A COMPARISON BETWEEN PULSE COMPRESSION OPTIONS FOR NLC*

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Abstract

We present a comparison, between options for pulse compression systems that provide rf power to the main linac of the Next Linear Collider (NLC). The parameters which are compared are efficiency, number of components and length of rf storage lines. Based on these parameters we produce a cost model for each system as a function of compression ratio, number of rf sources per unit system, and storage line parameters. The systems considered are Delay Line Distribution Systems (DLDS), Binary Pulse Compression (BPC), and Resonant Delay Lines (SLED-II). For all these systems we consider possible improvements through the use of several modes, active switches, and circulators.

1 INTRODUCTION

During the past few years high power rf pulse compression systems have developed considerably. These systems provide a method for enhancing the peak power capability of high power rf sources while matching the long pulse of that source to the shorter filling time of the accelerator structure. In particular, future linear colliders, such as the proposed NLC[1] require peak rf powers that cannot be generated by current state-of-the-art microwave tubes. The SLED pulse compression system [2] was implemented to increase the gradient of the two-mile linac at the Stanford Linear Accelerator Center (SLAC). One drawback of SLED is that it produces an exponentially decaying pulse. To produce a flat pulse and to improve the efficiency, the Binary Pulse Compression (BPC) system [3] was invented. The BPC system has the advantage of 100% intrinsic efficiency and a flat output pulse. Also, if one accepts some efficiency degradation, it can be driven by a single power source [4]. However, The implementation of the BPC [5] requires a large assembly of over-moded waveguides, making it expensive and extremely large in size. The SLED II pulse compression system is a variation of SLED that gives a flat output pulse [6]. The SLED II intrinsic efficiency is better than SLED, but not as good as BPC. However, from the compactness point of view, SLED II is far superior to BPC. Several attempts have been made to improve its efficiency by turning it into a system using active switching [7]. However, the intrinsic efficiency of the active SLED-II system is still lower than that of the BPC. The DLDS [8] is a similar system to BPC, but by sending the rf upstream twords the gun it utilzes the return delay of the electron beam to reduce the length of the over-moded waveguide assembly. However it still uses more over-moded waveguide than that required by SLED-II. To further enhance the DLDS a variation on that system, the Multi-moded DLDS (MDLDS) [9] was introduced, which further reduces the length of the waveguide system by multiplexing several low-loss rf modes in the same waveguide. The system has an intrinsic efficiency of 100%, and the total over-moded waveguide length has been reduced considerably.

We present a comparison, based on cost, for all various compression schemes that are available for the Next Linear Collider. In this comparison we do not describe the systems involved at any level of detail. The reader is referred to the cited references for details. However, it is our purpose to give an accurate formulation for the system efficiency, number of components, and length of delay lines or storage lines for each of these schemes as a function of compression ratio (the ratio of the source rf pulse width to the compressed pulse width). This will provide the basis for cost comparison. We will also extrapolate on the potential to expand and/or improve systems through the usage of

a. Multi-moded structures,
b. Active switching,
c. Circulators.

2 COST MODEL

Basically, the rf sources available now or in the near future will produce a pulse T of about 1.5 μs. The NLC accelerator structure needs a pulse of 380 ns. Hence, a pulse compression system which compresses the source rf pulse by a factor C_r=4 is required. The factor of 4 is the minimum required compression ratio. If rf sources can be improved to provide longer pulse lengths at the same peak power, one might utilize a bigger ratio.

To achieve this pulse compression a storage system is employed to store the rf power until it is needed. Different portions of the rf pulse T are stored for different amount of times. The initial portion of the rf pulse is stored for a time period t_m, the maximum amount of storage time for any part of T. The maximum value for t_m is

$$t_m^{\max} = \tau(C_r - 1) \qquad (1)$$

where $\tau = \dfrac{T}{C_r}$ is the accelerator structure pulse width, and C_r is the compression ratio. The value given in by Eq.(1) is typical for most systems with the exception of

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DLDS, which stores the energy for only half the time. The realization of the storage system is usually achieved using low-loss waveguide delay lines. These lines are usually guides that propagate the rf signal at nearly the speed of light. The maximum length required for these guides, per compression system, is

$$l^{\max} = t_m v_g \frac{C_r}{2}, \quad (2)$$

where v_g is the group velocity of the wave in the delay line. The total number of rf pulse compression systems required for the accelerator system is given by

$$N_c = \frac{N_a P_a}{P_k n_k C_r \eta_c}, \quad (3)$$

where N_a is the total number of accelerator structure in the linac, P_k is the klystron (or the rf power source) peak power, P_a is the accelerator structure required peak power, n_k is the number of klystrons combined in one pulse compression system, and η_c is the efficiency of the pulse compression system. Thus the total length of waveguide storage line for the entire linac is given by

$$L = l^{\max} N_c R_l = \frac{1}{n_k \eta_c} \frac{N_a P_a}{P_k} \frac{t_m v_g}{2} R_l \,. \quad (4)$$

where R_l is a length reduction factor which varies from one system to another and in general is also a function of the compression ratio. The total number of klystrons in the system is given by,

$$N_k = \frac{1}{C_r \eta_c} \frac{N_a P_a}{P_k} \,. \quad (5)$$

The cost of the rf system is divided into three different parts: cost of the klystron tube, the klystron power source and modulator, and the rf pulse compression and transportation system. The cost of the klystron tubes is given by

$$S^k = N_k A_k = \frac{1}{C_r \eta_c} \frac{N_a P_a}{P_k} A_{k0} \left(\frac{C_r}{C_{r0}} \right)^{a_k}, \quad (6)$$

where A_{k0} is the cost per klystron at a compression ratio C_{r0}. The exponent a_k is a number that depends on the details of manufacturing klystrons. For our present discussion we will assume that this number is 0.4 and C_{r0} =4 [10].

The cost of *conventional* modulators is also dependent on the compression ratio. If the klystron pulse width is increased the stored energy in modulator is increased and hence its cost. A fraction k_m^s of the modulator cost is due to its energy storage elements [11]. The rest of the fractional cost, $1 - k_m^s$, is due to the rest of the system, in particular the switching elements. Hence, a suitable model for the modulator cost is

$$S^m = N_k A_{m0} \left(1 + k_m^s \left(\frac{C_r}{C_{r0}} - 1 \right) \right) = \frac{1}{\eta_c} \frac{N_a P_a}{P_k} \left(\frac{1 - k_m^s}{C_r} + \frac{k_m^s}{C_{r0}} \right) A_{m0}, \quad (7)$$

where A_{m0} is the cost of the modulator per klystron at a compression ratio C_{r0}.

The cost of the rf pulse compression and power transmission is divided into two parts: a part that is dependent on the storage line length *L* and diameter *D*, and a part that is dependent on the number of components per pulse compression system n_c. The storage line cost is divided into two parts: the cost of the vacuum system, which is a very weak function of diameter, and the cost of the pipes, which is directly proportional to the diameter. The cost model is, then, given by

$$S^c = \left(A_l^v + A_l^p D \right) L + N_c A_c n_c = \frac{N_a P_a}{n_k P_k \eta_c} \left(\tau v_g \frac{(C_r - 1)}{2} R_l \left(A_l^v + A_l^p D \right) + \frac{1}{C_r} A_c n_c \right) \quad (8)$$

where A_l^v is the cost of vacuum system per unit length, A_l^p is the cost of waveguide pipe per unit length and diameter, and A_c is the cost per component. The total cost of the rf system normalized to the cost of one klystron A_{k0} is given by

$$S_r(C_r, D, n_k, R_l; k_m, k_l^p, k_l^v, k_c, k_m^s) =$$
$$\frac{P_a}{P_k \eta_c} \left(\frac{1}{C_r} \left(\frac{C_r}{C_{r0}} \right)^{a_k} + k_m \left(\frac{1 - k_m^s}{C_r} + \frac{k_m^s}{C_{r0}} \right) + \frac{k_c}{n_k} \left(\frac{(C_r - 1)}{2} R_l \left(k_l^v + k_l^p D \right) + \frac{n_c}{C_r} \right) \right) . \quad (9)$$

The parameters $k_m, k_l^{\cdot}, k_c, k_l^{r}$ are the normalized cost factors and are given by

$$k_m = \frac{A_{m0}}{A_{k0}}, k_c = \frac{A_c}{A_{k0}}, k_l^v = \frac{A_l^v \tau v_g}{A_c}, \text{ and } k_l^p = \frac{A_l^p \tau v_g}{A_c} \text{ cm-1} \quad (10)$$

The cost of the modulators and components are normalized to the cost of a klystron at a compression ratio C_{r0}. However, the cost of the delay line is normalized to the cost of a component. This is done because of the nature of the information available for the cost estimates at this time [12].

In the following we will compare all available pulse compression techniques based on the above-described criteria. To make the comparison more specific for the proposed NLC design we will make the following assumptions:

a. The operating frequency of the system is 11.424 GHz
b. The duration of the accelerator rf pulse is 380 ns.
c. The basic waveguide delay system uses the TE_{01} mode.
d. The next higher order modes that can be used are the two polarizations of the TE_{12}, and the two polarizations of the TE_{22} mode. Hence in calculating the efficiency of the compression system, the theoretical attenuation as a function of diameter for these modes is considered.
e. The efficiency of transmission from the klystrons to the pulse compression system and from the pulse

compression system to the accelerator structure is about 90%. Hence the total efficiency of the rf system is, $\eta_c = 0.9\eta_t\eta_i$; where η_i is the intrinsic efficiency of the system, and η_t is the efficiency of the delay lines. The maximum possible value is achieved with the DLDS using the TE_{01} mode in all waveguides.

f. The number of accelerator structures N_a is 9936 for 1 TeV collider, and the power needed per accelerator structure P_a is 170 MW.

g. Based on [12], we will assume that the ratios $k_c = 0.012$, $k_m = 0.5$, $k_l^v = 36$, $k_l^p = 1.4\,\mathrm{cm}^{-1}$, $k_m^s = 1/3$, $C_{r0} = 4$

h. The maximum amount of energy per rf pulse E^{max} that can be handled by rf components limits the maximum number of klystrons, n_k, that can be combined to provide power to a single pulse compression system; i.e., $n_k \le E^{max}/(P_k C_r \tau)$.

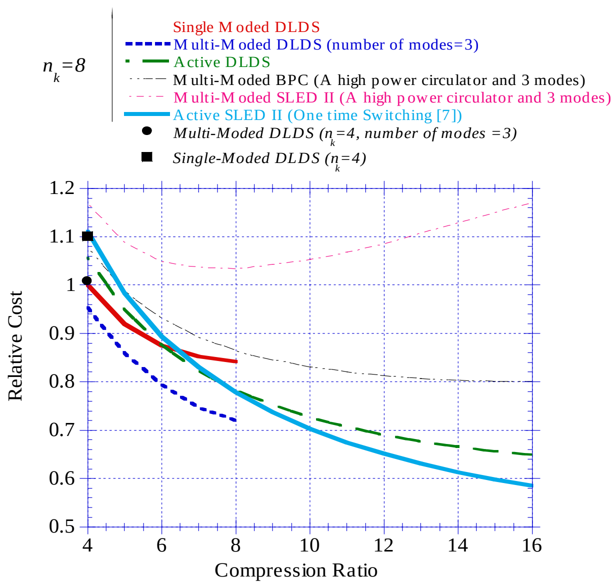

Fig. 1 Comparison between different pulse compression schemes. The relative cost is normalized to the cost of a single moded DLDS at a compression ratio of 4.

i. Because components vary in their complexity we will give different weights to them. Hence in counting the number of components n_c for each system, we will assume that some complex components are the equivalent of several simple components.

Fig. 1 shows the relative cost for several systems vs compression ratio. For each of these systems we calculated a general expression for the number of components, for the length reduction factor, and for the efficiency as a function of compression ratio.

3 CONCLUSION

For most systems there is a considerable cost reduction as one goes to higher compression ratios. This implies the need for rf power sources that are capable of longer pulse width.

The development of high power circulators, multi-moded technology and active super-high-power switches will result in a considerable cost reduction for the NLC

4 REFERENCES

[1] The NLC Design Group "Zeroth-Order Design Report for the Next Linear Collider," SLAC-Report-474, May 1996.

[2] Z. D. Farkas et. al., "SLED: A Method of Doubling SLAC's Energy," Proc. of the 9th Int Conf. on High Energy Accelerators, 1976, p. 576.

[3] Z. D. Farkas, "Binary Peak Power Multiplier and its Application to Linear Accelerator Design," IEEE Trans. MTT-34, 1986.

[4] P. E. Latham, "The Use of a Single source to Drive a Binary Peak Power Multiplier," Linear Accelerator Conference, Williamsburg, Virginia, 1988, CEBAF-R-89-001, pp. 623-624.

[5] Z. D. Farkas, et . al., "Two-Klystron Binary Pulse Compression at SLAC," Proc. of the IEEE Particle Accelerator Conference, Wasington DC, May 1993, p. 1208.

[6] P. B. Wilson, Z. D. Farkas, and R. D. Ruth, "SLED II: A New Method of RF Pulse Compression," Linear Accl. Conf., Albuquerque, NM, September 1990; SLAC-PUB-5330.

[7] S.G.Tantawi, et al. "Active High-Power RF Pulse Compression Using Optically Switched Resonant Delay lines" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES IEEE, Aug. 1997. vol.45, no.8, pt.2, p. 1486-92

[8] H. Mizuno, Y. Otake, "A New Rf Power Distribution System For X Band Linac Equivalent To An Rf Pulse Compression Scheme Of Factor 2**N," 17th International Linac Conference (LINAC94), Tsukuba, Japan, Aug 21 - 26, 1994, KEK-PREPRINT-94-112, Oct 1994. 3pp.

[9] S.G. Tantawi, et al. " A Multi-Moded RF Delay Line Distribution System for the Next Linear Collider," to be published in the proc. of the Eighth Workshop on Advanced Accelerator Concepts, Baltimore, MD, USA 6-11 Jul 1998.

[10] Robert M. Phillips, private communications.

[11] Richard Cassel, private communications.

[12] Michael L. Neubauer, private communications.