$t \approx \frac{C V_0}{v A d}, \quad (25)$$

the capacitor will be completely discharged. The calculation is not correct because it assumes constant drift velocity of the electrons: actually, while the electric field in the condenser decreases, the velocity will decrease as well. If we assume that the electron mobility is constant, i.e.,

$$v = \mu E,$$

then a simple calculation shows that the electric field will decrease with time as

$$E(t) = E_0 e^{-\frac{d A \mu}{C g} t},$$

i.e., with a time constant  $\tau = (e_0/d\mu)$  [exactly equal to  $t$  in Eq. (25)].

A risetime of 5 ps will be obtained with  $d = 1.8 \times 10^{-5}$  Coulomb/cc and  $\mu = .1 \text{ m}^2 \text{ V}^{-1} \text{ sec}^{-1}$ . The charge density implies an ionization level<sup>†</sup> of  $4.2 \times 10^{-6}$  for gas at NTP; the value quoted for the mobility is fairly typical for a gas. From these elementary considerations, one can conclude that given a fast source of ionization (like a 1-ps laser pulse) with sufficient energy to ionize a medium (with some quantum efficiency) the switching of an electrical pulse can be obtained.

The energy efficiency of this switch, however, is rather poor; the generation of a 1-ps laser pulse may have an efficiency (wall plug to light) as small as  $10^{-3}$ . The quantum efficiency in a medium is also very small, with only one notable exception, i.e., in a semiconductor.

<sup>†</sup> Ratio of number of ionized atoms/number of neutral atoms.

Switching in semiconductors has been achieved with impressive speed (a few picoseconds), but at low voltages — too low for our applications.

So far we have ignored the possibility of avalanche multiplication. In a gas, avalanche multiplication reduces the number of electrons to be generated by the laser, provided that the time of the avalanche growth is sufficiently fast. One electron drifting in a gas will multiply to  $N$  electrons according to:

$$N(t) = e^{\alpha v t},$$

where  $\alpha$  is the first Townsend coefficient,  $v$  is the electron drift velocity, and  $t$  is the time. Both  $\alpha$  and  $v$  are known (measured) functions of the ratio  $E/p$  (electric field/pressure). The drift velocity  $v$  depends only (with good approximation) on  $E/p$ , i.e.:

$$v = f_0(E/p).$$

The first Townsend coefficient  $\alpha$  is the inverse of the mean free path for ionizing collisions; the collision cross section is only a function of the drifting electron energy, i.e., it is constant for constant  $E/p$ ;

$$\alpha = p f_1(E/p),$$

because the number of scattering centers goes as  $p$ . The product  $1/\alpha v$  is the time that it takes to increase the number of electrons in the avalanche by  $e$ . From the two previous relations we conclude that

$$\frac{1}{\alpha v} \propto \frac{1}{p} \text{ for } E/p = \text{constant}$$

Hence, increasing  $p$  and  $E$  so that  $E/p = \text{constant}$  should decrease the avalanche growth time proportionally to  $p$ .

In these conditions the voltage will be applied to the switch for a very short time (less than 1 ns) to minimize the probability of prefire on an single electron emitted by the cathode. This probability can be minimized by:

1. applying the field for a very short time;

2. reducing the field on the cathode;
3. coating the cathode surface with an insulator.

Point 1 implies charging a few picofarads in a fraction of a nanosecond; quite a standard requirement for pulse power. The field reduction on the cathode surface can be obtained by shaping the electrodes.

### CONCLUSIONS

A new pulse power structure has been described that utilizes an easily accessible rectangular switch. The new structure is more "forgiving" (as far as risetime is concerned) than the radial line transformer, and contains fewer switching structures/unit length. The combination of the new structure with the switch proposed seems to offer interesting possibilities for a future linear collider.

### APPENDIX

Calculation of elastance: The elastance parameter is defined as

$$s = \frac{E^2}{\mathcal{E}/S},$$

where  $E$  is the accelerating field, and  $\mathcal{E}/S$  is the energy injected in a structure per unit length of accelerator. For RF-driven machines,  $s$  is proportional to the square of the frequency:

$$s = A\omega^2.$$

For the SLAC-type structure  $A = 2.310^{-8}$ ,  $s$  in  $V/C \cdot m^{12}$ . For pulse power structures, an approximate calculation of  $s$  is straightforward. We will start with the radial line transformer case, i.e., a structure made of parallel disks with a switch on the disk's periphery.

A length  $S$  of accelerator contains  $S/g$  sections,  $g$  being the gap between adjacent disks; the thickness of each disk is assumed to be negligible. The impedance seen at the disk's periphery (radius  $R$ ) is

$$Z = Z_0 \frac{g}{2\pi R}. \quad (A.1)$$

We calculate the energy/unit length as

$$\frac{\mathcal{E}}{S} = \frac{V_i^2 \tau}{gZ}, \quad (A.2)$$

where  $\tau$  is the pulse duration and  $V_i$  is the voltage injected at every disk's periphery. Recall the gradient gain (corrected for the presence of the iris):

$$G = 2 \sqrt{\frac{R}{\tau R c + g}}. \quad (A.3)$$

So that we can express  $V_i$  as a function of  $E_f$ , the final gradient, i.e.:

$$V_i^2 = \frac{g^2 E_f^2}{G^2}. \quad (A.4)$$

We obtain Eq. (17) by combining Eqs. (A.4), (A.3) and (A.2). Assuming that  $\tau = 2g/c$ , we can write ( $Z_0 c = \epsilon_0^{-1}$ )

$$\frac{\mathcal{E}_R}{S} = \pi \epsilon_0 g E_f^2 (\tau R c + g).$$

Finally, since

$$s = \frac{E_f^2}{\mathcal{E}/S},$$

we have, for the radial line elastance:

$$s = \frac{1}{\pi \epsilon_0 g (\tau R c + g)}. \quad (A.5)$$

We can proceed along the same line to calculate the elastance for the proposed structure. If we inject a pulse of amplitude  $V_0$  on a length  $S$ , we need an energy [Eq. (12)]:

$$\mathcal{E} = N \frac{V_0^2}{Z} \tau;$$

we now replace  $V_0$  in terms of  $E_f$ , using Eq. (9) for the gradient gain, and take into account

that the value of  $N$  is [Eq. (6)]:

$$N = \frac{w_1}{g_2 \cos \theta} ,$$

and obtain, for a pulse length of  $2w_2/c$ :

$$s = \frac{(1 + A_1)}{\epsilon_0 w_2^2 (1 + A_2)} , \quad (A.6)$$

with  $A_1 = g_1/w_1$ ;  $A_2 = g_2/w_2$ .

The expressions for the elastance presented here are approximate, because the effective accelerating field is less than the calculated value, due to the presence of the holes through which the beam is accelerated. The accelerating field/calculated field ratio is a function of  $r/g$  only (radius of the hole/accelerating gap):

$$\frac{E_{acc}}{E_{calc}} = \gamma = \gamma(r/g) ;$$

$\gamma$  is unity for  $r/g = 0$ , and zero for  $r/g = \infty$ . The exact behaviour of  $\gamma(r/g)$  requires detailed modeling of the actual structure. As a first guess, with some support from calculations and experimental data, we have taken  $\gamma = 1/\sqrt{2}$ .

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