Linear e^+-e^- Colliders Above 1 TeV (CM)*

Alfred A. Mondelli
Science Applications International Corporation
1710 Goodridge Drive
Mc Lean, Virginia 22102

Abstract

This paper describes the scaling of the e^+-e^- linear collider beyond Next Linear Collider (NLC) to TeV-class devices. The study includes considerations of interaction-point parameters, accelerator parameters, and cost parameters, so that a complete picture of the trade-off's between the various design options can be discerned. Detailed analyses are presented for three devices: (1) the NLC at 0.5 TeV(CM) and a luminosity of 2×10^{33} cm^{-2}-s^{-1}, (2) the NLC Upgrade at 1.5 TeV(CM), 2×10^{34} cm^{-2}-s^{-1}, and (3) a 3 TeV(CM) collider at 10^{35} cm^{-2}-s^{-1}. The study shows that while the NLC device will work well at X band drive frequencies, there is an advantage to building the NLC Upgrade at K_t band, and that the 3 TeV collider should be built at K_t band to achieve reasonable operating parameters.

INTRODUCTION

This study has focused on the scaling of linear colliders beyond the Next Linear Collider (NLC) to larger colliders having center-of-mass (CM) energy up to 3 TeV. The system luminosity is scaled as the square of the energy to preserve the counting rate. Sensitivity to wake fields at the low gradient envisioned for the NLC (33 MV/m) dictates that the frequency not exceed X band (≈12 GHz). The NLC Upgrade, with ≈100 MV/m gradient, however, can operate up to K_t band (≈20 GHz), provided that the assumed SLAC structure has been modified to reduce high-order wake fields responsible for the multi-bunch beam-breakup instability. Furthermore, building the NLC Upgrade at K_t band will make it expandable to a 3 TeV (CM) collider. This last device requires an efficiency obtainable only through high-frequency operation, and therefore should be designed at ≈20 GHz.

The character of these studies has been to reduce the parameter space to a plane, using known relationships together with the specification of known quantities, and to plot curves representing "constraints" on the parameter plane. The constraint inequalities map to allowed and forbidden regions of the plane. Parameter plane analyses are carried out first for the interaction point, which is independent of the accelerator model, and then for the accelerator scaling based on a SLAC-like rf linac. Typically, the allowed region in the accelerator parameter plane is closed at high frequencies by the transverse wake-field effects and is closed at low frequencies by the ac or rf power constraints. Since the wake-field limit is a very sharp cut off, one gains by operating at high frequencies.

The results of the study indicate that the optimal operating regime for the linear collider is ≈20 GHz, where wake-field effects are still tolerable, and the collider will have the efficiency needed to reach multi-TeV energy at high luminosity.

Table 1. Interaction-Point Parameters	NLC	NLC Upgrade	3 TeV Collider
CM Energy (γmc^2) [TeV]	0.5	1.5	3.0
Luminosity (L) [cm^{-2}-s^{-1}]	2×10^{33}	2×10^{34}	1×10^{35}
Aspect Ratio (R)	100	100	100
Average Beam Power (P_b) [MW]	0.5	3.0	10.0
Yokoya Parameter (A)	0.2	0.2	0.2
Disruption Parameter (D)	10	20	20
Number per Bunch (N)	1×10^{10}	1×10^{10}	2×10^{9}

INTERACTION-POINT PARAMETERS

Eleven quantities specify the IP. They are the beam size (σ_x, σ_y, σ_z), the number per bunch (N), the bunch repetition frequency (ν), the luminosity (L), the beamstrahlung loss (δ_{BS}), the average beam power (P_b), the beam energy (γ), the disruption parameter (D), and the Yokoya parameter ($A\equiv\sigma_z/\beta^*$). The IP parameters are subject to several types of constraints. A typical study consists of specifying γ, L, $R\equiv\sigma_x/\sigma_y$, P_b, and A. Using these five choices, together with the four equations that define L, δ_{BS}, D, and P_b, reduces the original eleven-parameter space to a two-parameter space, e.g. (σ_y,σ_z). Contours of the various curves of constraint are then plotted in this parameter space, yielding regions of the (σ_y-σ_z) plane that are allowed under the constraints[1].

Three different colliders have been studied, viz. the NLC, the NLC Upgrade, and a 3 TeV (CM) collider. The resulting IP parameters are summarized in Table 1.

0-7803-0135-8/91$03.00 ©IEEE

Table 2. Accelerator Model Parameters	**NLC (X Band)**	**NLC Upgrade (X Band)**	**NLC Upgrade (K_t Band)**	**3 TeV Collider (K_t Band)**
RF Frequency [GHz]	11.4	11.4	20.	20.
Average accelerating Gradient [MV/m]	33.	100.	100.	100.
σ_z [μm]	94.9	113.9	113.9	75.92
Bunches per RF Pulse	10	30	30	100
Structure Efficiency (η_s)	0.58	0.58	0.58	0.58
Total RF and Pulse Compression Efficiency (η_{RF})	0.20	0.30	0.30	0.30
a/λ	0.175	0.175	0.175	0.175
Ratio of Transverse Wake Field to Scaled-SLAC Wake Field	0.25	0.25	0.25	0.25
Length per Linac [km]	7.5	7.5	7.5	15.0
Average AC Power [MW/Linac]	13.3	79.5	26.5	88.
Peak RF Power [MW/Feed]	38.3	345.	115.	115.
Transverse Displacement (x/x_0)	<1.12	<1.12	<1.12	<1.12
Single-Bunch Energy Spread at Optimum Phase Advance	<0.005	<0.005	<0.005	<0.005
Length of RF Feed	2.	2.	0.9	0.9
Number of RF Feeds per RF Tube	8	4	8	8
Peak RF Power per Tube (before Pulse Compression) [MW]	50.	150.	100.	100.
Number of RF Tubes (both linacs)	938	1880	2080	4170
Total Capital Cost ($B)	1.7	2.2	2.3	3.7

ACCELERATOR MODEL

Accelerator Configuration

The linear collider is assumed to consist of several acceleration stages. The electron and positron bunches are injected into an S-band accelerating structure. At an energy of approximately 1 GeV they are transferred to damping rings to reduce their transverse emittances. On exiting the damping rings, the bunches must be recompressed into a single rf bucket, a process which increases the single-bunch energy spread. To control the energy spread the accelerating structure immediately following the damping ring is an S-band structure. During acceleration from the damping ring (≈1 GeV) to an energy of ≈10 GeV, adiabatic damping reduces the energy spread by ten fold. The bunches may then be further compressed from the S-band structure to a high-frequency structure (either X band or K_t band) for acceleration to the final energy.

The accelerator model considered in this study treats only the final, high-frequency structure, from nominally 10 GeV to the final energy of the collision. The accelerators for the linear collider are assumed to be based on a SLAC-type normal-conducting, traveling-wave rf linac driven by rf power amplifiers. These are assumed to be modulated rf power tubes with pulse compression to increase the peak output power per tube by a factor M_{pc}. Each rf tube, with pulse compression, is assumed to drive an accelerator module consisting of several feeds (typically 4-8 feeds per tube). The total rf efficiency is 20-30%.

Wake Field Effects

The longitudinal wake fields compete with the fundamental accelerating mode to cause energy spread within the bunch. The transverse wake fields lead to deflections of the beam from the axis, causing emittance growth. The longitudinal (monopole) wake fields scale as the square of the rf frequency, while the transverse (dipole) wake fields scale as its cube. To reduce the wake fields at high frequency, it is possible to enlarge the iris in the SLAC structure from its nominal value $a/\lambda \approx 0.11$ to $a/\lambda = 0.175$-0.20. The price of enlarging the iris is that the group velocity increases and the shunt impedance of the structure decreases, thereby requiring more rf power for a given accelerating gradient.

The effect of transverse wake fields can be controlled on a single bunch by using BNS damping[2]. The transverse wake field from bunch to bunch in a multi-bunch accelerator involves only the lowest order dipole mode (i.e. the beam-breakup mode). The structure must provide detuning for this mode so that its Q is ≈10-20, without destroying the Q or shunt impedance of the accelerating mode. Structures that meet this requirement have been designed at SLAC[3], for example. In such structures the BBU mode is essentially eliminated, and the total transverse wake field is reduced by a modest factor. For the present study the multi-bunch BBU has been neglected and the total transverse wake field has been assumed to be one-quarter of its value for a scaled SLAC structure. With this value, it is shown that BNS damping may not be required. An analytical calculation of the asymptotic bunch displacement under the influence of transverse wake fields with external focusing and a linear head-to-tail energy spread[4] is employed in these calculations.

Selection of Accelerator Parameters

Having selected γ, N, σ_z, and P_b from the IP model, the accelerator scaling can be carried out on a parameter plane spanned by peak accelerating field (E_0) and rf wavelength (λ). The scaling is carried out, as it is for the IP, by plotting curves of constraint on the E_0-λ parameter plane. The allowed region is defined by E_0 less than the breakdown field, average AC power less than a specified maximum, peak rf power per feed less than a specified maximum, minimum energy spread less than a specified value, growth of transverse bunch displacement less than a specified value, and accelerator length less than a specified value. Table 2 shows the accelerator parameters selected for the present study.

COST MODEL

The capital cost of an rf linear collider can be expressed as the fixed cost associated with the collider (i.e. all costs that do not scale with either the length of the accelerators or the number of rf drivers), the cost per unit length of accelerator (not including the costs associated with the rf drivers), and the cost associated with the rf drivers (including the modulator, rf tube, pulse compression system, and power transfer to the linac).

The fixed costs do not enter into the cost optimization described here, but they are a significant component of the total cost of the collider. Fixed costs have been estimated at $855M.

The costs per unit length consist mainly of the cost of the accelerator structure and vacuum system, magnets, and accelerator and klystron housings. The total of these costs has been estimated at $25M/km.

The costs associated with the rf drivers includes the modulator and tube costs as well as the cost of the pulse compression system (which is approximately the same with either BEC[5] or SLED-II[6]). These costs are approximately $0.5M/tube. The number of rf tubes is computed from the peak rf power per feed required together with a specification of the peak output power per tube and the power amplification factor due to pulse compression.

The results of the cost study are summarized in Table 2.

The NLC is assumed to be built at X band (11.4 GHz) and powered by rf sources with peak power of 50 MW. Since the accelerating gradient in the NLC Upgrade at X band are increased three-fold, the power requirements increase by a factor of nine over the NLC. One third of the increase has been absorbed by increasing the output power per tube from 50 MW to 150 MW.

For the K_t band NLC Upgrade the collider length is set to 7.5 km (≈100 MV/m), and the rf sources are assumed to yield 100 MW peak output power at 20 GHz. With 9.2-fold pulse compression and an output pulse duration of 0.9 μs at the rf tube, this system can drive eight 0.9 m feeds per tube. The system will consist of 2080 tubes, and will cost $2.3B.

The 3TeV (CM) collider at K_t band is a simple expansion of the NLC Upgrade to twice the length. The performance of each rf tube is the same here as in the K_t-band Upgrade, but there are now twice as many of them. The rf costs and length-associated costs are therefore double those in the Upgrade, bringing the cost of this device to $3.7B.

CONCLUSIONS

The scaling trends shown here lead to several interesting conclusions. The NLC will be built at X band, both because rf sources with the required power will not be available to build it at a higher frequency and because its low gradient makes it very susceptible to wake field effects at higher frequencies. Since the fixed costs are approximately 50% of the total NLC cost, it will make sense to reuse these facilities on several later upgrades.

Increasing the NLC gradient three-fold to reach the energy of the NLC Upgrade will require the installation of new rf sources with greater power and efficiency. While using 20 GHz sources for the upgrade requires that the entire X-band accelerator structure of the NLC be replaced with a K_t-band structure, this cost is offset by the saving of ≈500 tubes that is possible at 20 GHz. These two options for the NLC Upgrade are actually comparable in cost.

With the NLC Upgrade carried out at K_t band, the expansion to a 3 TeV (CM) collider will involve only the incremental costs (approximately $1.4B) associated with its greater length. On the other hand, if the NLC Upgrade is carried out at X band, the cost of building the 3 TeV (CM) system on the NLC site will be approximately $2.8B. On a new site, the 3 TeV device will cost $3.7B.

ACKNOWLEDGEMENT

It is a pleasure to acknowledge many interesting discussions on these questions with David Chernin at SAIC and with Martin Reiser and Victor Granatstein at the University of Maryland.

REFERENCES

* Work supported by the U.S. Department of Energy, Division of High Energy Physics.

1 A. Mondelli and D. Chernin, Proc. 1990 Linear Accel. Conf. (Albuquerque, NM, Sept. 10-14, 1990, LA-12004-C), p. 730.

2 V. Balakin, A. Novokhatsky, and V. Smirnov, Proc. 12th Intl. Conf. on High Energy Accelerators (Fermilab, 1983), p. 119.

3 R.B. Palmer, SLAC-PUB-4542 (July, 1988).

4 D. Chernin and A. Mondelli, Part. Accel. **24**, 177 (1989).

5 Z.D. Farkas, IEEE Trans. **MTT-34**, 1036 (1986).

6 P.B. Wilson, Z.D. Farkas, and R.D. Ruth, SLAC-PUB-5330 (September, 1990).