SLAC-PUB-2689
February 1981
(A)

CONF-810310-...

MASTER

PROSPECTS FOR VERY-HIGH-GRADIENT LINAC-COLLIDERS*

P. B. Wilson
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Abstract

The energy realistically attainable by an electron-positron storage ring is limited by the RF voltage and power requirements imposed by synchrotron radiation to about 100 GeV. To reach energies of 300 × 300 GeV and higher in a colliding beam machine of reasonable dimensions, we must look to the linac-collider operating at an energy gradient on the order of 100 MV/m. Proper choice of an RF structure for such a collider can minimize the total RF power requirement and the effects of longitudinal and transverse single-bunch beam loading. For an operating frequency in the range 4-6 GHz, the total RF power requirement for a 300 × 300 GeV collider with a luminosity of 10^{32} $cm^{-2}s^{-1}$ accelerating 10^{11} particles per bunch is on the order of 50 MW. To drive this collider, RF power sources are needed having a peak output power in the range 1-2 GW. Possibilities for attaining these peak power levels by direct generation and by energy storage and fast switching are discussed.

Need for High Gradient Linac-Colliders

If we consider the sequence of e^+e^- storage rings SPEAR/DORIS - PEP/PETRA - LEP, we find rough agreement with the following scaling laws with respect to energy E_0: circumference ~ E_0^2, RF power requirement (conventional RF systems) ~ E_0^2, cost ~ $E_0^{1.5}$. We can also define an average gradient E_{av} as the center-of-mass energy divided by the ring circumference. This gradient, which is a measure of how much real estate is required per unit of energy, scales as E_{av} ~ E_0^{-1}. If we use these laws to extrapolate to a 300 × 300 GeV machine, we find that the circumference would be about 300 km, the RF power requirement about 1 GW, the cost about 5 billion dollars and the average gradient about 2 MV/m. A superconducting or pulsed RF system could undoubtedly be used to reduce the RF power, but the cost and the voracious appetite for real estate of such a high-energy ring would remain as nearly insurmountable obstacles to its construction. If we are to collide electrons and positrons at an energy much beyond that foreseen for LEP (130 GeV with superconducting RF), we must turn to the concept of two opposing high gradient linear accelerators firing single bunches of electrons and positrons at each other: the linac-collider.

Rough Parameters for a 300 × 300 GeV Linac-Collider

We choose a gradient of 100 MV/m as being realistically attainable in a properly designed accelerating structure for short RF pulses (< 500 ns) at S-band frequencies or higher. A discussion of breakdown limits in RF structures and a justification of this choice of accelerating gradient is presented in a later section. The luminosity for a collider accelerating single bunches is given by

$$\mathscr{L} = \frac{N_b^2 f_r}{4\pi\sigma_x^*\sigma_y^*} \quad ,$$

where N_b is the number of particles per bunch, f_r is the repetition rate and σ_x^* and σ_y^* are the transverse beam dimensions at the collision point. Table I gives a consistent set of parameters for a 300 × 300 GeV collider with a luminosity of 10^{32} $cm^{-2}s^{-1}$. The disruption parameter and beamstrahlung parameter listed in

TABLE I

Parameters for a 300 × 300 GeV Collider

Accelerating Gradient	100	MV/m
Length (both linacs)	6	km
Luminosity	10^{32}	$cm^{-2}s^{-1}$
Particles per Bunch N_b	10^{11}	
Repetition Rate f_r	200	Hz
Beam Dimensions σ_x^*, σ_y^*	0.7	μm
Beta Function at Collision Point β^*	1	cm
Bunch Length σ_z	1	mm
Disruption Parameter D	0.95	
Beamstrahlung Parameter δ	0.05	
Average Current eN_bf_r	5	μA
Average Beam Power (both linacs)	3	MW

the above Table are defined and discussed elsewhere.[1-3] Very briefly, D is a measure of the fractional change in radial position of a typical particle in one bunch during its passage through the electromagnetic fields of the opposing bunch. D is proportional to $N_b\sigma_z/\beta^*$. For D the order of unity or larger, a pinch effect squeezes the bunches radially, enhancing the luminosity. For D = 0.95, this enhancement factor is a little over three.[2] The beamstrahlung parameter is the fractional energy loss due to synchrotron radiation produced by the particles in one bunch passing through the deflecting fields of the opposing bunch. At a given energy, δ ~ $N_b^2/\sigma_z\beta^*$. Many trade-offs between these parameters are possible for a fixed luminosity. For example, δ can be increased by lengthening the bunch, or by decreasing the charge per bunch and increasing the repetition rate to maintain the luminosity. It is important to realize that the single-bunch parameters N_b and σ_z, the beam-beam parameters $\mathscr{L}$, D and δ, the final-focus parameter β^* and the repetition rate f_r are all interrelated. The average power requirement, of course, is proportional to f_r. Later we will see that the energy spread due to single-bunch beam loading and the efficiency for the transfer of energy from the accelerating fields to the beam also depend upon N_b and σ_z. Thus Table I should not be considered an optimized parameter list. It is a possible starting point for a collider design that will serve to give us a feeling for the numbers involved.

In order to attain a gradient of 100 MV/m, both an appropriate accelerating structure and an adequate RF power source are needed. We consider the structure problem first. Once the structure design is chosen, the RF power requirement is also specified. In the concluding sections, present and future RF sources which might meet this requirement are considered.

Structure Parameters

We must first dispose of the question of traveling wave vs standing wave structures. For a standing wave structure, there is an unavoidable loss in efficiency due to reflected power during filling. For an unmodulated (flat-top) incident klystron pulse, the best one can do is to transfer 81% of the energy in the pulse into energy stored in the structure.[4] Furthermore, the parameter r/Q which, as will be shown later, determines the efficiency for conversion of stored energy into accelerating gradient, is usually lower for standing wave structures. For these reasons we consider only traveling wave structures here, although a parallel analysis could readily be made for the standing wave case. Following are some traveling wave structure parameters which are important for the design of a collider.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

(Invited paper presented at the 1981 Particle Accelerator Conference, Washington, D.C., March 11-13, 1981.)

Filling Time $T_f = L_s/v_g$, where L_s is the structure length per feed and v_g is the group velocity.

Attenuation Parameter $\tau = \omega L_s/2v_gQ = T_f/T_{f0}$, where ω is the RF angular frequency, Q is the unloaded Q of a shorted resonant section of structure and $T_{f0} = 2Q/\omega$ is the unloaded filling time of such a shorted section. Note that τ scales with frequency as $\omega^{3/2}$.

Shunt Impedance per Unit Length r. The accelerating gradient E_a at any point in the structure is related to the power dissipation per unit length in the walls of the structure by $E_a = r\, dP/dz$. Since E_a will vary over the structure length, we can define an average gradient $\bar{E}_a = V_s/L_s$, where V_s is the voltage gained in length L_s. In terms of the peak klystron power $\hat{P}_k$, we have

$$\bar{E}_a^2 = r\frac{\hat{P}_k}{L_s} f(\tau)$$

$$f(\tau) = (2/\tau)(1-e^{-\tau})^2 \approx 2\tau(1-\tau+\tau^2/2) \quad .$$

Note that r varies with frequency as $r \sim \omega^{1/2}$.

The Parameter k_0. defined by $E_a^2 = 4k_0w_s$ where w_s is the stored energy per unit length. k_0 is related to the ratio r/Q by $k_0 = (\omega/4)(r/Q)$. It has units of V/C/m or Ω/s/m. The average gradient over length L_s is

$$\bar{E}_a^2 = 4k_0 w_k \eta_s$$

$$\eta_s = (1-e^{-\tau})^2/\tau^2 = f(\tau)/2\tau$$

where w_k is the energy in the klystron pulse per unit length and η_s is the structure efficiency. k_0 has a strong dependence on frequency: $k_0 \sim \omega^2$. We can define a normalized peak power per unit length by $P_n = \hat{P}_k/(L_s r\bar{E}_a^2) = 1/f(\tau)$. The functions P_n and η_s are plotted in Fig. 1. The figure shows the incompatibility between minimum peak power requirement and good structure efficiency. The best compromise is given by a τ in the range 0.3–0.4.

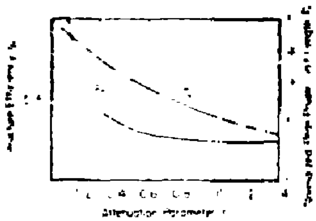

Fig. 1. Structure efficiency and normalized peak power per unit length as a function of the attenuation parameter τ.

The Ratio $\hat{E}_s/E_a$. where $\hat{E}_s$ is the peak electric field on the surface of the structure. The maximum attainable gradient is presumably limited by breakdown effects initiated by electric fields at the surface of the structure. The breakdown field at the surface may be a function of frequency, pulse length and the detailed physical and chemical surface properties. A low ratio $\hat{E}_s/E_a$ is obviously desirable, but may not be the controlling factor. For the SLAC disk-loaded structure, $\hat{E}_s/E_a = 2.1$. This structure has been tested in a traveling wave resonant ring to $E_a = 40$ MV/m without breakdown.[5] The maximum surface field was therefore about 85 MV/m with no breakdown at an effective pulse length on the order of 1 μs. On the other hand, an S-band standing wave side-coupled structure for a medical linac showed breakdown at $\hat{E}_s = 74$ MV/m for a pulse length of 4 to 5 μs.[6] A shorter pulse length appears to be helpful in increasing the breakdown limit, as might be expected. The value of $\hat{E}_s/E_a$ can be lowered to about 1.6 in a disk-loaded structure by proper disk shaping and choice of mode.[7] Still lower values of $\hat{E}_s/E_a$ are possible: a structure has been developed[6] at Varian with $\hat{E}_s/E_a = 1.23$. Note, finally, that the breakdown field should increase with increasing frequency. In view of the preceding facts, a gradient of 100 MV/m does not seem unreasonable for very short pulse lengths, perhaps at a frequency somewhat greater than S-band, assuming also that careful attention is paid to the details of structure geometry.

Higher-Order Modes. Higher-order longitudinal modes are important for single-bunch beam loading. To compute these effects, it is useful to introduce the concept of the wake potential, or wake function. If a point unit charge is sent along the axis of a traveling wave structure, it will interact with all modes having a phase velocity equal to the particle velocity v_e (usually taken as $v_e \approx c$). The strength of the interaction with the n-th mode is characterized by the parameter $k_n = E_n^2/4w_n$, where E_n is the synchronous axial field and w_n the energy per unit length. The total wake field seen at distance ct behind the unit exciting charge can be shown to be[8]

$$w(t) = 2\sum_n k_n \cos\omega_n t \quad ,$$

where ω_n is the angular frequency of the n-th mode. In any practical calculation of the wake function, a finite number of modes are computed and an approximation is made for the very high frequency modes. The wake function computed[8] in this manner for the SLAC disk-loaded structure is shown in Fig. 2.

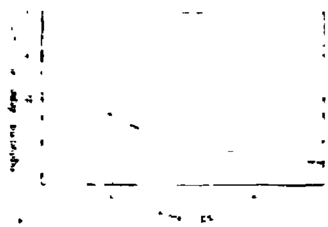

Fig. 2. Longitudinal wake potential per cell for the SLAC disk-loaded structure.

It is important to know how the magnitude of the wake varies as a function of the radius a of the beam aperture. For the SLAC structure (a = 1.16 cm), a computation of the wake for various values of a shows[3] that w(0) varies as $a^{-1.64}$. Of course, the value of k_0 for the fundamental mode will also decrease with increasing a, as shown in Fig. 3. Near a = 1.16, k_0 varies as $a^{-0.66}$. Thus the wake at t = 0 and the corresponding single-bunch beam loading effects decrease faster with increasing beam aperture than does the fundamental mode structure parameter k_0.

The transverse deflection wake must also be considered in the design of a collider.[10] For dipole deflecting modes in a disk-loaded structure, the synchronous E_z field component varies linearly with radius from zero on the axis to E_n at the radius of the beam aperture. For each mode an interaction parameter k_n can be defined as in the longitudinal case using $E_z = E_n$ at r = a. If a unit charge passes through the structure at radius r_1, the deflection wake at a distance ct behind the charge is given by[8]

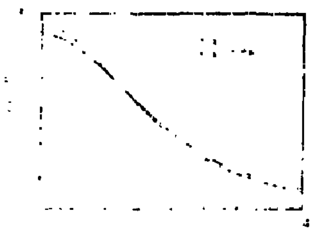

Fig. 3. Structure parameter k_0 as a function of beam aperture radius for a disk-loaded structure for two values of disk thickness t (t/λ = 0.056 for the SLAC structure).

$$w_\perp(\tau) = (2r_\perp c/a^2)\sum_n (k_n/\omega_n)\sin\omega_n\tau \quad .$$

with units of volts per coulomb per meter ($ew_\perp/c$ gives the transverse momentum kick per unit length of travel through the structure). For small τ, the transverse wake increases linearly from zero at $\tau = 0$ with slope $(2r_\perp c/a^2)\sum k_n$. The transverse dipole wake is seen to decrease more rapidly with increasing disk hole radius than the longitudinal wake by an additional factor of a^{-2}. This dependence on a has been varified for the SLAC structure; computations[9] show that the slope of the dipole wake for $\tau = 0$ varies as $a^{-3.44}$.

Promising Structures for Colliders

Several different structures are under investigation at SLAC which might have higher values of r/Q (or k_0) than the disk-loaded structure for a given beam aperture. Some of these structures are described and illustrated in Ref. 11. Of particular interest because of its simplicity and because it has been the subject of the most extensive past measurements is the jungle gym structure (a round pipe loaded by pairs of transverse bars having an alternating vertical and horizontal alignment). The group velocity of the jungle gym structure tends to be considerably higher than for the disk-loaded structure. Typically, $v_g/c \approx 0.20$ for the $\pi/2$ mode (taking the periodic length to be between adjacent bar pairs), and ≈ 0.10 for the $\pi/3$ mode. Table II compares the parameters of several structures at three frequencies of interest for a collider. Values of r, k_0, Q and v_g/c for the $\pi/2$-mode jungle gym are scaled from values measured[12] at 714 MHz for a structure used for several years as an RF cavity in the Cornell synchrotron. Values for the $\pi/3$-mode jungle gym are estimated from some old measurements[13] made at the Stanford University Microwave Laboratory. Some of the newer structures being measured at SLAC appear to give similar values for v_g/c and k_0 for the $\pi/3$ mode.[5] The k_0 for the disk-loaded structure with a = 1.50 is obtained from Fig. 3; v_g/c is scaled as a^4. The disk and washer structure is shown for comparison. Note that, although the Q and shunt impedance are very high, the value of k_0 is very low compared to the jungle gym.

RF Power Requirements for a 300 × 300 GeV Collider

Using the structure parameters given in Table II, the unloaded RF power requirements can be estimated for two 3-km linacs operating at a gradient of 100 MV/m. We assume 1000 RF power sources spaced 6 m apart and a repetition rate of 200 Hz. The first column in Table III gives the klystron (or power source) pulse length, assumed to be equal to the filling time. In the second

TABLE II

Comparison of Structure for a Collider

	r (MΩ/m)	k_0 (V/pC/m)	Q	v_g/c	L_s (m)	T_f (μs)	τ
	2856 MHz						
Disk-Loaded (a = 1.16 cm)	56	19	13,300	.012	3	.83	.57
Disk-Loaded (a = 1.50 cm)	46	16	13,000	.035	6	.57	.40
Disk and Washer	76	11	32,000	—	-	—	—
Jungle Gym (π/2)	51	25	9,000	.20	6	.10	.10
Jungle Gym (π/3)	60	30	9,000	.10	6	.20	.20
	4040 MHz						
Jungle Gym (π/2)	61	50	7,500	.20	6	.10	.18
Jungle Gym (π/3)	71	60	7,500	.10	6	.20	.35
	5712 MHz						
Jungle Gym (π/2)	72	100	6,500	.20	6	.10	.28
Jungle Gym (π/3)	85	120	6,500	.10	6	.20	.57

TABLE III

RF Power Requirements for a 3×3 km Collider with E_a = 100 MV/m

	T_p (μs)	W_k (J)	η_s	$\hat{P}_k$ (MW)	$\bar{P}_k/\bar{P}_{tot}$ (kW)/(MW)
	2856 MHz				
Disk-Loaded (a = 1.16 cm)	.83	1320	.58	1600	270
Disk-Loaded (a = 1.50 cm)	.57	1340	.68	2350	275
Jungle Gym (π/2)	.10	650	.91	6500	130
Jungle Gym (π/3)	.20	620	.82	3100	120
	4040 MHz				
Jungle Gym (π/2)	.10	335	.84	3400	67
Jungle Gym (π/3)	.20	350	.71	1750	70
	5712 MHz				
Jungle Gym (π/2)	.10	190	.76	1900	38
Jungle Gym (π/3)	.20	210	.58	1050	42

column, $W_k = L_s w_k$ is the energy in the klystron pulse. The efficiency for transfer of energy from the RF source pulse to effective stored energy in the structure is η_s. The peak power that each klystron or power source must deliver is $\hat{P}_k$. The last column gives the average power per klystron, $\bar{P}_k$, and the total RF power requirement, $\bar{P}_{tot} = 1000\,\bar{P}_k$. Note the expected correlation between high structure efficiency and high peak power. The last entry in the Table is clearly the most favorable. The total average RF power requirement is less than 50 MW, and the peak power per source is only 1 GW. But is the stored energy adequate to accelerate the required charge per bunch? The energy required by each bunch per klystron is $6eE_aN_b$ = 10J. This is modest compared to the fundamental-mode stored energy of 210J, and would indicate an energy spread due to beam loading on the order of 2½%. However, higher-order modes also contribute to beam loading and to the energy spread. These effects are considered in the next section.

Single-Bunch Beam Loading

An analytic expression which describes the SLAC wake potential to an accuracy of better than a few percent for 0 < τ < 50 ps is

$$w(\tau) = A\exp\left[-(\tau/B)^\alpha\right] \quad ,$$

where A = 7.92 V/pC/cell = 75.5 V/pC/m, B = 6.13 ps and

$n = 0.605$. The contribution to the beam loading voltage at time t due to a charge $dq = I(\tau)d\tau$ at time τ is $w(t-\tau)\,I(\tau)\,d\tau$. The principle of causality for charges traveling close to the velocity of light requires that the wake vanish for $\tau > t$. In computing the beam loading voltage, we need only consider contributions from charge elements that are ahead in the bunch (earlier in time) such that $\tau < t$. Thus the total single-bunch beam loading voltage is

$$E_b(t) = \int_{-\infty}^{t} w(t-\tau)\,I(\tau)\,d\tau \quad .$$

Plots of this expression using the SLAC wake function and a Gaussian bunch $I(t) = \exp\left[-t^2c^2/2\sigma_z^2\right]$ are shown in Fig. 4 for three bunch lengths. Note that the amplitude of the beam loading voltage depends strongly on bunch length, and that peak voltage occurs well behind ($t > 0$) the bunch center.

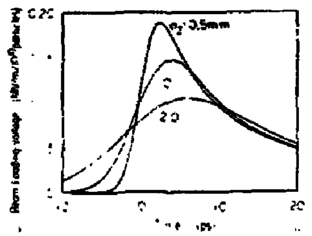

Fig. 4. Single-bunch beam loading voltage for the SLAC disk-loaded structure for three values of bunch length.

The total energy gain per unit length in the presence of an external RF accelerating gradient can be obtained by superposition:

$$E(t) = E_a\left[\cos\,(\omega t - \theta) - E_b(t)/E_a\right] \quad ,$$

where θ is the phase angle of the bunch center with respect to the crest ($\theta > 0$ is ahead of the crest). The average energy gain per particle in a bunch with charge $q = eN_b$ is

$$\bar{E} = \frac{1}{q}\int_{-\infty}^{\infty} E(t)\,I(t)\,dt \quad .$$

The beam efficiency (ratio of energy gained by the beam to the stored energy per unit length) is

$$\eta_b \equiv \frac{q\bar{E}}{w_s} = \frac{4eN_b k_0 \bar{E}}{E_a^2} \sim \frac{\omega^2 N_b}{E_a} \quad .$$

Finally, we must consider the energy spread within the bunch due to single-bunch beam loading. The actual energy distribution function dN/dE can be quite complex, and there is not space to display these functions in detail here. The width of this distribution can be minimized by adjusting the phase angle θ. In Fig. 5 this optimum phase angle is shown as a function of the number of particles per bunch for three bunch lengths and two RF frequencies. The wake for the SLAC disk-loaded structure is again used (this is the only structure that is at present amenable to an analytic calculation of the wake), and an unloaded gradient of 100 MV/m is assumed. The energy spread at the optimum phase angle is shown in Fig. 6. The energy spread is defined such that 90% of the particles are contained within this width. Note that for $N_b = 10^{11}$, the energy spread is less than 2% for all cases except $\sigma_z = 2$ mm at 5712 MHz.

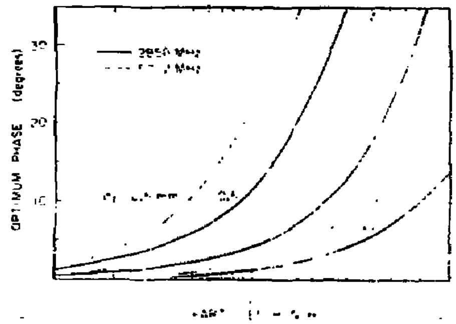

Fig. 5. Phase angle which minimizes the single-bunch beam loading energy spread as a function of particles per bunch for $E_a = 100$ MV/m.

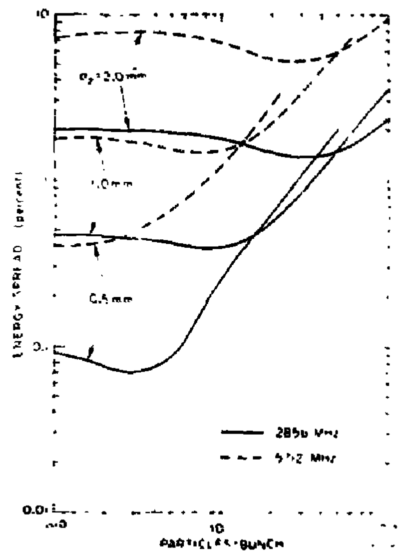

Fig. 6. Minimum energy spread as a function of particles per bunch.

As the number of particles per bunch increases, the phase angle θ increases and the average energy gain per particle will decrease. This is shown in Fig. 7. As $\bar{E}$ falls below about 0.9 E_a, it might be desirable to work with θ closer to the crest and accept an energy spread which is somewhat larger than the minimum. Many such trade-offs are possible which cannot be described in detail here.

Finally, the beam efficiency as a function of particles per bunch is shown in Fig. 8. Because we have chosen a very high gradient, the efficiency is quite low, about 1%, for $N_b = 10^{11}$ at 2856 MHz. The efficiency increases to about 4% at 5712 MHz.

The preceding results are summarized in Table IV for our standard collider conditions: $E_a = 100$ MV/m, $N_b = 10^{11}$, $\sigma_z = 1.0$ mm. A $\pi/3$-mode jungle gym structure is assumed. We can extrapolate from the computed results for a disk-loaded structure to the jungle gym structure

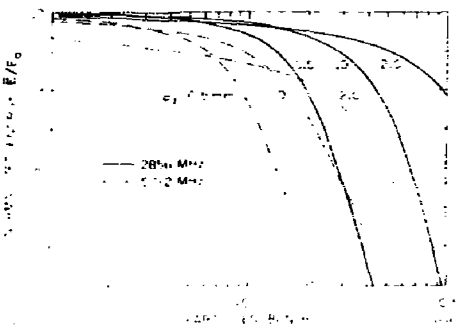

Fig. 7. Normalized energy as a function of particles per bunch at minimum energy spread.

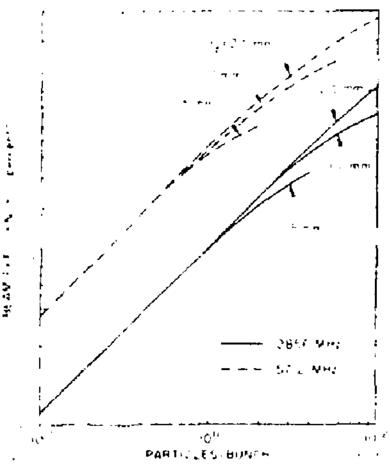

Fig. 8. Beam efficiency as a function of particles per bunch at minimum energy spread.

TABLE IV

Single-Bunch Collider Parameters at Three Frequencies

Frequency (MHz)	w_k (J/m)	η_s	$\mathcal{E}_s$ (J/m)	η_b	$\bar{E}/E_a$	$\Delta E/E_a$ (%)
2856	101	.82	82	1.9	.98	0.6
4040	58	.71	41	3.6	.955	1.2
5712	35	.58	20	7.1	.92	2.2

using the difference in stored energy per unit length. Taking $w_s(JG)/w_s(DL) = x = 0.47$, the values of $\Delta E/E_a$ in Table IV have been scaled from Fig. 6 in proportion to $x^{-1/2}$, while E/E_a has been scaled from Fig. 7 using $1-x^{-1/2}$. The efficiency scales as x^{-1}.

Bunch Trains

It is possible to improve the effective luminosity and beam efficiency of a collider by accelerating trains of bunches spaced apart by about ten wavelengths or more. At this bunch spacing, higher modes have effectively decohered, and for each following bunch only the superposition of the fundamental beam loading voltages from those bunches which have already passed through the structure need be considered. Successive bunches can be directed, using fast kickers, to different interaction regions. This allows a number of experiments to be run in parallel, although at successively lower energies for each successive bunch.

The long-range fundamental-mode wake per bunch is $\Delta E_0 = 2k_0 q = 2eN_b k_0$. The average energy of the n-th bunch is therefore

$$\bar{E}(n) = \bar{E}_1 - (n-1)\Delta E_0 = E_a\left[\frac{\bar{E}_1}{E_a} - (n-1)\frac{\Delta E_0}{E_a}\right] \quad .$$

The efficiency for m bunches is, using $q/w_s = 2\Delta E_0/E_a$,

$$\eta_b(m) = \frac{q}{w_s}\sum_{1}^{m}\bar{E}(n) = 2m\,\frac{\Delta E_0}{E_a}\left[\frac{\bar{E}_1}{E_a} - \frac{(m-1)}{2}\frac{\Delta E_0}{E_a}\right] \quad .$$

Results for a train of four bunches with $N_b = 10^{11}$, assuming a $\pi/3$-mode jungle gym structure at $E_a = 100$ MV/m are given in Table V. Note that the beam efficiency is quite reasonable at the two higher frequencies, while the energy of the fourth bunch is still an acceptable fraction of the unloaded energy. For convenience, the peak power per klystron (source) and the total average power is repeated from Table III.

TABLE V

Collider Parameters for a Train of Four Bunches

Frequency (MHz)	$\eta_b(4)$ (%)	$\bar{E}(4)/\bar{E}_1$	$\bar{P}_{tot}$ (MW)	$\hat{P}_k$ (MW)
2856	7.4	.95	120	3100
4040	14.2	.90	70	1700
5712	26.5	.805	42	1050

Power Sources

As we have seen from previous sections, a peak power in the range 1 to 3 GW in the frequency range 5712 to 2856 MHz is required to attain a gradient of 100 MV/m in accelerating structures which seem promising for a linac-colliding. The required pulse length is about 200 ns. In Table VI some present and potential power sources are listed which might meet this requirement.

The first row gives approximate parameters for a conventional klystron now under consideration[14] at SLAC. The pulse length of this device (≈ 1 us) is longer than required for our present application, but of course the peak power is too low. A 1 GW peak power klystron at 3.35 GHz with a very short pulse length (≈ 15 ns) has been built by Varian, but the tube failed before it could be tested to full power and the development has not been pursued further.[15] A more promising method for extending the power capability of a conventional klystron has been suggested by Lebacqz.[16] By placing seven cathodes and beams within the same vacuum envelope, arranged in a hexagonal manner around a central beam, the power output could be increased to the level of 1 GW. The cost and focusing power requirements of such a tube would be considerably less than seven times that of a single unit. The MEQATRON, proposed by Maschke,[17] also employs a multiple-beam array (using electrostatic focusing) to achieve a high net perveance. Although no tube of this type has yet been designed at the required peak power level, the basic concept seems promising.

A very high peak power output (500 MW at 3.2 GHz and 30 ns pulse length) has been obtained from a coaxial

TABLE VI

High Power Pulsed RF Sources

	Micro-Perveance ($10^{-6}A/V^{3/2}$)	Beam Voltage (kV)	Beam Current (kA)	Beam Impedance (Ω)	Estimated Efficiency (%)	RF Power (MW)
Conventional Klystron	2	450	0.6	750	55	150
Multiple Beam Klystron	7 × 2	450	4.2	110	55	1050
Crossed-Field Amplifier	13	600	6.0	100	50	1800
Photocathode Device A	10	600	4.6	130	65	1800
Photocathode Device B	10	1000	10.0	100	75	7500

magnetron.[18] The beam parameters and potential power output at 50% efficiency are given in the third row of Table VI. Although the device as constructed is an oscillator, it might well be possible to produce an amplifier counterpart.

The final two rows in Table VI represent a possible new concept for a high peak power microwave device. The concept is illustrated in Fig. 9. A photocathode is illuminated by a laser modulated at a microwave frequency. Bunches of electrons emitted during the peaks of the laser illumination are accelerated to high voltage and at the same time compressed in lateral dimensions to a sufficiently small fraction of an RF wavelength for good coupling to the fields in an RF output cavity. Because the electrons are emitted in bunches from the cathode, the long drift length required by a klystron for bunching at relativistic velocities is eliminated. By emitting the bunches at low density from a cathode with a large area, then compressing the beam laterally after the electrons have attained a high velocity, the effects of longitudinal and transverse space charge defocusing are reduced. The concept of a photocathode microwave device has been under study by a group[19] at SLAC. The device has been proposed independently by R. O. Hunter of Western Research Corporation.[20] In particular, Hunter introduced the idea of lateral compression after emission at low density to reduce space charge effects.

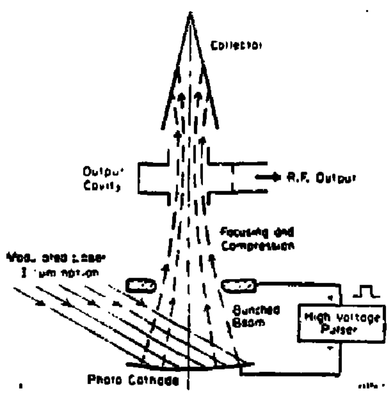

Fig. 9. Schematic of a photocathode microwave device.

Energy Storage and Switching

Another method for obtaining very high peak pulsed power is by storing the energy from a klystron pulse over a relatively long period in a high Q resonator, then switching the stored energy out rapidly in about the filling time of the structure. A schematic of the method is shown in Fig. 10. Detailed expressions for

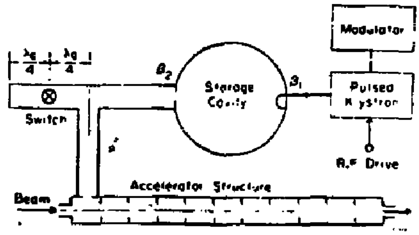

Fig. 10. Pulse compression by energy storage and switching.

the efficiency of energy transfer between the klystron pulse and storage cavity are given in Ref. 21 and are summarized in the Appendix. As an example, consider an 80 MW peak power klystron with a pulse length of 4 μs. A copper energy storage cavity with a radius of 30 cm would have an unloaded TE-mode Q_o of 3.4×10^5 at 5712 MHz. Energy can be transferred to the cavity with an efficiency of 67%, and from the cavity to two π/3-mode jungle gym structures 3 m in length ($\tau = 0.28$) with an efficiency of 58%. Thus the stored energy per unit length is 21 J/m, the unloaded gradient is 100 MV/m, and the total energy of a 3-km accelerator is 300 GeV. By doubling the pulse length to 8 μs, the gradient increases to 133 MV/m and the total energy to 400 GeV. This, of course, assumes an ideal switch and ignores breakdown limitations. Figure 11 shows the energy as a function of klystron pulse length for two frequencies and klystron peak power levels. Note that the unloaded Q of a spherical resonator in a TE mode is just the radius divided by the skin depth.

The idea of energy storage and switching was introduced by Birx, Dick, Little, Mercereau and Scalapino.[22] The critical component in the technique is the switch. Birx and Scalapino[23] describe an electron beam switch and show that an electron density of at least $10^{12}/cm^3$ is needed to produce an adequate short. A low pressure gas discharge switch has subsequently been developed at Lawrence Livermore Laboratory; a peak power of 160 MW has been switched at S-band using a shorted length of S-band waveguide as a storage cavity.[24] With an adequate development effort, energy storage with fast switching could provide an alternative means to attain the peak power required to drive a high energy collider.

Appendix

Let $T_o = 2Q_o/\omega$ be the unloaded filling time for an energy storage cavity, T_p the klystron pulse length, β_1 the input cavity coupling coefficient and β_{20} the output coupling coefficient with the switch off. Define $\mu = \mu_o(1+\beta_1+\beta_{20})$ where $\mu_o = T_p/T_o$. Then the efficiency

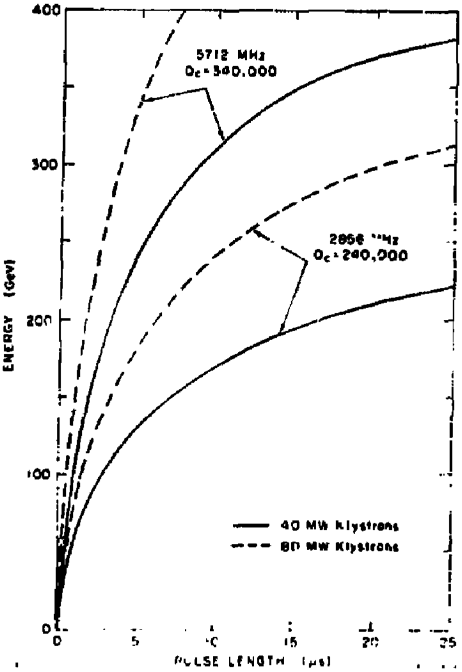

Fig. 11. Energy as a function of pulse length for a 3-km accelerator using energy storage and switching.

for the transfer of energy from the klystron pulse to the storage cavity is (see Ref. 21 for details),

$$\eta_c = \frac{2(1 - e^{-\mu})^2}{\mu} \cdot \frac{\beta_1}{1 + \beta_1 + \beta_{20}} .$$

By adjusting β_1, the efficiency can be optimized for a given value of μ_0. In the limit $\mu_0 << 1$, the maximum efficiency approaches 81.5%. The maximum efficiency as a function of μ_0 is shown by the top curve in Fig. A-1 ($\tau = 0$, $\nu_0 = \mu_0$).

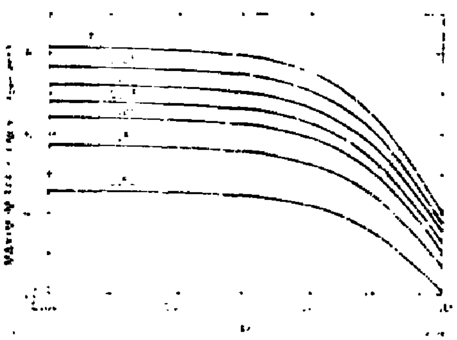

Fig. A-1. Maximum energy transfer efficiency vs ν_0.

Next, we give the efficiency for transfer of energy from the cavity to the structure (again see Ref. 21 for a detailed derivation). Define $T_F = L_s/v_g$, $\nu_0 = T_s/T_0$ and $\nu = \nu_0(1 + \beta_1 + \beta_2)$ where β_2 is the output cavity coupling coefficient with the swith on. Then

$$\eta_s = \frac{2\nu(e^{-\tau} - e^{-\nu})^2}{(\nu - \tau)^2} \cdot \frac{\beta_2}{1 + \beta_1 + \beta_2} ,$$

assuming a constant impedance structure. Again, the efficiency can be maximized for a given ν_0 and τ. The maximum efficiency is plotted in Fig. A-1 as a function of ν_0 for various values of τ.

Acknowledgements

The author gratefully acknowledges the help of T. Knight in computing the beam loading and total voltage functions which provide the basis for Figs. 4-8.

References

1. J. E. Augustin et al., Proc. of the Workshop on Possibilities and Limitations of Accelerators and Detectors, FNAL, October 1978, p. 89.
2. R. Hollebeek, SLAC-PUB-2535 (1980). To be published in Nucl. Instrum. Methods.
3. J. Jaros, AATF/80/22, Stanford Linear Accelerator Center. Unpublished.
4. P. B. Wilson, IEEE Trans. Nucl. Sci. NS-26, No. 3, 3255 (1979).
5. G. A. Loew, private communication.
6. V. A. Vaguine, IEEE Trans. Nucl. Sci. NS-24, No. 3, 1084 (1977).
7. P. B. Wilson et al., Particle Accelerators 1, 223 (1970).
8. K. L. F. Bane and P. B. Wilson, Proc. of the 11th Int. Conf. on High Energy Accelerators, Birkhäuser Verlag, Basel, 1980, p. 592.
9. K. L. F. Bane, private communication.
10. The single-bunch emittance growth due to the transverse wake in a linac is considered by A. W. Chao, B. Richter and C. Y. Yao, Proc. of the 11th Int. Conf. on High Energy Accelerators, Birkhäuser Verlag, Basel, 1980, p. 597.
11. G. A. Loew and P. B. Wilson, Proc. of the 11th Int. Conf. on High Energy Accelerators, Birkhäuser Verlag, Basel, 1980, p. 393.
12. M. Tigner, IEEE Trans. Nucl. Sci. NS-18, No. 3, 249 (1971).
13. See, for example, Microwave Laboratory reports ML-416, ML-432, ML-504, ML-520, ML-557 and ML-581, Stanford University (April 1957 – February 1959).
14. G. Konrad, private communication.
15. Rome Air Development Center, Report No. RADC-TR-70-101 (July 1970).
16. J. Lebacqz, private communication.
17. A. W. Maschke, BNL-51094, Brookhaven National Laboratory (September 1979).
18. W. M. Black et al., International Electron Devices Meeting, Washington, D.C., December 1979, p. 175.
19. W. B. Atwood, M. Briedenbach, C. Sinclair, and P. B. Wilson.
20. R. O. Hunter, private communication.
21. P. B. Wilson, AATF/80/20, Stanford Linear Accelerator Center (1980), unpublished.
22. D. L. Birx et al., Appl. Phys. Lett. 32, 68 (1978).
23. D. L. Birx and D. J. Scalapino, J. Appl. Phys. 51, 3629 (1980).
24. R. Alvarez, D. L. Birx, D. Byrnes and D. J. Scalapino, private communication.