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RF SYSTEMS AND ACCELERATING STRUCTURES FOR LINEAR COLLIDERS*

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ABSTRACT

This paper presents some of the new design requirements for linear colliders and describes the types of RF systems and accelerating structures that might produce very high energies and gradients within reasonable power consumption limits. Directions for future research are indicated.

INTRODUCTION

The interest in linear colliders with possible energies of several hundreds of GeV poses new challenges to the designers of RF systems and accelerating structures. This paper addresses some of the questions that must be answered to permit building such machines: (1) What kinds of structures are to be selected to produce the highest possible accelerating gradients and energies?, (2) What power sources and possible storage devices are needed to supply these structures with RF energy at the lowest possible consumption of AC input power?, and (3) How can the beam induced longitudinal and transverse wake fields which respectively produce energy spread and emittance growth within a given bunch and between multiple bunches be minimized and compensated for?

Before we start answering these questions, let us look at the basic design objectives for a linear collider. The ultimate goal is to maximize the luminosity

$$\mathscr{L} = n_{pps}\, n_b \frac{N^2}{4\pi\sigma^{*2}}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \qquad (1)$$

where n_{pps} is the RF pulse repetition rate, n_b is the number of bunches per pulse, N is the number of particles per bunch and $\sigma^* = \sigma_x^* = \sigma_y$ is the transverse bunch dimension (round beam) at the collision point. It is assumed that n_b is a small number and that each e^+ bunch can only interact with its counterpart e^- bunch, after which they are both unusable because of the "beamstrahlung" effect. This effect which causes beam energy spread at the collision point, together with the limitations on minimum attainable transverse emittance, probably sets an upper limit on N on the order of $10^{11}\ e^{\pm}$. Assuming $\sigma^* \sim 10^{-4}$ cm, we obtain $\mathscr{L} = 8 \times 10^{28}\ n_{pps}\, n_b\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$. We see that the product $n_{pps}\, n_b$ must be at least 10^3 if ultimate luminosities of $\sim 10^{32}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$ are to be reached. This sets the framework within which the RF systems must be designed.

DESIGN CRITERIA

If we begin by considering room temperature (RT) systems, the first choice to be made is between traveling-wave (TW) and standing-wave (SW) structures. It has been shown1) in this regard that under optimized conditions, the minimum RF power necessary to reach a given accelerating voltage in a given time is always greater by 23% for a SW structure than for a TW structure. Hence, we will limit our discussion to TW structures. Furthermore, we will assume that the train of bunches (n_b) is relatively short in time compared to the filling time of the structure, $t_F = \ell/v_g$, where ℓ is the length of a section and v_g is the group velocity. This assumption can be fulfilled, either by taking a very small number of bunches (n_b = 1 or 2) or if possible, as will be discussed later, by spacing them very closely together. Then, the RF pulse (t_{RF}) need not be much longer than t_F and power consumption is minimized.

The energy V of a TW accelerator section of length ℓ, shunt impedance r and attenuation τ with peak power input P, as shown in Fig. 1a, is given by

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$$V = [2\tau(1 - \tau)P\ r\ \ell]^{1/2}. \qquad (2)$$

This expression is valid for low τ ($\tau < 0.3$) regardless of whether the section is of constant-impedance or constant-gradient type. Since $\tau = \omega t_F/2Q$, expression (2) can be rewritten as

$$V = [Pt_F(1 - \tau)\ \frac{r\omega}{Q}\ \ell]^{1/2}. \qquad (3)$$

Here Pt_F is the energy delivered by the source during one filling time and $r\omega/Q$ (called $4k_1$ in other publications[1]) is equal to E^2/W where E is the accelerating field on axis and W is the energy stored per unit length. Note in expression (3) that $W\ell = Pt_F\ (1 - \tau)$ and that as $\tau \rightarrow 0$, the energy from the source and the energy stored become equal. The effective gradient is

$$\frac{V}{\ell} = [\frac{Pt_F}{\ell}\ (1 - \tau)\ \frac{r\omega}{Q}]^{1/2}. \qquad (4)$$

If we define the conversion efficiency from AC to RF power as η and the total AC power as P_{AC}, then for a multisection linac of total length $L = n\ell$

$$V_T = [\frac{\eta P_{AC}}{n_{pps}}\ (1 - \tau)\ \frac{r\omega}{Q}\ L]^{1/2}. \qquad (5)$$

If we obtain the expression for n_{pps} from (5) and substitute it in (1), we get:

$$\mathscr{L} = (\frac{n_b\ N^2}{4\pi\sigma^{*2}})\ (\frac{\eta P_{AC}}{V_T^2})\ (1 - \tau)\ (\frac{r\omega}{Q})\ L. \qquad (6)$$

Expressions (3) through (6) point toward some major design implications: (a) For a given AC power, gradient and total energy vary as $\eta^{1/2}$, luminosity varies as η; hence the importance of optimizing klystron-modulator-power-supply efficiency to save AC power. (b) The same dependences hold for $(r\omega/Q)$. Since r/Q varies as ω, $r\omega/Q$ varies as ω^2. Hence there is an advantage in going to higher frequencies. This advantage is off-set by the disadvantage of smaller cross-sectional dimensions which lead to larger wake fields as discussed below, and greater difficulties in building high power klystrons. (c) The attenuation per section τ and the filling time t_F should be low, and conversely, the group velocity v_g should be high. (d) For a given P_{AC}, gradient and energy are increased if the repetition rate n_{pps} is reduced, assuming there is no upper limit on peak power. On the other hand, there is the conflicting requirement that higher luminosity requires higher n_{pps}.

The subject of beam induced longitudinal and transverse wake fields is too long to be treated here in detail[3]. Exact calculations of the wake functions have been obtained for the cylindrically symmetrical SLAC disk-loaded waveguide and experimental agreement for the longitudinal field has been reasonable[4]. Independently of these calculations, R. Miller[5] has shown that if one assumes that the energy left by the beam is deposited only in a cylinder of radius equal to the disk aperture (a), the longitudinal wake function varies as a^{-2} and the transverse dipole wake function varies as a^{-4}. We see that any enlargement of the iris pays off very rapidly. On the other hand, this reduces r/Q and a compromise must be reached. Another approach is to go to more open structures as shown later in Fig. 2, where the effective aperture "visible" by the beam is increased. A figure of merit, B, which describes the quality of the structure, has been defined[1] as the ratio of $\Sigma k_n/k_1$ where $2k_n = \frac{\omega_n}{2}\ (\frac{r}{Q})_n$ is the wake amplitude for the n^{th} mode ($n = 1$ is the accelerating mode). $B \gtrsim 6$ for the present SLAC structure ($a = 1.116$ cm). It could perhaps be reduced to $\gtrsim 3$ through a more open structure design.

SYSTEMS AND STRUCTURES

Let us now look at some practical implications of these criteria. For reference purposes, columns (1) and (2) in Table I give data relevant to the SLAC Linear Collider (SLC) using

TABLE I

Numerical Examples for Various Systems and Structures

Klystron Peak Power	SLAC Disk-Loaded Structure			Cross-Bar Structure		Cross-Bar Structure with Energy Compression			
P(MW)	38 MW SLED II	120 MW	3720 MW	4270 MW	2400 MW	120 MW	80 MW	40 MW	40 MW
f (MHz)	2856	2856	2856	2856	4000	2856	4000	2856	4000
r/Q (ohms/m)	4400	4400	4400	6700	9380	6700	9380	6700	9380
ℓ (m/section)	3.05	3.05	3.05	6	6	6	6	6	6
τ (nepers)	0.57	0.57	0.57	0.119	0.197	0.119	0.197	0.119	0.197
t_F (μsec)	0.83	0.83	0.83	0.133	0.133	0.133	0.133	0.133	0.133
η_{COMP}	0.53	1	1	1	1	0.48	0.48	0.48	0.48
n (sections)	960	960	960	488	488	488	488	488	488
N_K (klystrons)	240	240	240	488	488	488	488	488	488
L (m)	2928	2928	2928	2928	2928	2928	2928	2928	2928
V/ℓ (MV/m)	17.95	17.95	100	100	100	100	100	50	50
V_T (GeV)	52.6	52.6	293	293	293	293	293	146	146
$Pt_{RF/\ell}$ (J/m/pulse)	15.57	9.83	305	94.6	53.2	200	111	50	27.7
t_{RF} (μsec)	5	1	1	0.133	0.133	10	8.3	7.4	4.15
η_{pps}	180	180	180	180	180	180	180	180	180
η	0.30	0.23	0.23	0.23	0.23	0.4	0.4	0.4	0.4
$P_{AC/K}$ (kW/klystron)	114	94	2904	444	250	540	298	133	75
P_{AC} (MW)	27.4	22.5	697	217	122	264	146	65	36

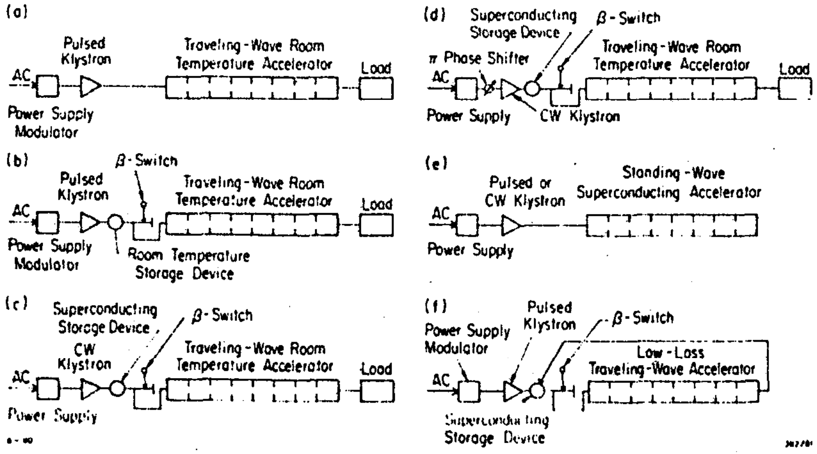

Fig. 1 Possible RF Systems and Accelerating Structures for Linear Colliders.

the existing disk-loaded waveguide at 2856 MHz, with respectively a 38 MW klystron and SLED II (t_{RF} = 5 μsec) or a 120 MW klystron without SLED (t_{RF} = 1 μsec). Such a klystron is presently under consideration at SLAC and would give the same final energy (52.6 GeV). Note that expressions (2) through (5) were not used in these two cases because $\tau > 0.3$ and SLED requires modified equations $^{2)}$. The values of the conversion efficiency η are obtained from experience with practical klystron-modulator designs. The "compression" efficiency η_{COMP} (0.53 for SLED II) is a measure of the effectiveness of SLED II (38 MW, 5 μsec) as a "pulse compressor" as compared to the equivalent flat RF pulse generated by a 120 MW, t_F = 0.83 pulse. P_{AC} is lower for the 120 MW case than for SLED II because the klystron-modulator system, although less efficient (0.23 vs 0.3), is on for less time (1 μsec vs 5 μsec). Column (3) gives an idea of how much power would be needed with the SLAC structure to obtain gradients of 100 MV/m, assuming that the structure could sustain such gradients. Note that at SLAC the existing structure was only tested up to 46 MV/m. Each klystron would have to produce 3720 MW of peak power and P_{AC} would be close to an exorbitant 700 MW! Clearly, another way must be found.

Suppose now that we turn to other structures of the cross-bar type (see possible examples in Fig. 2). The advantages of these structures are that they have a much higher group velocity, a higher r/Q and that they are more "open" as mentioned above. Column (4) shows an example for a Jungle Gym structure at 2856 MHz with an assumed group velocity v_g/c = 0.15 and r/Q = 6700 ohms/m. The example at 4000 MHz (λ = 7.5 cm) in column (5) assumes that all dimensions have been scaled to preserve the same group velocity. We see that P_{AC} is now coming down to more tolerable values. However, assuming that these structures can sustain 100 MV/m, which of course has not been proven, there remains a basic problem: how do we get peak powers of 2 to 4 GW which would require klystron beam voltages up to 2 MV and currents of 5 kA at AC-to-RF efficiencies of η = 0.23? A possible scheme is shown in Fig. 1b. A pulsed klystron is used to charge a storage cavity, and a switch at the output of this cavity can modify the output coupling β of the cavity (hence the name of β-switching): if activated at the end of the charging time, the switch moves the effective waveguide short, thereby causing the stored energy to be discharged into the accelerator. The output pulse has an exponential decay. Energy compression schemes of this type have first been suggested by Scalapino and Birx, and have been studied by Farkas, Hogg and one of the co-authors$^{6-10)}$. A specific series of examples using high-Q room-temperature cavities has been worked out in detail.$^{10)}$ The cavity that has been assumed is spherical (with a $Q \sim 240,000$ and a diameter of 60 cm at 2856 MHz) and probably needs to be split at the "equator" for proper mode separation. The β-switch may be a low pressure plasma discharge or an intense electron beam across a waveguide.$^{7)}$ The value of β would have to be changed from << 1 to 200-400 within a few nanoseconds. With these assumptions and η_{COMP} on the order of 0.48, one obtains the examples shown in columns (6) through (9) for gradients of 100 MV/m, and 50 MV/m respectively. With the longer t_{RF}, it is assumed that η can be increased from 0.23 to 0.4 because the modulator can be made more efficient. All examples have been worked out for the canonical length L = 2928 m of the present SLAC linac.

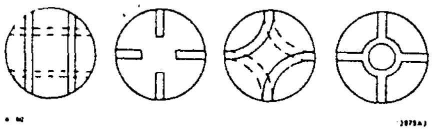

Fig. 2 Jungle Gym and Other Possible Cross-Bar Structures.

Figs. 1(c) and (d) suggest two other variations using CW klystrons. D. Farkas at SLAC$^{8)}$ has performed a low power test and worked out a detailed example which combines the use of superconducting cavities and β-switching with a π-phase shifter in the klystron input, à la SLED. With this scheme, one can in principle generate quasi-rectangular RF pulses of very high power with a compression efficiency of up to 80%, assuming a Q_o for the storage cavity of ∿ 10^{11}. The scheme has the advantage that the klystron being CW, a higher η (∿ 0.6) may be attainable but the refrigeration power may be high.

The ideas discussed so far have all assumed that after passage of the bunches, the RF energy stored in the accelerator is dissipated in the structure and in the load. In the proposed³⁾ SLC, for example, each bunch extracts only 400 joules out of a total of ∿ 11,000 joules stored (3.6%). For three bunches (two e^- and one e^+), this amounts to only 11%, the rest going to waste. Obviously, it would be much better if this energy could be saved, recovered or used. One apparent solution would be the classical CW standing-wave superconducting linac shown in Fig. 1e. Unfortunately, this type of accelerator has not produced stable gradients above 5-10 MV/m and the theoretical limit for Nb seems to be 30 MV/m. Even at this level, the losses for a Q improvement factor of 5×10^5 would be 36 W/m at 1.85°F or 36 KW/m at RT for a refrigerator efficiency of 10^{-3}. Another alternative shown in Fig. 1f consists of a low-loss accelerator of the TW type in which the power left over after passage of the beam can be scavenged and returned to the storage cavity through a feedback loop. This solution is in principle feasible but it requires a three-way coupling system to the cavity whose construction would be quite complicated. Again, the refrigeration power may be high.

Another method of making the process more efficient is to inject a longer train of bunches. Because of the wake fields they leave behind them, successive bunches would normally acquire successively less energy (typically ΔV ∿ 1.5 GeV/bunch for the SLC). If however one injects the first bunch before the structure is entirely filled, a constant although lower (by n_b ΔV) output energy may be obtained.

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