MINIMIZING RF SYSTEM COSTS IN A LINEAR COLLIDER BY AN OPTIMIZED CHOICE OF BEAM AND STRUCTURE PARAMETERS

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Abstract

In the design of future linear colliders it will be important to reduce the cost of the RF system by minimizing the total number of major system components (klystrons, modulators and pulse compression systems). In this paper we develop a procedure for performing this minimization by varying appropriate accelerating structure and beam parameters while maintaining a constant luminosity, AC "wall-plug" power and net beam-loaded accelerating gradient. Results for both standing-wave and traveling-wave accelerator structures are presented, including the plane-wave transformer and more conventional disk-loaded structures having cells with shaped (as opposed to purely cylindrical) outer boundaries and irises.

1. INTRODUCTION

The process for choosing the parameters of a linear collider proceeds in two, roughly separable, stages. First, given energy and luminosity goals, limitations on final focus optics, and limitations imposed by beam-beam effects such as beamstrahlung and pair production, the bunch dimensions and charge are chosen. Next, the rf accelerating gradient, number of bunches (related to the rf pulse length) and repetition rate are chosen, consistent with the desired luminosity and a reasonable ac "wall-plug" power. Alternatively, in a well-known optimization technique, the accelerating gradient is allowed to vary, and a balance is struck between length-related and power-related costs to find the gradient and associated ac power which minimize the total cost. This optimization is very loose, since the cost coefficients entering into the equation are only approximately known, and further, cost variations about the minimum are second order. In the case of a linear collider, there are further social and political constraints on both the allowable ac power and total collider length. In this paper we assume that both the allowable ac power and accelerator length (or loaded accelerating gradient for a given final energy) have already been fixed by these considerations.

Having fixed the luminosity, the accelerator length and the ac power, the primary goal in the following analysis will be to minimize the rf system cost by adjusting the accelerating structure parameters (primarily the field attenuation parameter, τ) and the beam parameters (spacing between bunches and number of bunches) to minimize the number of rf system components: klystrons, modulators and pulse compression/rf power distribution systems. The analysis is applied to the parameters of the 11.4 GHz, 1 TeV NLC linear collider design as outlined in the Zero-Order Design Report (ZDR [1]).

2. TRAVELING-WAVE STRUCTURES

The NLC 1 TeV design is based on an unloaded gradient of 85 MV/m, a beam loading gradient of 21.5 MV/m (bunches with a charge of 1.1×10^{10} electrons spaced 16 λ, or 1.4 ns, apart) and an on-crest loaded gradient of 63.5 MV/m. The required rf power of 145 MW/m is provided by a binary pulse compression system with a power gain of 3.5 driven by four 75 MW klystrons and delivering 1,040 MW to 7.2 m of accelerating structure (four 1.8 m sections). The power provided by this "power unit" of 4 klystrons, 2 modulators and one pulse compression system is assumed to be fixed in the following analysis. The loaded gradient is given for the NLC detuned accelerating structure [2] by:

$$G_L = 55.5 = (\alpha\rho)^{1/2}\left(1-e^{-2\tau}\right)^{1/2}(96.3) \quad - \\ \rho N\left(\frac{1}{2}-\frac{\tau e^{-2\tau}}{1-e^{-2\tau}}\right)\left[(141.7)/\Delta T\right] \qquad (2.1)$$

Here α is the relative power per unit length, normalized to 145 MW/m. It is inversely proportional to the separation between power units, and directly proportional to the total number of power units in the linac. The quantity ρ gives the relative shunt impedance, compared to 79MΩ/m for the center cell in the NLC structure design; N is the bunch charge, normalized to 1.1×10^{10}; and ΔT is the separation between bunches in ns (which must be an integer multiple of the damping ring rf period of 1.40 ns). The numerical constants are in MV/m.

Equation (2.1) gives the dependence of the unloaded and beam loading gradients on the attenuation parameter τ for a constant gradient accelerating structure. The field profile for the Gaussian detuned NLC structure differs somewhat from a true constant gradient; moreover, the structure parameters vary considerably along the length of the structure (the shunt impedance varies by about $\pm$ 20%). Therefore, the constants in the square brackets are adjusted to give the unloaded and beam loading gradients obtained from an exact calculation. The effective shunt impedances for the unloaded and beam loading gradients are 78.2 MΩ/m and 80.5 MΩ/m respectively for τ = 0.51). In spite of the approximation underlying Eq. (2.1), we expect that it will adequately represent scaling as function of τ to the precision needed for the optimization proceedure to be carried out here.

A further complexity in Eq. (2.1) is that the effective unloaded gradient is reduced by off-crest operation necessary for BNS damping, by an overhead allowance for feedback and by an allowance for stations off for repair. A reduction factor of 0.91, contained in the 96.7 MV/m constant, takes this overhead into account. The effective loaded gradient is then 55.5 MV/m for $\alpha = \rho = N = 1$, ΔT = 1.4 ns and τ = 0.51. This effective gradient is conserved in this analysis.

For the 1 TeV NLC design given in the ZDR, a luminosity of $1.1 \times 10^{34}/cm^2/sec$ is obtained for a train of 90 bunches spaced 1.4 ns apart. The bunch train length is therefore 125 ns. For a structure filling time of 100 ns, and allowing 15 ns for rise time due to phase switching, the rf pulse length is 240 ns. To keep the ac power constant, the quantity $(T_p/240\ \text{ns})f_r\,\alpha$ must be conserved where f_r is the pulse repetition rate (120 Hz in the NLC design). To keep the luminosity constant, the quantity $N^2 n_b\ f_r = 10{,}800$ must also be conserved. As a further consideration, we must allow for the possibility that the Q of the structure can change following design improvements. The time constant of the NLC structure is 195 ns, and the filling time is then T_F = (195 ns) τ Q_r where Q_r is the improvement factor compared to Q = 6980. The beam pulse length is $\Delta T(n_b\ -1)$. Putting these considerations together, to conserve both ac power and luminosity:

$$\alpha f_r\left[195\tau Q_r + \Delta T\left(\frac{10{,}800}{f_r N^2} - 1\right) + 15\right] = 28{,}800 \qquad (2.2)$$

The quantity in square brackets is the total pulse length, $T_p = T_F + T_{beam}$ + 15 ns. For specific values of ΔT, f_r, Q_r and ρ, the quantity N_r can be eliminated between Eqs. (2.1) and (2.2) to obtain $F(\alpha, \tau) = 0$. This can be evaluated to find the value of τ which gives the minimum value of α.

The above procedure has been carried out for six cases: bunch spacings of 1.4, 2.8 and 4.2 ns with repetition rates of 60 and 120 Hz. The minimum values of α for these cases are shown in Table 1, together with corresponding values of τ, N and N_b at α_{min}, for the standard NLC structure with $\rho = 1$, $Q_r = 1$ (denoted by NLC-1 in the Table). Recently, changes in the geometry of the individual cells in the NLC structure have lead to a 20% improvement in shunt impedance (ρ = 1.2) and higher Q (Q_r = 1.12). The Q has been increased by making the outer cell wall elliptical in longitudinal cross-section, and the r/Q has been improved by giving these iris a tear-drop shape with a slight bulge. Results of the minimization procedure for these new parameters are shown as NLC-2 in Table 1.

3. STANDING-WAVE STRUCTURES

The minimization procedure described above can also be applied to standing-wave structures. Based on a normalizing shunt impedance of 79 MΩ/m, the expression analogous to Eq. (2.1) for a standing-wave structure is

$$55.5 = \frac{2\beta^{1/2}}{1+\beta}(\alpha\rho)^{1/2}(97.2) - \frac{\rho N}{1+\beta}\left[(139)/\Delta T\right] \qquad (3.1)$$

where β is the cavity coupling coefficient. A reduction factor of 0.91 is again included in the constant 97.2 MV/m to allow for the required overhead.

An advantage of a standing-wave structure is that beam loading compensation is exact if the beam is switched on at time $T_s = T_F \ln(1/b)$, where b is the ratio of the beam loading gradient to the on-crest unloaded gradient,

$$b = 0.651\left(\frac{\rho}{\alpha\beta}\right)^{1/2}\frac{N}{\Delta T} \qquad (3.2)$$

The beam pulse length is again given by $T_b = (n_b - 1)\Delta T$, and to preserve the luminosity $N^2\ n_b\ f_r$ = 10,800. Analogous to Eq. (2.2), to conserve ac power and luminosity

$$\begin{aligned}&\alpha f_r\left\{\frac{195\,Q_r}{1+\beta}\ln\left[1.536\left(\frac{\beta\alpha}{\rho}\right)^{1/2}\frac{\Delta T}{N}\right]\right\} + \\ &\alpha f_r\left\{\Delta T\left(\frac{10{,}800}{f_r N^2} - 1\right) + 15\right\} = 28{,}800\end{aligned} \qquad (3.3)$$

The quantity in the curly brackets is the rf pulse length in ns. Again, N can be eliminated between Eqs. (3.1) and (3.3) to obtain $F(\alpha, \beta) = 0$, which can be solved for minimum α as a function of β for various values of ΔT, f_r, ρ and Q_r. This minimization has been carried out for several standing-wave structures. First, if we assume the NLC structure is converted to a π-mode structure (denoted as PMS) with the same average beam aperture as the center cell of the TW structure, but with fully rounded outer cell boundary, we obtain [3]: ρ = 1.00, Q_r = 1.50. A second interesting structure is the plane wave transformer (PWT) structure proposed by D. A. Swenson [4]. If the iris aperture radius of this structure is opened up to 4.7 mm, the r/Q is expected to decrease by about 40% to 3.8 kΩ/m. This is about 35% of the value for the NLC structure. The scaled Q of the PWT is 44,500. The introduction of this support rods is expected to reduce this substantially (by about 25%) to 33,000. Thus the high shunt impedance, 132 MΩ/m (ρ = 1.67), comes principally from the large increase is Q (Q_r = 4.73). This has the disadvantage of making the filling time and rf pulse length longer. Minimum values of α, together with associated values of β, N, n_b and T_p, are shown in Table 2 for the PMS and PWT structures for various values of f_r and ΔT.

4. DISCUSSION

From the first entry in Table 1, it is seen that the parameters as given in the ZDR for the NLC-1 structure (τ = 0.51, N = 1, n_b = 90 and t_p = 240 ns) are close to optimum. However, it has recently been realized that by increasing the bunch spacing to 2.8 ns the beam loading could be reduced, allowing a reduction in the unloading gradient and a corresponding decrease in the number of power units required for the linac. The parameters presently under consideration are based on using six 1.8 m NLC-2 structures per power unit (giving α = 0.66) together with τ = 0.54, N = 1.0, n_b = 82 and T_p = 362 and a relative luminosity of 0.91. These values are not too different than the optimum parameters given in the third row of Table 1. The luminosity could be regained by a slight increase in bunch charge. The τ parameter is too low, but it cannot be increased without reducing the structure group velocity, which leads to an unacceptable increase in dipole wakefield. A modest further reduction in α could be made by increasing ΔT to 4.2 ns, but at the expense of higher N (enhancing both wakefields and beam-beam effects), a longer klystron pulse length (equal to 4 T_p), and a still greater optimum τ. All of the 60 Hz solutions, while giving a modest reduction in α, lead to unacceptably long klystron pulse lengths.

In the standing-wave case, the PMS structure gives results which are closely comparable to the traveling wave, NLC-2 results; possibly this structure should be given further consideration. The slight reduction in α offered by the PWT structure is offset by the mechanical complexity of this structure and the difficulty in cooling the irises.

5. ACKNOWLDEGMENTS

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6. REFERENCES

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

[2.] *Ibid.*,Sec. 8.2.

[3.] V. Srinivas, SLAC; private communication.

[4.] Donald A. Swenson, "The Plane Wave Transformer Linac Structure", Proceedings of the 1988 European Particle Accelerator Conference (EPAC 88), p. 1418.

Table 1: Minimum α and Associated Parameters for two NLC Traveling-Wave Structures

ΔT (ns)	f_r (Hz)	α_{min} NLC-1	α_{min} NLC-2	τ NLC-1	τ NLC-2	N NLC-1	N NLC-2	n_b NLC-1	n_b NLC-2	T_p(ns) NLC-1	T_p(ns) NLC-2
1.4	120	0.99	0.87	0.47	0.45	0.96	0.88	98	116	243	274
1.4	60	0.84	0.75	0.67	0.62	0.77	0.72	305	350	570	639
2.8	120	0.74	0.64	0.67	0.64	1.17	1.07	65	75	325	372
2.8	60	0.65	0.57	0.91	0.86	0.96	0.89	195	228	734	837
4.2	120	0.65	0.56	0.79	0.76	1.35	1.23	49	60	372	429
4.2	60	0.58	0.51	1.06	1.01	1.11	1.03	145	171	826	950

Table 2: Minimum α and Associated Parameters for two Standing-Wave Structures

ΔT (ns)	f_r (Hz)	α_{min} PMS	α_{min} PWT	β PMS	β PWT	N PMS	N PWT	n_b PMS	n_b PWT	t_p(ns) PMS	t_p(ns) PWT
1.4	120	0.82	0,87	2.79	5.77	0.85	1.12	124	71	291	277
1.4	60	0.73	0.60	2.34	3.38	0.70	0.69	371	376	655	800
2.8	120	0.64	0.60	2.15	3.91	1.07	1.34	78	50	375	402
2.8	60	0.58	0.44	1.86	2.48	0.89	0.85	230	248	821	1079
4.2	120	0.57	0.50	1.90	3.27	1.25	1.54	57	38	420	477
4.2	60	0.53	0.39	1.67	2.15	1.03	0.98	168	186	910	1239