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RF Pulse Compression
for Future Linear Colliders*

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ABSTRACT

Future (nonsuperconducting) linear colliders will require very high values of peak rf power per meter of accelerating structure. The role of rf pulse compression in producing this power is examined within the context of overall rf system design for three future colliders at energies of 1.0–1.5 TeV, 5 TeV and 25 TeV. In order keep the average AC input power and the length of the accelerator within reasonable limits, a collider in the 1.0–1.5 TeV energy range will probably be built at an x-band rf frequency, and will require a peak power on the order of 150–200 MW per meter of accelerating structure. A 5 TeV collider at 34 GHz with a reasonable length (35 km) and AC input power (225 MW) would require about 550 MW per meter of structure. Two-beam accelerators can achieve peak powers of this order by applying dc pulse compression techniques (induction linac modules) to produce the drive beam. Klystron-driven colliders achieve high peak power by a combination of dc pulse compression (modulators) and rf pulse compression, with about the same overall rf system efficiency (30-40%) as a two-beam collider. A high gain (6.8) three-stage binary pulse compression system with high efficiency (80%) is described, which (compared to a SLED-II system) can be used to reduce the klystron peak power by about a factor of two, or alternately, to cut the number of klystrons in half for a 1.0–1.5 TeV x-band collider. For a 5 TeV klystron-driven collider, a high gain, high efficiency rf pulse compression system is essential.

RF PARAMETERS FOR FUTURE LINEAR COLLIDERS

Linear colliders as they exist at present (the SLC collider at SLAC), and as they are foreseen for the future (we will not consider superconducting colliders here), require very high values of peak rf pulse power per meter of accelerating structure. For example, at the SLC operating gradient of 21 MV/m, the required peak power is 13 MW/m. Since each klystron feed 12 m of structure, a klystron output power of about 160 MW would be required without rf pulse compression. A SLED-type pulse compression system with a power gain of 2.6 reduces the required klystron output power to about 60 MW.

The s-band (2.856 GHz) SLC linac produces an energy of about 50 GeV in a length which is slightly less than 3 km. A world-wide effort is now underway to design a next-step linear collider with a center-of-mass energy of 500 GeV. One straightforward way to achieve such a machine is to extend the length of an SLC-like linac by a factor of 10, to around 30 km. There is, in fact, a proposal for such an s-band linear collider (SBLC) being put forward by the DESY laboratory in Hamburg, Germany. While the technology for such a collider is indeed quite close to that in existence today, it is difficult to extend this design to higher energies without the length becoming uncomfortably long and the AC power consumption becoming uncomfortably high. To reach energies of 1 TeV and beyond, it is necessary to consider higher rf frequencies and higher accelerating gradients.

Two basic rf considerations in scaling a collider linac with frequency and gradient are AC power consumption, and the threshold gradient for the capture of electrons at rest by a velocity-of-light traveling wave (rf breakdown occurs at gradients well above this threshold). At 2856 MHz, the dark current threshold gradient is about 15 MV/m. It is certainly possible to operate a linac somewhat in excess of this threshold gradient, but it would be dangerous to propose a design exceeding the threshold by too large a factor. With frequency, the dark current capture threshold scales as $G_{th} \sim \omega$ and the accelerator length as $L \sim E/\omega$, where E is the center-of-mass collision energy. At constant repetition rate and ratio of rf pulse length to structure filling time, the AC power would also scale as $P_{ac} \sim E/\omega$. In going to a higher machine energy, it is therefore clearly desirable to go to a higher rf frequency. There are, however, major disadvantages that go along with a higher frequency. The dipole mode (deflecting) wake potential per unit length of structure increases roughly as ω^3, and this in turn leads to tighter alignment and manufacturing tolerances.

At SLAC, a linear collider design has been proposed (the NLC, or Next Linear Collider) at a frequency of 11.4 GHz. There is no strong theoretical reason for this exact choice of frequency. The original (rather weak) considerations behind this frequency choice for an NLC were first, to stay within the x-band frequency range, and second, to be an integral multiple of the SLC frequency of 2856 MHz. X-band was taken as an upper frequency limit because the technology is still relatively "comfortable" at this frequency; that is, rf components are reasonable in their size, weight, tolerances, price and availability. Also, small industrial accelerators are routinely built at this frequency. It was also felt that high power klystrons could be built at 11 GHz with a power output in the 50–100 MW range. As it turned out, building a klystron with this output power and also high efficiency (> 50%) was perhaps a greater challenge than had been expected.

Table 1 shows some basic rf-related parameters for several possible future linear colliders. All entries assume a repetition rate of 120 Hz. The active linac length includes both e^+ and e^- linacs, and assumes two 10 GeV injectors plus a 7% overhead for off-crest (BNS) operation and klystron failure management.

Table 1

Basic RF Parameters for Future Linear Colliders

Center-of-mass energy (TeV) [equivalent proton energy (TeV)]	RF frequency (GHz)	Accelerating gradient unloaded/loaded (MV/m)	Group velocity (v_g/c) [iris radius (a/λ)]	Pulse length (ns) [fill time (ns)]	Peak power (MW/m) [pulse energy (J/m)]	Accel-erator structure length (m)	Active linac length (km)	AC power (MW) [rf system efficiency (%)]
1.0 [10]	11.4 4×SLC	85/63	.06 [.175]	220 [100]	145 [32]	1.8	17	185 [34]
1.5 [LHC]	11.4	100/75	"	"	200 [44]	"	21	225 [50]
5 [SSC]	34 12×SLC	200/150	.10 [.215]	50 [20]	535 [27]	0.6	35	225 [50]
25 [250]	103 36×SLC	440/330	.167 [.265]	12 [5]	1805 [22]	0.25	80	415 [50]

The first entry shows the NLC parameter choices for a 1 TeV collider, with a loaded gradient that is just at the dark current capture threshold. The rf system components (klystron, modulator and rf pulse compression system) are based on modest extrapolations of demonstrated technology, backed by simulations. The PPM-focused klystrons (one for every two accelerating structures) have an output power of 72 MW, a pulse length of 1.2 μs, a microperveance of 0.75 and a simulated efficiency of 63% (1) The modulator has an overall efficiency of 75%, based on a Blumlein-type pulse forming network (PFN) and a pulse transformer with a turns ratio of 7:1. This low turns ratio allows a high efficiency for the transfer of energy stored in the PFN through the pulse transformer to the flat top portion of the high voltage pulse applied to the klystron cathode [see (2) for a brief discussion of modulator efficiency]. The rf pulse compression system is a SLED-II type system (3) with a compression ratio of 5, a power gain of 3.6 and an overall efficiency of 72%, including a 5% allowance for losses in the components of the pulse compression system, and a 5% allowance for losses in the power transmission components from klystron to pulse compression system to accelerating structure. The overall rf system efficiency is then the product of the three subsystem efficiencies (klystron, modulator, rf pulse compression), or respectively 63% × 75% × 72% = 34%.

The next entry in Table I shows basic parameters for a 1.5 TeV x-band collider based on technology that might be achieved after another 5 years or so R&D. The klystron has a peak power output of 112 MW at an efficiency of 70%. This output power and efficiency might be achieved by either a cluster klystron (4) or a sheet beam klystron (5). It is assumed that the klystron has a gridded gun to switch the beam (eliminating the need for a modulator), and that this switching can be accomplished with an efficiency of 90%. The pulse compression system is assumed to be a three stage binary pulse compressor (BPC), with an efficiency of 80% (including a 5% allowance for power transmission losses), and a power gain of 6.4 (8×0.80). The BPC system is based on the use of lumped resonant elements, rather than smooth delay lines, thus reducing the delay line length per unit of delay by a factor of 50 or so. Details are given in a later section. The overall rf system efficiency is therefore 70% × 90% × 80% = 50%.

The 1.5 TeV collider in Table I is probably close to the energy limit that can be achieved with x-band technology. Still higher energies will require still higher rf frequencies. The next entry, a 5 TeV center-of-mass collider, has an rf frequency of 34 GHz and a loaded gradient of 150 MV/m (the dark current capture gradient is about 185 MV/m). An rf frequency on the order of 30 GHz is not unreasonably "exotic." Prototype accelerating structures have been built at this frequency, and it is indeed the frequency chosen for the CLIC linear collider proposed at CERN, Geneva, Switzerland. Extensive R&D has been carried out at 30 GHz in support of the CLIC proposal [see, for example, Ref. (6)]. Specific beam parameters for a 5 TeV collider with a luminosity of 2.5 $\times 10^{35}$/cm^2/sec have also been suggested (7). An rf system efficiency of 50% is again assumed.

The final entry in Table I, a fairly wild extrapolation into the future, is for a 25 TeV linear collider operating at an rf frequency of 103 GHz. In itself, this high a frequency is not of concern. Generating and transmitting megawatts of CW power in low-loss overmoded waveguide components at 100 GHz and above is routine in plasma fusion technology. The AC wall plug power and accelerator length are, however, approaching the limits of what might be socially and politically acceptable. The accelerating gradient is well below limits set by dark current capture or rf breakdown, but average and peak pulse surface heating must be considered. The rf energy per pulse is actually less than that for the 1 TeV x-band design, but the surface area per meter of length is down by a factor of nine. Thus the average power dissipation per unit area of cylindrical structure surface (proportional to ωU_m, where U_m is the energy per pulse per meter) is about six times that at x-band, or about 20 W/cm^2. Careful cooling channel design should be able to take care of this heat load. The surface temperature rise at the end of the pulse (proportional to $G^2\omega^{1/2}\tau_p^{1/2}$ where τ_p is the pulse length) is up by a factor of about 20 over that at x-band, to about 200°C. This is probably above the threshold for surface degradation due to the stresses induced by temperature cycling. Perhaps a surface treatment, or a new structure design, can be developed to ameliorate this effect.

The scaling with rf frequency and collider energy implicit in Table I is approximately

$$\omega \sim E^{2/3}$$

$$G \sim \omega^{3/4} \sim E^{1/2}$$

$$L \sim E^{1/2}\ ,$$

where G is the accelerating gradient. As frequency is increased, the iris opening is increased ($a/\lambda \sim \omega^{0.2}$) to ameliorate wakefield effects and to increase the group velocity ($v_g \sim \omega^{1/2}$), which in turn increases the section length such that $L_s \sim \omega^{-1}$. However, a larger iris opening also reduces the normalized elastance approximately as $s_n \sim \omega^{-1/6}$. The peak rf power per meter and the energy per pulse per meter then scale approximately as

$$\hat{P}_m \sim \frac{G^2}{s_n\omega^2\tau_f} \sim \omega^{7/6} \sim E^{0.8}$$

$$U_m \sim \omega^{-1/3} \sim E^{-0.2}\ .$$

The total AC power is then $P_{ac} \sim U_m L \sim E^{0.3}$.

COMMENTS ON RF SYSTEM EFFICIENCY

Following are some general comments on the efficiencies of the three major subsystems which make up the rf system for a klystron-driven linear collider. At a constant beam voltage, the rf output of a klystron (or other microwave rf source) increases as the beam current increases. However, a higher beam current, I_b, at a given beam voltage, V_b inevitably leads to a lower efficiency because of the detrimental effects of space charge forces. These forces tend to blow apart the sharply defined bunches needed for high output efficiency. The microperveance (defined as $K_\mu = I_b/V_b^{3/2} \times 10^6$) is commonly taken as a measure of these space charge effects. Very roughly, the maximum klystron efficiency [see, for example, the plot in (4)] can be taken as

$$\eta_{\rm kly} \approx 0.80 - 0.15\ K_\mu \quad .$$

On an efficiency versus perveance plot, this line forms an upper envelope for efficiency values obtained from both measured performance and from simulations. The intercept at zero perveance has some theoretical justification (8). Low frequency, long pulse or CW klystrons tend to fall closer to this performance limit than high frequency, high peak power tubes. The klystron output power is then

$$P_k = 10^{-6} \eta_{\rm kly} K_\mu V_b^{5/2} = 10^{-6} \left(0.8 K_\mu - 0.15 K_\mu^2\right) V_b^{5/2} \quad . \qquad (1)$$

A modulator provides the klystron beam voltage, usually by charging the capacitors in a PFN to voltage $V_{\rm PFN}$ and then switching this energy (usually by a thyratron) through a step up pulse transformer with turns ratio n. The efficiency for this transfer of energy stored on the PFN through the pulse transformer into the flat-top portion of the output pulse is the energy transfer efficiency, η_E. This efficiency is less than unity mainly because of energy lost in the rise and fall times of the output pulse. In turn, the rise and fall times are roughly proportional to the transformer turns ratio, and to the square root of the pulse length. These relationships can be summarized as:

$$V_b = nN_\ell V_{\rm PFN} \tag{2a}$$

$$\eta_E = \frac{AT_k}{T_k + BnT_k^{1/2}} \tag{2b}$$

$$\eta_{\rm mod} = \eta_{ps}\eta_E \ . \tag{2c}$$

Here T_k is the flat-top portion of the modulator output pulse; N_ℓ is the number of stages in the modulator PFN ($N_\ell = 2$ is a Blumlein voltage doubling arrangement, etc.); the constant A takes account of transformer core losses, resistive losses in the transformer windings and leads, and losses in the thyratron (0.97 might be a reasonable value for A); η_{ps} is the efficiency for converting energy from the AC line to energy stored on the PFN, taking into account losses in the power supply and charging circuit (90% is easy, 95% is hard).

The rf pulse compression system compresses the klystron output pulse by a ratio $R = T_k/T_{\rm rf}$, where $T_{\rm rf}$ is the pulse length delivered to the accelerating structures. The net pulse compression efficiency is the product of an intrinsic efficiency, $\eta_{\rm int}$, and a loss efficiency, $\eta_{\rm loss}$, which is less than one due to copper losses, unwanted reflections, and mode conversion in a system using overmoded components. The intrinsic efficiency is 100% for a binary pulse compression system (9), or BPC; for a SLED-II system it is a decreasing function of compression ratio ($\eta_{\rm int} = 0.86$, 0.80, 0.75, and 0.64 for R = 4, 5, 6, and 8 respectively). The loss efficiency component also tends to decrease with increasing R for both types of compression systems. Summarizing:

$$\eta_{pc} = \eta_{\mathrm{int}}(R)\ \eta_{\mathrm{loss}}(R) \tag{3a}$$

$$G_p = \eta_{pc}\ R\ , \tag{3b}$$

where G_p is the power gain.

The preceding equations show that the three system efficiencies cannot be optimized separately, without leading to inconsistent results. The same conclusion also applies to system costs. For example, a good klystron efficiency implies a low perveance and therefore a high beam voltage for a given power output. From Eq. (2), a high beam voltage implies some combination of a large transformer turns ratio (resulting in low η_E), or a value of $N_l > 1$ (more difficult technically and more expensive), or a high V_{PFN} (more expensive power supplies and thyratrons). A high pulse compression efficiency implies low compression ratio, and therefore more klystron power at a shorter pulse length. If the perveance is increased to obtain the higher power, klystron performance suffers. If the beam voltage is increased, either the modulator efficiency must decrease, or the cost must increase. In either case, the shorter klystron pulse length also tends to decrease the modulator efficiency. If the pulse compression system is eliminated entirely, as in a two-beam accelerator, more dc pulse compression must be carried out in the induction linac modules. The net rf system efficiency tends to be about the same (on the order of 30-40%).

HIGH GAIN RF PULSE COMPRESSION SYSTEMS

If an efficiency greater than 70% is desired, it is not possible to use a standard SLED-II type pulse compression system with a compression ratio greater than six.

The intrinsic efficiency (75%) at R=6 limits the power gain to 4.5. The effect of copper losses in the delay lines and other waveguide components will further reduce the efficiency, resulting in a net power gain of perhaps 4.2. To achieve high gain at high efficieny, other methods of pulse compression must be considered. Some possibilities which can deliver a flat output pulse with very high intrinsic efficiency are: "chirping," binary pulse compression, and use of an active switch to change the reflection coefficient of the iris in a SLED-II compression system. In the chirping scheme, the frequency is modulated along the pulse such that the back of the pulse, traveling at a faster group velocity, catches up with the front of the pulse in a dispersive structure. It is used to produce very high gains in optical compression systems, but it is not inherently superior to the BPC method in microwave systems using waveguide transmission components. Copper losses limit any compression method to the same maximum energy storage time (and compression ratio for a given output pulse length), depending on achievable Q's for the delay components. An active switch (a laser-driven silicon wafer), which could be applied to increase the efficiency of a SLED-II system at large compression ratios, is currently being investigated at SLAC (10). This work, however, is at a preliminary stage, and in any case the switch will impose some limitation on peak power which is not yet well defined. Therefore, we focus our attention on the possibility of achieving higher power gains using a BPC system with a compression ratio $R \geq 8$.

As mentioned previously, the 1.5 TeV NLC design in Table I is based on a three-stage binary pulse compression system with an efficiency of 84% (excluding power transmission losses). The design is based on using a relatively small number of overmoded, TE_{01}-mode cylindrical cavity resonators. A certain amount of ripple (a few percent) can be tolerated on the output pulse of the BPC system. Essentially, pulse compression is achieved in such a BPC system by slicing the klystron pulse into a number of time bins equal to the compression ratio, and then stacking these bins to form the compressed output pulse. Amplitude ripple can therefore be compensated by phase modulating the individual time bins, half with a positive phase variation and half with an equal negative phase variation. This same scheme can also compensate for the effects of modulator ripple on the klystron output, and more importantly, to produce an amplitude ramp at the beginning of the rf pulse which is needed to compensate for beam loading (11). This ability to produce an arbitrary amplitude modulation on the rf pulse is one of the strong points of rf pulse compression. Of course, energy is lost in the compensation process, so it is desireable to keep the peak-to-peak ripple amplitude to the order of a few percent.

The Q_0 of a TE_{01}–mode cylindrical copper resonator at 11.4 GHz is (ignoring coupling holes),

$$\begin{aligned} Q &= \frac{2.58 \times 10^4}{y^3 + (2.44/n)(1-y^2)^{3/2}} \\ y &\equiv \lambda/\lambda_c \;=\; 0.61(\lambda/a) \\ L_c &= n(\lambda_g/2) \;\approx\; n(\lambda/2) \;. \end{aligned} \qquad (4)$$

Here L_c and a are the length and radius of the cavity, assumed to be n half-wavelengths long. The first term in the denominator represents the loss in the cylindrical outer wall, and the second term the loss in the two end walls. Some preliminary simulations indicate that an adequately flat pulse can be created using seven cavities per stage in a BPC system with delay lines replaced by discrete cavities. If the length of each cavity is kept to 1.5 m, the delay circuit length for one stage of compression is less than the 8-m spacing between compression systems (assuming four cavities in one direction, a bend, and three cavities in the reverse direction). For this cavity length, $n \approx 110$. If we now choose y so that the loss in the cylindrical outer wall is 10% of the loss in the end walls, we have an $a = 12.5$ cm and $Q = 1.1 \times 10^6$. From $T_0 = 2Q/\omega$, we have $T_0 \approx 30\ \mu$s. Using $\eta(\text{loss}) = \exp(-2T_D/T_0)$ to calculate the loss per stage in a BPC system with delay times of 220 ns, 440 ns, and 880 ns (for the 1.5 TeV collider in Table I), we calculate $\eta(220\text{ ns}) = 0.985$, $\eta(440\text{ ns}) = 0.97$, and $\eta(880\text{ ns}) = 0.94$. The net loss efficiency is $\eta_{\text{loss}} = 90\%$. This leaves an allowance of 2% per stage for other component losses in order to achieve an overall efficiency of 84%.

Table 2
RF Source Requirements for Future Colliders Using Binary Pulse Compression

Energy (TeV) [frequency (GHz)]	Station length (m) [structures /station]	Compression ratio [power gain]	$\widehat{P}_{rf}$/station (MW) [pulse energy/ station (J)]	Klystron peak power (MW) [T_k (ns)]	Number of stations [number of klystrons]
1.5 [11.4]	7.2 [4]	8 [6.4]	1440 [317]	112 [1760]	2960 [5920]
5.0 [34]	4.8 [8]	16 [12.8]	2570 [128]	100 [800]	7400 [14,800]
25 [104]	4.0 [16]	32 [25]	7220 [87]	144 [385]	20,250 [40,500]

The first entry in Table 2 shows the rf power source requirements for a 1.5 TeV collider using the BPC system just described. The second entry, based on a BPC system with a compression ratio of 16, gives source requirement for the 5 TeV collider in Table 1. A BPC with R = 8 at 34 GHz could be scaled directly from the 11.4 GHz design above, since both the loss decrement time and the delay time scale as $\omega^{-3/2}$. To go to R = 16, the Q and therefore the scaled cavity length must be doubled. However, since the number of accelerating structures per rf station is also doubled, there is room to do this. The same reasoning applies to the design of a BPC system for the 25 TeV machine. However, as the cavity length is increased relative to the wavelength, the cavity becomes more overmoded. The loaded Q for a BPC cavity is $Q_L/Q_0 = T_k(2NT_0)$, where N is the number of cavities per stage. This ratio is $\approx 4 \times 10^{-3}$ for $N = 7$ and a first stage efficiency of 94%. Thus, unless care is taken, the bandwidth of the system could overlap a number of parasitic modes. These modes can be moved around in frequency to clear space for the desired mode by tailoring the radial profile of the cavity end disks, or longitudinal profile of the cylindrical outer surface. The use of an "open resonator" type of cavity (12) can also be considered.

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