Binary Peak Power Multiplier and its Application to Linear Accelerator Design

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Abstract —This paper describes a new method of pulse compression, the binary power multiplier (BPM), a device which multiplies RF power in binary steps. It comprises one or more stages, each of which doubles the input power and halves the input pulse length. Practical designs are described and expressions for their compression efficiency are derived. The usefulness of pulse compression for accelerator design is illustrated and compared with the pulse compression system currently in use at the Stanford Linear Accelerator Center.

Nomenclature

C_f Compression factor.
E Local accelerating gradient, MV m^{-1}.
E_a Average accelerating gradient, MV m^{-1}.
f Frequency, MHz.
L Section length, m.
M Multiplication factor.
p_d Power dissipated per unit length, MW m^{-1}.
P_d Power dissipated in the section, MW.
P Power transmitted, MW.
P_{pk} Klystron peak power, MW.
P_m Modulator power, kW.
P_{ac} ac line power, kW.
s Elastance per unit length, MΩ m^{-1} μs^{-1}.
T_f Section fill time, μs.
T_0 Unloaded (internal) time constant, μs.
T_k Klystron pulse length, μs.
v_g Group velocity, m μs^{-1}.
V Particle voltage, MV.
w Energy stored per unit length, J m^{-1}.
W Energy stored in the section, J.
α_t Delay line attenuation, Np/μs.
η_s Section efficiency.
η_k Klystron efficiency.
η_{pc} Compression efficiency.
τ Accelerator section attenuation, Np.

I. Introduction

THE VOLTAGE gained by a charged particle traversing an accelerator section divided by the section length, the average gradient, varies with the peak power amplitude into the section. High gradients are especially important for a new type of electron–positron collider, the linear collider [1], where two linear accelerators produce particle beams which are brought into collision once and then are discarded. This new type collider is more efficient at high particle energies than an electron–positron storage ring.

The first attempt to achieve electron–positron collisions with a linear collider [2] is the Stanford Linear Collider (SLC), presently nearing completion at the Stanford Linear Accelerator Center (SLAC). While not a true linear collider (the SLC uses the SLAC accelerator to inject electrons and positrons into two arcs, which bend the beams into collision), it will nonetheless serve the dual purpose of a unique physics tool and a demonstration of some aspects of linear collider technology. Proposed future positron–electron colliders [3] would be capable of investigating fundamental processes of interest in the 1–5-teravolt beam energy range. At the SLC gradient of about 21 MV/m (megavolt/m), this would imply prohibitive lengths of about 50–250 km per linac. We can reduce the length by increasing the gradient but this implies high peak power. Using the SLAC accelerator sections, operating at 2856 MHz, a 100-MV/m gradient requires 750-MW (megawatts) peak power.

Another requirement of multiteravolt colliders is high average power. For a given gradient, both peak and average powers depend on section fill time. The fill time is defined as the time it takes for RF energy to propagate from the accelerator section input to its output. The peak power increases as we decrease the fill time from its value where the peak power has a broad minimum. On the other hand, the average power decreases monotonically as the fill time is decreased. Thus, we can reduce the average power at the expense of increased peak power. We can trade higher peak power for lower average power. Pulse compression is a means to obtain high peak power. It adapts the relatively long source pulse length to the relatively short accelerator section fill time. If we can compress with nearly 100-percent efficiency, we can increase peak power without increasing average power.

To produce the unloaded 21-MV/m SLC gradient, which requires 160-MW peak power, SLAC uses a compression system SLED [4] which compresses a 50-MW, 5-μs klystron pulse into an effective 160-MW, 0.82-μs pulse. (The fill time of the SLAC accelerator section is 0.82 μs.) SLED has the following shortcomings. Its maximum efficiency of 81 percent can only be reached at a compression ratio of about 3:1, and it drops off sharply if the compression ratio either decreases or increases. Moreover, the com-

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pressed pulse varies with time, which reduces the efficiency when it is used as the power input to an accelerator section. With the binary power multiplier (BPM), we have a rectangular (flat) output pulse, and if we reduce dissipation we can approach 100-percent efficiency. In its high-power portion, the BPM has only delay lines and 3-dB couplers which are capable of carrying very high peak power. The 3-dB sidewall couplers tested at SLAC at 2856 MHz did not break down at peak power levels in excess of 500 MW.

II. General Description of the BPM

The binary power multiplier (BPM) includes a front-end, a pair of high-power amplifiers (klystrons), and one or more compression stages. Refer to Fig. 1. The front-end consists of a power splitter and two biphase modulators, which code the klystron inputs in time bins equal to the final compressed pulse length with either zero or 180° phase shift. The phase changes must occur in an interval short compared to the compressed pulse length. The klystron outputs are connected to one or more pulse compression stages. Each stage consists of a 3-dB hybrid with one output port connected to a delay line whose delay is half the input pulse length and the other output port connected to zero delay transmission line. Each stage converts its two coded inputs into two outputs whose power amplitudes are twice those of the two input amplitudes, and are appropriately coded for the next stage. An n-stage BPM starts with two klystron pulses of unity power amplitude and 2^n duration in units of the compressed pulse length, and ends up with two pulses of 2^n power amplitude and unity pulse length, assuming lossless delay lines. The active control elements of the BPM, the biphase modulators that do the coding, operate at low power, and only passive devices are needed in the high-power portion of the BPM. The BPM can also transform a continuous wave input into a train of pulses, although the output duty cycle is constrained to discrete values (powers of 2).

III. Single-Stage BPM

Because of its simplicity, we explain first the operation of a single-stage BPM, which consists of a front-end and a single compression stage, as shown in Fig. 1. The low-level output of a single source is divided by the 3-dB coupler H_i to drive two high-power klystrons, K_a and K_b. Each pulse duration is determined by the klystron modulators M_a and M_b and is set to twice the compressed pulse length. The biphase modulator ϕ_b codes the two klystron outputs as shown in (b) and (d) of Fig. 1. Here, a plus sign indicates zero phase and a minus sign indicates a phase shift of 180°. Time is in units of the compressed output pulse length. The function of the phase shifter ϕ_v (not coded) is to ensure that the klystron outputs are precisely in phase or 180° out of phase. The two klystron outputs are connected to the two inputs of the 3-dB coupler H. The properties of the 3-dB hybrid (with properly chosen reference planes) are such that if the phase between the two

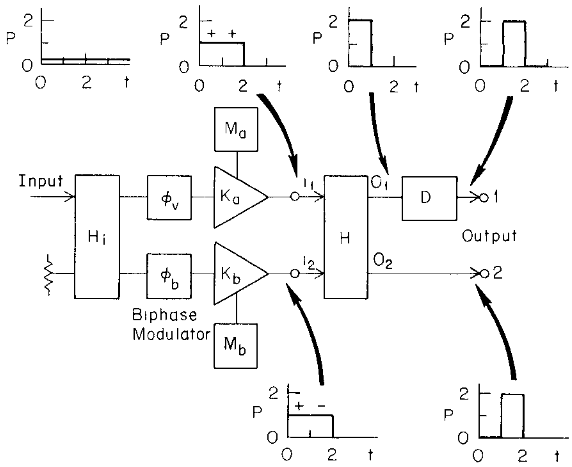

Fig. 1. Diagram of a single-stage BPM.

inputs is zero the combined power appears at terminal O_1, and when the phase is 180° the combined power appears at O_2. Terminal O_1 of the hybrid H is connected to the delay line D, whose time delay is the compressed pulse length. After a time interval equal to one half the input pulse duration, the phase shift of biphase modulator ϕ_b is changed by 180°. As a consequence, during the second half of the input pulse, the combined output of the two klystrons exits terminal O_2 of the hybrid. As the RF at terminal O_1 is delayed by half the pulse duration, the two outputs appear simultaneously at the two outputs of the BPM. The two klystron pulses are transformed into two output pulses; the duration of each pulse is one-half and the peak power is double the output of a single klystron.

IV. Multiple-Stage BPM

To obtain 2^n power multiplication, we place n stages in tandem and form an n-stage BPM. The delay of the ith stage delay line is $2^{n-i}T_f$. T_f is the output pulse duration and $i = 1, 2, 3, \cdots, n$. The input pulse length is $2^n T_f$.

To set the stage for the explanation of a multistage BPM, we digress and discuss the 3-dB hybrid in more detail. We arbitrarily designate two isolated ports of the hybrid as input ports, and the other pair as output ports. The properties of the hybrid are such that if power is supplied to input 1 the phase of the RF is the same at both output ports, and if power is supplied to input 2 the phases of the RF at the two outputs are opposite. Using superposition, we derive from the above properties the following rules.

1) If both inputs are supplied with power of equal amplitude and the same phase, then the combined input power exits output 1.

2) If both inputs are supplied with power of equal amplitude and opposite phase, the combined input power exits output 2.

3) The power exiting either output has the same phase as the power supplied to input 1.

Applying the above hybrid properties, we have the following input coding for any stage.

Stage	1																2								3				4		0
Input 1	+	+	+	−	+	+	−	+	+	+	+	−	−	−	+	−	+	+	+	−	+	+	−	+	+	+	+	−	+	+	+
Input 2	+	+	+	−	+	+	−	+	−	−	−	+	+	+	−	+	+	+	+	−	−	−	+	−	+	+	−	+	+	−	+

Fig 2 Coding for a four-stage BPM input stage and resultant coding at each stage input.

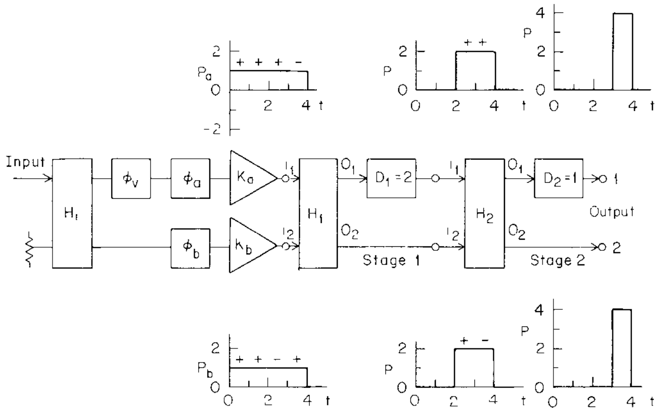

Fig. 3. Diagram of a two-stage BPM

1) Input 1 coding is the same as that of input 1 of the following stage during the first half of the pulse and is the same as the coding of input 2 of the following stage during the second half of the pulse.

2) Input 2 coding is identical to that of input 1 during the first half of the pulse and is opposite during the second half of the pulse.

Since we know the input to the last stage, we can work backward and determine the input coding for a multistage BPM. This is illustrated in Fig. 2, which shows the coding at each stage input of a four-stage BPM. Plus signs indicate zero phase and minus signs 180°. Each phase lasts for a duration T_f.

A two-stage BPM is shown in Fig. 3. A biphase modulator ϕ_a and an additional stage have been added to the single-stage BPM of Fig. 1.

Clearly, if we operate at low power, the klystrons are not necessary. If we combine the two outputs of the last stage, we have a single input pulse and a single compressed output pulse.

V. Compression Efficiency

The discussion in terms of power multiplication by 2^n is based on the assumption that the dissipation losses are zero. Nearly zero dissipation is possible with short pulses and even with long pulses if the delay lines and couplers are superconducting or if they operate in the circular TE_{01} mode. But in general each delay line causes some attenuation, so that the power multiplication factor M_i for the ith stage is not 2, but rather

$$M_i = 1 + e^{-2\tau_i}, \qquad \tau_i = 2^{n-i} T_f \alpha_i \tag{1}$$

where τ_i is the attenuation, in nepers, of the ith stage delay line, T_f is the duration of the output pulse, and α_i is the attenuation in nepers per unit time delay.

The multiplication factor M, the ratio of the BPM output to input peak power amplitude, is the product of the multiplication factors of the individual stages

$$M = \prod_{i=1}^{n} \left(1 + e^{-2\tau_i}\right). \tag{2}$$

The compression efficiency is

$$\eta_{pc} = \frac{M}{2^n}. \tag{3}$$

If the BPM is used to increase the peak power into an accelerator section, then the compressed pulse length is made equal to the section fill time. To account for the unequal powers into the two accelerator sections, the expression for the power multiplication factor of the last stage is slightly modified and is given by

$$M_l = \frac{\left(1 + e^{-\tau_f}\right)^2}{2}. \tag{4}$$

Here, τ_f is the attenuation of the last stage delay line. For small attenuation, this reduces to the previous expression for a single-stage power multiplication:

$$M_l = 1 + e^{-2\tau_f} \approx 2(1 + \tau_f).$$

The attenuation is proportional to the time delay; therefore, to obtain high efficiencies for large compression factors or for long compressed pulses, we must have delay lines with low attenuation per unit time delay.

VI. Delay Line Design

The delay lines can be sections of loaded or unloaded waveguides. For either loaded or unloaded guide the attenuation in nepers per unit time delay $\alpha_t = p_d/2w$. Here, p_d is the power dissipated per unit length and w is the energy stored per unit length. The total attenuation for a section with a time delay T_d is $\tau_d = \alpha_t T_d$. The attenuation per unit time delay is the attenuation per unit length multiplied by the group velocity.

A smooth waveguide delay line is preferred because its attenuation per unit time delay is less than that of the same diameter loaded line. The smooth line has the additional advantages that it is easier to manufacture, is easier to cool (especially important if the line is superconducting), has wider bandwidth and, hence, better step response, and is characterized by a lower field for a given transmitted power.

The dissipation by a guide operating in the circular TE_{01} mode decreases as the frequency increases, and can approach negligible loss. Low-loss couplers are also available in this mode. Round guides operating in the TE_{11} mode have the smallest diameter at a given frequency. For the above reasons, we examine the TE_{11} and TE_{01} modes in round pipes. Their attenuations per unit time delay are, for TE_{11}

$$\alpha_t = \frac{R_s c}{a\eta}\left[\left(\frac{\lambda}{\lambda_c}\right)^2 + 0.419\right] \tag{5}$$

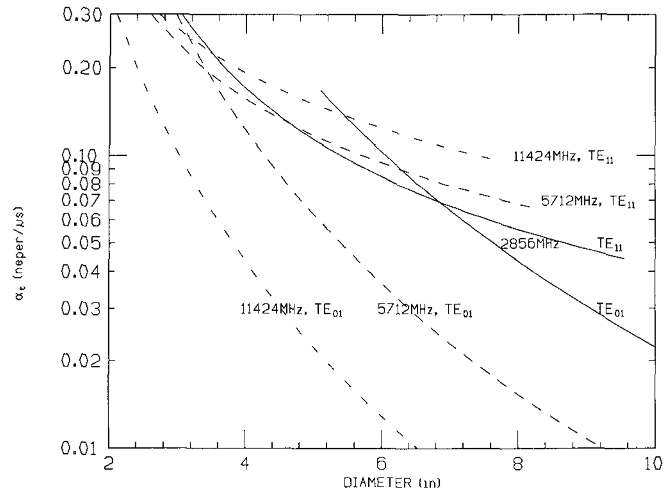

Fig. 4. TE_{11} and TE_{01} attenuation as a function of diameter.

and for TE_{01}

$$\alpha_t = \frac{R_s c}{a\eta}\left(\frac{\lambda}{\lambda_c}\right)^2. \tag{6}$$

Here, c is the velocity of light, a is the radius, and η is the free-space impedance. For a copper pipe $R_s = 0.0261\sqrt{f}$ and the attenuations, in Np per μs, in a guide of diameter D (cm) operating at a frequency f (MHz) for the indicated modes are, for TE_{11}

$$\alpha_t = \frac{0.0414\sqrt{f}}{D}\left[\frac{3.09\times10^8}{D^2 f^2}+0.419\right] \tag{7}$$

and for TE_{01}

$$\alpha_t = \frac{5.56\times10^7}{D^3 f^{3/2}}. \tag{8}$$

Plots of α_t as a function of diameter for several frequencies are shown in Fig. 4. Because we are interested in delay line attenuation, it is given in nepers per microsecond rather than in nepers per meter. The attenuation is plotted versus guide diameter (rather than the more usual frequency) at several frequencies which represent present and contemplated accelerator operating frequencies. For $\tau \ll 1$, the multiplication factor is $2(1-\tau)$ and the efficiency is $1-\tau$. As $\tau = \alpha_t T_d$, we can estimate from these plots the reduction of the multiplication factor and of the efficiency due to attenuation.

However, a 1-μs smooth delay line is 300 m long. We overcome this problem by folding the line to make it compact. Fig. 5 is a plan schematic illustrating the design of two BPM stages using folded delay lines. The side-coupled hybrids H_1 and H_2 and their input and output designations correspond to the hybrids H_1 and H_2 of Fig. 3. The realization of the folded lines exploits the property of the hybrid that if the two output ports are shorted, the power into the first input port exits the second input port traveling in the opposite direction. This is shown symbolically as heavy curved arrows through the coupling apertures of the hybrids used to effect such reversal of direction. The direction of power flow in two adjacent lines can also be reversed by using a cavity to couple power between the two lines. The particular configuration of Fig. 5 indicates that the assembly could be put in commercially available vertical cryostats.

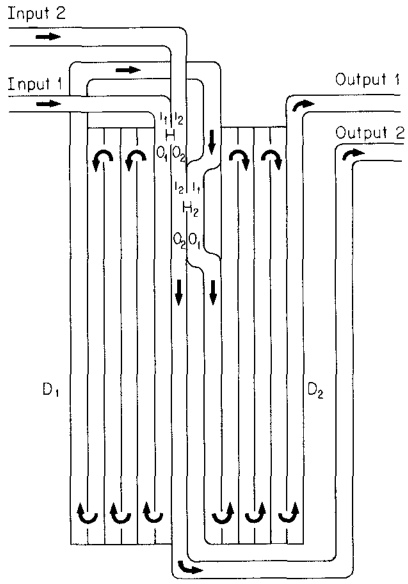

Fig 5. Two BPM stages using folded delay lines

The delay lines can be shortened by loading the guide. A TE_{01} loaded line is most suitable because it carries no axial current and, therefore, has the lowest attenuation per unit time delay. It is also easy to manufacture. Still, a smooth line has even lower attenuation. At 2856 MHz, for example, a low group velocity delay line made of 5.4-in diameter TE_{01} coupled cavities has an $\alpha_t = 0.163$ Np/μs. A smooth guide with the same diameter operating in the TE_{11} mode has $\alpha_t = 0.1$ Np/μs. Thus, lightly loaded TE_{01} delay lines seem to be a good compromise.

In addition to power lost by delay line dissipation, there is residual power loss because only when the two input powers to the hybrid are equal is it possible to adjust the phase between the two inputs so that all power exits one output with zero residual power at the other output. Fortunately, as will be shown, the ratio of residual power to power lost by delay line dissipation is itself proportional to dissipation loss. Since the delay line loss must be kept low in any case, the reduction in compression efficiency due to residual power loss is insignificant.

Consider the effect when the powers at the inputs of a hybrid coupler are unequal. Let the output to input power ratio of the delay line preceding input 1 of a hybrid be f^2. Consequently, the power to input 1 of that hybrid is f^2 times less than the power into its input 2. With no loss in generality, it may be assumed that the power at input 1 is f^2 and at input 2 is unity. Also, assume that the coupling is C. If the phase is adjusted for maximum power at output 1, the two output powers P_{o1} and P_{o2} are

$$P_{o1} = \left(f\sqrt{1-C^2}+C\right)^2 \quad P_{o2} = \left(fC-\sqrt{1-C^2}\right)^2. \tag{9}$$

For all power f^2+1 to exit output 1 with no power at output 2 requires

$$C^2 = \frac{1}{1+f^2}. \quad (10)$$

If the phase is adjusted for maximum power at output 2, the two output powers are

$$P_{o1} = \left(f\sqrt{1-C^2} - C\right)^2 \quad P_{o2} = \left(fC + \sqrt{1-C^2}\right)^2. \quad (11)$$

For all power f^2+1 to exit output 2 with no power at output 1 requires

$$C^2 = \frac{f^2}{1+f^2}. \quad (12)$$

For equal power inputs ($f^2=1$), both conditions are satisfied in $C^2=1/2$; that is, the coupling is 3 dB, and all power exits one output.

With unequal power inputs, there is no value of coupling that can satisfy both conditions. While it is possible to choose a coupling that causes all powers to exit one output only, this coupling will not permit all power to exit the other output. Since the BPM ideally requires that all power be directed to either output, it is impossible to adjust the coupling to accommodate unequal power inputs.

Fortunately, the power ratio f^2 is close to 1, since the delay attenuation is required to be low. Therefore, a coupling of 3 dB is nearly ideal; that is, the residual power is small compared to delay line dissipation, and its effect on compression efficiency is small. For 3-dB coupling ($C^2 = 1/2$), the fractional residual power p_{or} at either output is

$$p_{or} = \left[\frac{f}{\sqrt{2}} - \frac{1}{\sqrt{2}}\right]^2. \quad (13)$$

Let the fractional power loss by delay line dissipation be δ, so that $f^2 = 1-\delta$. Substituting $\sqrt{1-\delta}$ for f, we have

$$p_{or} = 1 - \frac{\delta}{2} - \sqrt{1-\delta}. \quad (14)$$

For $\lambda \ll 1$, this reduces to $p_{or} = \delta^2/8$, which is of second order in δ. The ratio of the residual to dissipation power is therefore $\delta/8$. For example, for a 1-dB delay line attenuation, $\delta = 0.26$, and the residual power is only 1/24 of the dissipation power.

VII. Accelerator Design Using Pulse Compression

Before comparing systems, we will derive the expressions for the system parameters when pulse compression is used. The energy required to reach an average accelerating gradient E_a in a lossless section [5] is

$$U_{as} = \frac{E_a^2 L}{s}. \quad (15)$$

Here, L is the length of the section, and s is the elastance per unit length. The klystron energy is this ideal energy divided by the RF-to-accelerating-energy conversion efficiency η_{rf}, which in turn is the product of the section efficiency η_s, the transmission-line efficiency η_t, and the compression efficiency η_{pc}. The peak power P_{pk} and average power P_{ak} required to produce E_a are

$$P_{pk} = \frac{E_a^2 L}{s\eta_s\eta_t\eta_{pc}C_f T_f} \quad P_{ak} = f_r \frac{E_a^2 L}{s\eta_s\eta_t\eta_{pc}}. \quad (16)$$

Here, n_s is the number of sections per klystron, f_r is the pulse repetition rate, and C_f is the compression factor. The power multiplication factor $M = \eta_{pc}C_f$, and the section efficiency η_s for a constant impedance section is

$$\eta_s = \frac{(1-e^{-\tau})^2}{\tau^2}. \quad (17)$$

The section attenuation in nepers τ and the section fill time (also compressed pulse length) T_f [6] are

$$\tau = \frac{T_f}{T_0} \quad T_f = \frac{L}{v_g} \quad (18)$$

where v_g is the group velocity and T_0 is the unloaded (internal) time constant. The values of s, v_g, and T_0, the three parameters that characterize a traveling-wave accelerator section, can be obtained from such computer codes as URMEL [7] and TWAP [8]. They are defined by

$$s = \frac{E^2}{w} \quad v_g = \frac{P}{w} \quad T_0 = \frac{2w}{p_d} \quad (19)$$

where E is the accelerating gradient, w is the energy stored per unit length, P is the power transmitted, and p_d is the power dissipated per unit length. In general, these parameters are functions of distance along the section (α_t, which has already been defined in connection with BPM delay lines, is the reciprocal of T_0). Since linear dimensions vary in inverse proportion to frequency f, we infer from the above definitions that for the same group velocity and same mode

$$s \propto f^2 \quad \text{and} \quad T_0 \propto f^{-3/2}. \quad (20)$$

For a structure of a given material, η_s depends only on T_f. The value of η_{pc} depends on T_f and on the compression factor $C_f = T_k/T_f$, where T_k is the klystron pulse length.

For a given T_0, both η_s and the product $\eta_s T_f$ in (16) are functions of T_f only. The product $\eta_s T_f$ as a function of T_f starts at zero and reaches a broad maximum when $T_f = 1.257T_0$, while η_s starts at unity and decreases as T_f increases. Therefore, for a given gradient, section length, and T_0, with no pulse compression, both peak and average powers depend on section fill time only. The average power decreases and approaches a minimum, and the peak power increases as we decrease the fill time from its value where the peak power has a broad minimum. This is illustrated in Fig. 6, which shows plots of peak and average powers per section, with and without pulse compression, required to produce a 21-MV/m gradient for a disk-loaded section having SLAC section parameters of $s = 76.4$, $T_0 = 1.44$ μs, $L = 3$ m but allowing T_f to vary. The plotted points correspond to the SLAC section tradeoff T_f of 0.82 μs. With pulse compression, the tradeoff T_f is lower than without pulse compression; hence, for the same length, we

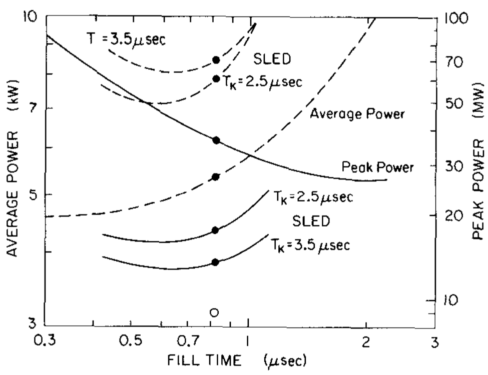

Fig. 6. Peak and average power per section versus fill time, with and without pulse compression.

TABLE I
SYSTEMS TO OBTAIN 21-MV/m GRADIENT AT SLAC

SYSTEM	M	η_{pc}	η_{rf}	U_k VA	T_k μs	P_{pk} MW	P_{ak} kW	η_{ar}	P_m kW	P_{act} MW
NO PC	1	1	.532	130	.82	159	23.4	179	131	31.5
SLED	3.18	.52	.277	250	5.0	50	45.1	.332	136	32.5
1 STAGE BPM	1.8	.9	.532	145	1.64	88.3	26.1	.247	105	25.3
2 STAGE BPM	3.18	.8	.426	163	3.28	50	29.3	.331	88.4	21.2
3 STAGE BPM	6.4	.8	.543	127	3.28	39	23.0	.331	69.0	16.6
(T_f = 0.41 μs)										

have higher group velocity with the advantage of larger aperture size. With 100-percent efficiency pulse compression, the average power is the same as with no compression, and the peak power is reduced by the compression factor, as shown by the single point in the figure.

The modulator line power P_m is the klystron average RF power P_{ak} divided by the klystron efficiency η_k

$$P_m = \frac{P_{ak}}{\eta_k}, \qquad \eta_k = \frac{0.398T_k}{(T_k+1)}, \ T_k \text{ in } \mu s. \tag{21}$$

The above expression for the klystron efficiency is based on measurements at SLAC, but is generally correct. It is the product of the klystron beam to RF efficiency, about 0.5, the modulator efficiency, about 0.8, and the efficiency due to beam pulse rise time, $T_k/(T_k+1)$. If we do not consider any other ac losses, such as klystron focus coil power or refrigerator power when superconducting, then the ac to RF conversion efficiency is $\eta_{ar} = \eta_k$.

Using the above expressions, we obtain the power requirements of several systems to drive the SLAC Linear Collider. Because of practical considerations, such as loss in the arcs, the required beam energy is 66 GeV rather than the 50-GeV center of mass design energy, and the required gradient $E_a = 21$ MV/m. The following parameters are used: $s = 76.4$ V/pC-m, $T_f = 0.82$ μs, $L_s = 3$ m, $\eta_t = 0.891$. There are 240 klystrons, and each klystron drives four sections. A $f_r = 180$ pulses per second (pps) is assumed. The values are listed in Table I.

The first line of Table I is the system presently used at SLAC and is the benchmark design to which the other systems will be compared. The second line of Table I shows that with no pulse compression the RF efficiency increases, but because the ac to RF efficiency is reduced, the improvement in ac efficiency is not significant. Moreover, with no pulse compression, there is no option of also operating with a long beam pulse. There is even a better reason why SLAC uses pulse compression: 159-MW klystrons do not exist. The systems with one-, two-, and three-stage BPM's require, respectively, 7, 11, and 15 MW less ac power. They save klystron average power as well, and because the klystrons are average power limited, they permit higher pulse repetition rates. The last line in Table I is a three-stage BPM with a compressed pulse equal to a shorter fill time of 0.41 μs. It illustrates that for a given klystron pulse length the advantage of BPM over SLED becomes more pronounced as the compressed pulse gets shorter. The listed compression efficiencies assume 6-in-diameter TE_{11} delay lines.

VIII. ACCELERATOR DESIGN USING BPM WITH SUPERCONDUCTING DELAY LINES

With SLED, we can nearly eliminate the reduction in efficiency due to dissipation loss by making the internal time constant of the energy-storing cavities large compared with the pulse length. But we cannot eliminate the reduction in efficiency due to reflections and the exponential pulse shape. Moreover, the compression efficiency drops off rapidly as we deviate from a compression factor of about 3. In contrast to the low-attenuation delay line, the BPM compression efficiency is essentially 100 percent. We can make the attenuation effectively zero even for long pulses by making the delay line out of superconducting material.

But, in calculating the ac to RF conversion efficiency, we must include the power required by the refrigerator

$$P_{rd} = \frac{2\alpha_t T_d R_f}{I_f} P_{ak}. \tag{22}$$

Here, α_t is the attenuation per μs of a copper delay line, T_d is the total time delay, R_f is the refrigeration factor, and I_f is the improvement factor [9]. The total ac power is

$$P_{ac} = P_m + P_{rd} = P_m\left(1 + \frac{2\alpha_t T_d R_f \eta_k}{I_f}\right). \tag{23}$$

The ac to RF conversion efficiency when refrigerator power is taken into account is

$$\eta_{ar} = \frac{P_{ak}}{P_{ac}} = \frac{\eta_k}{1 + \dfrac{2\alpha_t T_d R_f \eta_k}{I_f}}. \tag{24}$$

Two systems, one with a two-stage and the other with a three-stage BPM, both using superconducting delay lines, are illustrated in Table II. We assume lead or niobium delay lines at 4.2K with $R_f = 1000$ and $I_f = 4000$. We have obtained under various experimental conditions fields which would correspond to gigawatt delay line power levels [9]. Work is being done in Europe to coat niobium

TABLE II
SYSTEMS TO OBTAIN 21-MV/m GRADIENT AT SLAC USING SUPERCONDUCTING DELAY LINES

SYSTEM	M	η_{rf}	U_k VA	T_k μs	P_{pk} MW	P_{ak} kW	η_{ar}	P_m kW	P_r kW	P_{ac} kW	P_{act} MW
2 STAGE BPM	4	.532	130	3.28	39.8	23.4	.318	70.6	3.32	74	17.8
3 STAGE BPM	8	.532	130	6.56	19.9	23.4	.312	67.7	7.73	75.4	18.1

and niobium–tin on copper. If successful, it will make the use of superconducting delay lines even more attractive. With superconducting delay lines, the BPM requires about 14 MW less ac power than the benchmark system of Table I. Also, it halves klystron average power, and consequently the pulse repetition rate can be doubled. Finally, it permits 0.82 or 1.6 μs beam pulse operation at a reduced gradient of 15 MV/m. With 70-MW, 3.28-μs klystrons, we reach 28 MV/m, an 84-GV (gigavolt) beam. With 50-MW, 6.56-μs klystrons, we reach 33 MV/m, a 100-GV beam with a moderate incremental refrigeration cost and an additional 13 MW of ac power. This is moderate compared to the alternative of adding 360 klystron-modulators and 48 MW of ac power.

IX. THE BPM AT HIGH FREQUENCIES

For the same group velocity and section efficiency, the elastance per unit length varies as the frequency squared; therefore, the peak and average powers vary as the wavelength squared. Thus, increasing the accelerator operating frequency reduces both peak and average powers. The attenuation per unit time delay varies as the 3/2 power of the wavelength. Therefore, to maintain the section efficiency, increasing the frequency by a factor r requires a decrease in the fill time by $r^{3/2}$. Table III lists the system parameters at 4 and 10 times the SLAC frequency. We retain the section attenuation and consequently the fill time $T_f = 0.82/8 = 0.1025$ μs. We can change the fill time by changing either the length, the group velocity, or both. The first line retains the group velocity, the second the length, and the third the aperture radius a of the 2856-MHz SLAC accelerator section. If we keep the group velocity, both average and peak powers decrease by r^2. The undesired consequences are very short sections and a factor r reduction in aperture size. If we keep the length, then the group velocity decreases by r. If s were independent of v_g, then it would increase by r^2, the peak power would be reduced by r, and the average power would be reduced by r^2. But since s decreases as v_g increases, the reduction in peak and average power is less than indicated above. The local section parameters were obtained using the computer code URMEL [7]. Since the group velocity approaches the particle velocity (the section need not be completely filled when the particle is injected), T_k is less then T_f in lines 2 and 3. The SLC peak and average powers per unit length are 4.2 MW/m and 3.8 kW/m, respectively. Although it is contemplated that high-particle energy linear colliders will operate at much higher gradients than the 21-MV/m SLC gradient, we retained it to facilitate comparison with the 2856-MHz parameters.

TABLE III
SYSTEMS TO OBTAIN 21-MV/m GRADIENT AT HIGH FREQUENCIES

Same	v_g m/μs	a cm	L_s m	s V/pC-m	U_k VA	T_k μs	P_{pk} MW	P_{ak} kW	p_{pk} MW/m	p_{ak} kW/m
$f = 11424$ MHz										
v_g	3.50	.290	.36	1222	.224	.102	2.19	.040	6.08	.111
L	29.4	.494	3	831	2.45	.092	26.7	.444	8.9	.148
a	90.0	1.16	9.84	267	26.0	.070	371	1.82	37.7	.185
$f = 28560$ MHz										
v_g	3.50	.116	.095	76400	.009	.026	.359	.001	3.75	.011

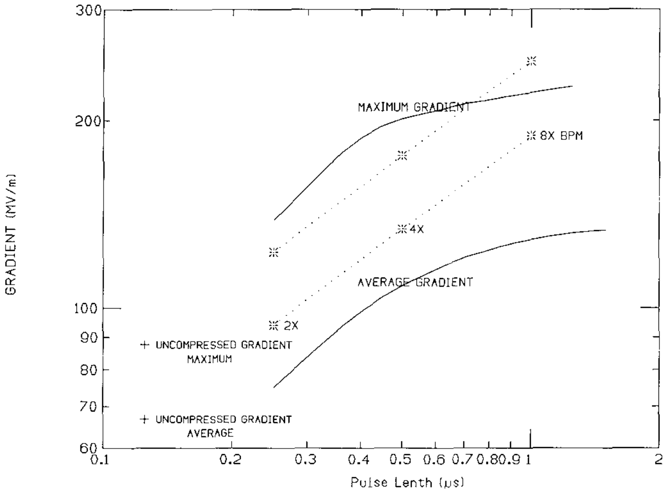

Fig. 7. Gradient versus uncompressed pulse length.

For the same accelerator section efficiency, increasing the frequency by r decreases α_t by $r^{-3/2}$. As the delay line time delay is proportional to fill time, it also decreases by $r^{3/2}$. But with the delay line, we have the freedom to increase the diameter and also to operate in the TE_{01} mode considerably above cutoff, where at high frequencies we can have negligible loss even with a small-diameter pipe. Couplers operating in this mode are available. Thus, in the millimeter-wave region we can obtain nearly ideal peak power multiplication with a BPM using copper delay lines. For example, at $4 \times 2856 = 11\,424$ MHz, the attenuation is 0.05 Np/μs, as indicated in Fig. 6.

Increasing the frequency tenfold, to 28 560 MHz, results in the parameters shown in the last line of Table III. Because of the short length per feed, we have one source feeding ten sections. The power fed to each section can be transmitted via an overmoded circular TE_{01} guide. The required multiplication factor is peak power divided by source peak power. Using a 100-kW, 0.83-μs source and a five-stage BPM, we obtain a 21-MV/m gradient. The longest required time delay is 0.41 μs. Since 100-kW CW amplifiers are available at this frequency and, as noted previously, the BPM can transform CW power into a train of pulses, with 100-kW amplifiers, we can increase the pulse repetition rate to 30 000 pps.

Using 3 sections, an average RF power of 3.36 kW/m (about the same as currently required to attain the 21 MV/m for the Stanford Linear Collider) and the 38-MW, 1.6-μs gyroklystron currently being developed [10] in conjunction with a four-stage ($\times 16$) BPM, we obtain a gradient of 100 MV/m. The gradients versus pulse length attainable with 30-MW power into a SLAC section scaled to 10 GHz ($T_f = 0.125$ μs, $L = 0.46$ m with SLED and with the BPM) are shown in Fig. 7.

While microwave frequencies were emphasized, the BPM can be implemented at any frequency (such as optical) where hybrids, delay lines, biphase modulators, and amplifiers are available.

X. Conclusions

To produce the high-gradient accelerators for future linear colliders requires hundreds of megawatts of peak power per unit length of structure. Pulse compression is a promising technique to reduce the capital cost per unit peak power by an order of magnitude. It matches the section fill time, which turns out to be fractions of a microsecond, to the typical modulator pulse lengths of several microseconds. The pulse compression system (SLED) presently used at SLAC provides a modest compression ratio at an efficiency of the order of 50 percent. The SLED system is being used at the European Center for Nuclear Research, Geneva, Switzerland, at the Deutsches Electronon-Synchrotron DESY, Hamburg, Germany, and at the Institute of High Energy Physics, Beijing, China. However, future linear colliders require more efficient pulse compression and much greater compression ratios. Moreover, in order to reduce the average power costs, the necessity of shorter wavelengths, where high peak power sources are scarce, is indicated. A program to produce a prototype BPM at a wavelength of 2.6 cm is under way at SLAC. Experimental results should be available in the near future, and will be submitted to this transactions. It has been shown that practical BPM designs at high frequencies that yield large compression ratios at nearly 100-percent efficiency are possible. Thus, the BPM appears to have the potential to become a major application in the production of high peak power for future linear colliders.

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