LCC-0151
SLAC-TN-0-048
June 2004

Linear Collider Collaboration Tech Notes

A Two-Stage Bunch Compressor Option for the US Cold LC

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June 2004

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Abstract

To increase the luminosity or improve the stability of the US Cold LC design, it would be advantageous to decrease the bunch length below the specified 300 μm. It is unlikely that further compression would be possible with the single stage compressor proposed in TESLA design and thus in this note we scale the two-stage NLC bunch compressor design to the US Cold LC design. The primary difficulties with this scaling are related to the much larger (factor of 3.6 times larger) longitudinal emittance in the US Cold LC design.

Introduction

In this note, we will consider a two-stage bunch compressor for the US Cold linear collider design [1] to produce bunch lengths of roughly 100 μm. The present single-stage compressor is designed to reduce the bunch length from 6 mm in the damping ring to 300 μm at injection into the linacs. It is difficult to design a single-stage compressor that will compress a bunch by much more than this factor of 20. The NLC X-band uses a two-stage compressor design to reduce the bunch length by a factor of 50.

In the following, we start with a short discussion on luminosity scaling to justify the desire for a shorter bunch length and then will discuss the two-stage design. Finally, we will conclude with a list of outstanding issues and suggestions for further improvements.

Luminosity Scaling

There are many different ways to parameterize the luminosity in a linear collider. Assuming that flat beams are chosen to constrain the beamstrahlung, the luminosity can be rewritten using Y and δ_B as:

$$L \propto P_{beam} \sqrt{\frac{\delta_B \sigma_z}{\gamma \varepsilon_y \beta_y}} H_D \left(1 + (1.5\mathrm{Y})^{2/3}\right)$$

It does not make sense to reduce the vertical beta function much beyond the bunch length because the hourglass effect will reduce the luminosity while the smaller beta function will require tighter tolerances in the final focus.

It is frequently noted that, for small Y, the final term can be dropped and the luminosity is effectively determined by the beam power, the vertical emittance, and the beamstrahlung energy spread. Of course, this is a scaling law and like all scaling laws it is not valid to use for detailed comparisons. Furthermore, for most normal conducting linear collider designs, which operate with Y between 0.1 and 0.3, the final term is important and actual changes the scaling.

A more appropriate expression for the next generation of linear colliders with Y less than 0.3 might be:

$$L \propto P_{beam} \sqrt{\frac{1}{\gamma \varepsilon_y \beta_y}} n_\gamma H_D$$

This expression is more closely related to the quantity that describes the luminosity near the center-of-mass as well as being more accurate over the range.

Alternately, the luminosity can be written in terms of the disruption which should not be allowed to become too large or the single bunch kink instability will eliminate any luminosity gains.

$$L \propto \frac{P_{beam}}{E_{cms}} \frac{D_y}{\sigma_z} H_D$$

Thus for a given beam power and maximum vertical disruption parameter, the only path to increasing the luminosity is to decrease the bunch length. Simulation studies have found that the single bunch kink instability starts to become important at disruption parameters in excess of 10. The present TESLA parameters specify a vertical disruption parameter of roughly 25 well beyond the threshold for the single bunch kink instability. The most straight-forward path to increasing the luminosity and/or decreasing the vertical disruption to improve the collider stability is to decrease the bunch length from the specified 300 μm.

Two-Stage Bunch Compressor

The basic NLC two-stage compressor was designed in 1994 [2,3,4] and is described in detail in Chapter 5 of the Ref. [5]. The design was re-optimized in 1999 to reduce the cost of the sub-system [6]. It is designed to take a bunch with a length of 5 to 6 mm from the NLC damping ring and compress it to a length between 150 and 90 μm. The compressor is a two-stage design because it is difficult to perform the factor of 50 compression in a single-stage system due to longitudinal nonlinearities, collective effects such as coherent synchrotron radiation, and chromatic aberrations.

The first stage of the NLC bunch compressor performs a factor of 10 compression which is similar to that performed by the SLC bunch compressor. The beam is then accelerated by a factor of 4 from 1.98 GeV to 8 GeV where the fractional beam energy spread decreases from roughly 1% to 0.25%. At this point, the bunch length is further compressed by another factor of five and the final energy spread increases to about 1.5%.

As a first attempt to shorten the bunch for the US Cold LC, we will scale the NLC compressor to the US Cold design. The primary constraints on the design are the longitudinal phase space from the US Cold damping ring (identical to the TESLA damping ring) which is about 3.6 times larger than in the NLC design and the incoherent synchrotron radiation emittance growth, which sets the length of the bending sections;

formulas for the emittance growth can be found in Ref. [7]. Other differences arise because of the relatively low rf frequency in the superconducting design. Parameters for the two systems are listed below in Table 1.

The first stage is designed to compress the beam by a factor of 11 down to a bunch length of 500 mm. The beam is then accelerated from 5 GeV to 20 GeV (a factor of 4 in energy) to decrease the incoherent energy spread and then it is compressed by a factor of ~5 in a second stage down to a final bunch length of 110 μm as in the NLC design.

The design parameters are chosen so that the fractional emittance growth due to incoherent synchrotron radiation is held fixed despite the higher beam energy and larger horizontal emittance.

The first stage is quite similar to the NLC design except the R56 of the wiggler is slightly smaller because of the larger incoming energy spread and the rf voltage is higher because of the slightly lower rf frequency, the higher beam energy, and the larger incoming longitudinal emittance.

The intermediate linac is assumed to accelerate the beam by a factor of four in energy to decrease the incoherent energy spread. It is certainly possible to reduce the length of this intermediate linac however the final energy spread will increase in proportion and the alignment tolerances will become tighter. As it is, the dispersive emittance dilution in the superconducting linac will increase by a factor of ~10 due to the larger product of the injection energy and the fractional energy spread – see Eq. (37) of Ref. [8]. The primary sources of dispersive emittance dilution are beam-to-quad offsets and rf deflections; these are summarized in Table 3.3.4.3 of Ref. [1].

The second compressor is assumed to be composed of a 180 degree turn-around and a chicane like the NLC design. The 180 degree arc will allow for feed-forward from the damping ring extraction to compensate for extraction kicker jitter and other beam extraction difficulties. In the US Cold case, the length of the arc is comparable to that of the arcs for the dog-bone damping ring and thus a $5/3\pi$ arc was assumed that would be installed in the same tunnel as the dog-bone ring arc at the low-energy end of the linac.

Although the 180 degree turn-around enables a feed-forward system, there is a major drawback. The spin depolarization which arises from the beam energy spread and the spin precession through the arc equal to $[1-exp(-(\gamma\delta_E\Theta/860)^2)]$ – see Eq. 5.7 of Ref. [5]. Because of the large longitudinal emittance in the US Cold design, for the same bunch length, the energy spread times the beam energy is about 3.6 times larger than in the NLC design and the spin depolarization is roughly 10% through the 180 degree arc.

The rf section after the 180 degree arc is very large. This arises for two reasons: first the beam energy is over two times higher than the NLC design and second the rf frequency is roughly 9 times lower than in the NLC design. Thus, one would expect that the rf section would need to be about 22 times the voltage as for the NLC case. The situation is actually worse if the higher-order longitudinal nonlinearities are also compensated by placing the bunch off the rf zero-crossing as is done for the NLC design [9]. In fact, this method of compensation does not work for the US Cold design because the bunch has to be placed so far off the zero-crossing due to the relatively low rf frequency that the rf system will decelerate the beam to a stop.

Summary

A two-stage bunch compressor is scaled from the NLC design to the US Cold LC design. The major difficulties that arise are related to the relatively low frequency rf system (1.3 GHz) which require extremely lengthy rf systems, adding roughly 45 GeV of rf to each injector system, and the larger longitudinal emittance which require a higher compression energy. The higher compression energy leads to longer bending sections to minimize the synchrotron radiation but will also lead to larger transverse dispersive emittance growth in the main linac and large spin depolarization. Future studies should consider the feasibility of higher frequency rf systems but the larger longitudinal phase space is difficult to compensate. In addition, studies should re-examine the option of using nonlinear magnetic fields to compensate the longitudinal nonlinearities through the compressor system although in earlier studies for the NLC system this did not look favorable.

Table 1. Parameters for a two-stage compressor for the NLC and the US Cold LC.

	NLC	US Cold
Damping ring extraction		
Energy [GeV]	1.98	5
Bunch length [μm]	5500	6000
Fractional energy spread [%]	0.1	0.13
Normalized X emittance [m-rad]	3e-6	8e-6
First compressor		
R56 wiggler [m]	0.48	0.37
Length wiggler [m]	50	80
Fractional X emittance growth [%]	1	1
Rf freq. [GHz]	1.4	1.3
Rf voltage [MV]	140	490
Rf phase [deg]	-102	-106
Bunch length [μm]	500	500
Fractional energy spread [%]	1.0	1.6
Intermediate linac		
Initial Energy [GeV]	1.98	5
Final Energy [GeV]	8	20
Fractional energy spread [%]	0.25	0.39
Second compressor		
R56 arc [m]	0.24	0.24
Angle of arc [deg]	180	+240 / –60 → net 180
Length arc [m]	165	1510

Fractional X emittance growth [%]	4	4
Bunch length [μm]	800	1100
Fractional depolarization	0.7%	10.9%
Rf freq. [GHz]	11.424	1.3
Rf voltage [MV]	620	30,700**
Rf phase [deg]	-103	-155**
Final energy [GeV]	7.85	-7.67**
R56 chicane [m]	0.043	0.043
Length chicane [m]	30	110
Fractional X emittance growth [%]	1	1
Bunch length [μm]	110	110
Fractional energy spread [%]	1.5	2.0

References

[1] The US LC Technology Options Study is located at: http://www.slac.stanford.edu/xorg/accelops.

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