A 30 GHz 5-TeV LINEAR COLLIDER

J.P. Delahaye†, G. Guignard†, J. Irwin‡, T.O. Raubenheimer†, R.D. Ruth‡, I. Wilson†, P.B. Wilson‡
† CERN, 1211 Geneva 23, Switzerland ‡Stanford Linear Accelerator Center, California, USA

Abstract

We present parameters for a linear collider with a 3 to 5 TeV center-of-mass energy that utilizes conventional rf technology operating at a frequency around 30 GHz. We discuss the scaling laws and assumed limitations that lead to the parameters described and we compare the merits and liabilities of different technological options including rf power source, accelerator structure, and final focus system design. Finally, we outline the components of the collider while specifying the required alignment and construction tolerances.

1 INTRODUCTION

Over the last decade, there has been an extensive effort in developing designs for a 0.5 to 1 TeV center-of-mass energy (cms) $e+e-$ linear collider[1]. At this time, many of these designs are well advanced and have moved to the stage where detailed engineering is being performed and much of the required technology has been, or is being, demonstrated in dedicated test facilities. Thus, it seems timely to look to the next stage in linear collider development.

In the past, there have been a number of studies of very high-energy linear colliders; for example Ref. [2]. More recently a working group at 1996 DPF/DPB Snowmass meeting was dedicated to the study of a 5 TeV e^+e^- collider and this group concentrated mostly on advanced acceleration and collision techniques[3]. In this paper, we will continue a discussion, that was started in Ref. [4], on the possibility of a 3 to 5 TeV e^+e^- linear collider based on relatively conventional rf power with a frequency around 30 GHz and having a luminosity ($\mathcal{L}$) of 10^{35}cm^{-2}s^{-1}.

The rf frequency is similar to that studied as part of the Compact LInear Collider (CLIC) project. The relatively high rf frequency was chosen because it allows for much higher acceleration gradients *without* significantly more severe alignment tolerances[5]:

$$y_{tol} \sim \sqrt{\Delta\epsilon/\epsilon}\, G^{1/2}/\omega^{7/16} \qquad (1)$$

where $\Delta\epsilon/\epsilon$ is the relative emittance dilution, G is the gradient, and ω is the frequency. Even though the wakefields are much stronger in the high-frequency structures, this scaling arises because the optimized charge and bunch length are much smaller and thus the *effect* of the wakefields and the required tolerances are comparable to that in lower frequency designs. We believe that the primary difficulty presented by the higher frequency choice is the present lack of high power rf sources.

In the following sections, we will first discuss the constraints imposed by the beam-beam interaction, then we will describe the determination of the collider parameters and, finally, we will estimate the impact that these parameters have on the various subsystems of the collider.

2 BEAM-BEAM INTERACTION

The primary difficulty when considering a very high energy e^+e^- collider is the beam-beam interaction at the collision point (IP). Because the beams must be very dense to provide useful $\mathcal{L}$, they have very strong electro-magnetic fields. These fields have two primary effects: first, they cause the particles to radiate beamstrahlung photons which induces a large energy spread, smearing the $\mathcal{L}$ spectrum, and, second, e^+e^- pairs can be produced in the strong fields creating a potential background source.

Two approaches have been or are being investigated to avoid these problems: the muon collider[6], where the relatively massive particles are far less sensitive to the beam-beam forces, and charge compensation, where the beam fields are compensated by co-moving beams or plasma return currents.

Unfortunately, both of these solutions also have significant difficulties. Thus, in this paper, the approach is to optimize the parameters of a conventional e^+e^- linear collider to maximize the amount of $\mathcal{L}$ close to the full cms energy while accepting a substantial smearing in the lower energy $\mathcal{L}$ spectrum. The $\mathcal{L}$ spectrum can be parameterized in terms of Υ, a measure of the field strengths, n_γ, the average number of photons radiated per particle, and δ_B, the energy loss due to the beamstrahlung[7]:

$$\Upsilon \approx \frac{5}{6}\frac{r_e^2\gamma N}{\alpha\sigma_z(\sigma_x+\sigma_y)} \quad n_\gamma \approx \frac{2r_e\alpha N}{\sigma_x+\sigma_y}\frac{1}{\sqrt{1+\Upsilon^{2/3}}} \qquad (2)$$

$$\delta_B \approx \frac{5}{4}\frac{\alpha\sigma_z\Upsilon^2}{\lambda_c\gamma}\frac{1}{(1+(1.5\Upsilon)^{2/3})^2} \qquad (3)$$

where r_e, α, and λ_c are the classical electron radius, the fine structure constant, and the Compton wavelength and γ and N are the beam energy and the number of particles per bunch.

Now, in general, the width of the $\mathcal{L}$ spectrum is described by δ_B but the amount of luminosity at the full cms energy $\mathcal{L}_{100\%}$ is a function of n_γ:

$$\mathcal{L}_{100\%} \approx \mathcal{L}_0\frac{(1-e^{-n_\gamma})^2}{n_\gamma^2} \qquad (4)$$

where $\mathcal{L}_0$ is the luminosity of the collider which scales as n_γ when $\Upsilon \ll 1$ and $n_\gamma^{3/2}$ when $\Upsilon \gg 1$.

At cms energies of roughly 1 TeV, the collider parameters can be chosen so that the effects on the $\mathcal{L}$ spectrum are relatively insignificant. In particular, Υ can be kept around 0.3, where the radiation effects can still be described classically, n_γ is close to 1, and δ_B is around 10%. In this regime, the luminosity at full cms energy scales as $\mathcal{L}_{100\%} \sim (1-e^{-n_\gamma})^2/n_\gamma$ which peaks at an n_γ of 1.26.

Unfortunately, it is difficult to attain similar parameters at higher energies. In particular, because Υ is proportional to the beam energy, Υ will have a value that exceeds 1 and, in practice, is the order of 10. In this regime, δ_B is essentially proportional to n_γ and the luminosity at full cms

0-7803-4376-X/98/$10.00 © 1998 IEEE

energy is $\mathcal{L}_{100\%} \sim (1 - e^{-n_\gamma})^2/\sqrt{n_\gamma}$; this is roughly constant for n_γ between 1.6 and 3.5 with a peak at $n_\gamma = 2.34$.

3 PARAMETER DETERMINATION

The parameters of a linear collider are inter-related in a complex manner making their straightforward determination difficult. In the following, we present the principal arguments that lead to the values listed in Table 1. First, we consider issues in the IP region. A straightforward extrapolation from the 1 TeV collider designs shows that to gain an order of magnitude in $\mathcal{L}$ without significantly increasing the beam power, and thereby the ac power consumption, requires decreasing the vertical spot size. The vertical spot size is limited by three effects: the optics, the beam emittances, and beam jitter.

Center-of-mass Energy [TeV]	3	5
$\mathcal{L}$ (with pinch) $[10^{33} cm^{-2} s^{-1}]$	113	125
$\mathcal{L}$ (with FF dilution) ($\mathcal{L}_0$)	90	100
$\mathcal{L}$ within 5% of cms energy	46	44
$\mathcal{L}$ Enhancement (H_D)	1.8	1.8
Num. photons/particle (n_γ)	1.6	1.7
Beamstr. param. (Υ)	6	13
Part. per bunch (N) $[10^{10}]$	0.3	0.3
Emit. at DR ($\gamma\epsilon_{x/y}$) $[10^{-8}]$	40 / 0.5	40 / 0.5
Emit. at FF ($\gamma\epsilon_{x/y}$) $[10^{-8}]$	50 / 1	50 / 1
IP beta funct. ($\beta^\star_{x/y}$) [mm]	8 / 0.10	8 / 0.10
IP beam size ($\sigma^\star_{x/y}$) [nm]	39 / 0.70	31 / 0.54
Bunch length (σ_z) [μm]	35	35
Bunches per train (n_b)	200	200
Bunch spacing (Δt) [ns]	0.5	0.5
Rep. rate (f_{rep}) [Hz]	96	60
Loaded gradient (G) [MV/m]	150	200
Beam loading [%]	14.8	12.3
Total linac length [km]	24	30
Structure length [cm]	63	70
Shunt impedance [MΩ/m]	87.5	87.5
rf → beam eff. [%]	27.3	21.7
ac → rf eff. [%]	45	45
ac power [MW]	235	330

Table 1: Parameters for 3 and 5 TeV colliders.

Ground motion measurements at SLAC have shown that, if the final doublet magnets are anchored firmly to the ground, the natural seismic motion will cause the beam centroids to jitter by less than 0.3 nm at the IP[8]; in the NLC design, these anchors are constructed from optical interferometers and piezo-electric movers. We will assume this sets a lower limit on the spot size. Given additional constraints from the final focus optics as well as the emittance generation and preservation, we have assumed a minimum vertical spot size of 0.5 nm; this is roughly 10 times smaller than that in the 1 TeV NLC and CLIC designs.

Now, given this vertical spot, the horizontal and vertical emittances are constrained by the 'Oide' effect where synchrotron radiation in the final FD doublet leads to chromatic dilution of the spot. Assuming a doublet with apertures roughly $\frac{1}{2}$ that in the NLC design, the smaller apertures are possible because the beam sizes are also smaller in the FD, the Oide effect limits the emittances to:

$$\gamma\epsilon_x \lesssim 80 \times 10^{-8}\,\text{m-rad} \qquad \gamma\epsilon_y \lesssim 1 \times 10^{-8}\,\text{m-rad}\,. \quad (5)$$

Next, we have chosen to limit n_γ, which constrains the ratio N/σ_x, to the lower end of the range discussed in the previous section, *i.e.*, around 1.6. This provides the largest *fractional* contribution of $\mathcal{L}_{100\%}/\mathcal{L}_0$ while still maximizing the absolute value of $\mathcal{L}_{100\%}$. In this case, the $\mathcal{L}$ within 5% of the cms energy is about 45% $\mathcal{L}_0$ which is the same percentage as that in the 1 TeV NLC design.

Finally, the desired luminosity determines the total beam power. For the 3 TeV collider, the luminosity is scaled with E^2 as desired by the physics while for the 5 TeV parameters the same $\mathcal{L}$, as assumed by the Snowmass working group studying 5 TeV colliders[3], namely $10^{35}\text{cm}^{-2}\text{s}^{-1}$, has been chosen.

At this point, we need to consider constraints from the linacs. First, to attain optimal rf-to-beam efficiency, we must consider trains of bunches that are long compared to the accelerator structure fill time. Second, to prevent beam break-up, the spacing between these bunches is limited by the decay of the transverse wakefield. Given the wakefield of the present CLIC structure design[9] or that of an NLC DDS structure scaled to 30 GHz, the minimum bunch spacing that could be considered is about 12 rf buckets. We have chosen a spacing of 15 rf buckets or 0.5 ns at 30 GHz; this differs significantly from the assumption in Ref. [4].

Next, the gradient is determined from conflicting requirements between the beam dynamics, which are easier with high gradients, the collider length, and the rf-to-beam efficiency, which is greater for low gradients. In this frequency regime, the maximum gradient is not thought to be limited by rf breakdown but instead by heating and the associated fatigue. A straightforward calculation would suggest that 200 MV/m is possible although this will need to be verified with detailed tests. In these parameters, we have chosen to minimize the collider length and thus assumed a loaded gradient of 200 MV/m for the 5 TeV parameters and 150 MV/m for the 3 TeV parameters.

Finally, the bunch charge and length need to be determined and, again, there is a trade between increasing the rf-to-beam efficiency, reducing the effect of the transverse wakefield, and controlling the energy spread induced by the longitudinal wakefield. The optimal scaling[5]

$$N \sim G\omega^{-3/2} \qquad \sigma_z \sim G^{-1}\omega^{-5/8} \qquad (6)$$

leads to a bunch length that we felt was too small (15 μm) and thus we limited the bunch length to 35 μm, about 100 times smaller than in the damping rings. We then limited the bunch charge to keep the energy spread required for 'autophasing', a standard method of controlling the single bunch beam break-up, to less than 1%. This results in a smaller beam loading and a lower rf-to-beam efficiency, but keeps the transverse emittance dilution acceptable.

The final parameters are listed in Table 1 for both 3 TeV and 5 TeV cms energies; in both cases, the injection systems are assumed to be similar and thus the beam parameters are similar. It should be noted that we have included substantial emittance and IP spot size dilution based on tolerances similar to those in the CLIC and NLC designs.

4 COLLIDER SUBSYSTEMS

4.1 RF Power

Attaining an acceleration gradient of 200 MV/m requires 480 MW of rf power in each accelerator structure. This power could be generated using the CLIC Two-Beam Accelerator (TBA) concept, the Relativistic-Klystron TBA[10], or advanced klystrons, such as a sheet-beam or cluster klystron, with rf pulse compression[11]. All of these sources are expected to have efficiencies between 45 and 55%, but, of course, all require extensive R&D; we have assumed 45% in our parameter list.

4.2 Injector Complex

The e^- and e^+ sources are expected to be relatively simple. The required charges and beam currents are significantly lower than in the NLC design and thus the sources could be similar. Of course if desired, the conventional positron source could be complemented using a helical undulator after the IP to generate polarized positrons.

The damping rings are required to produce beams with emittances that are a factor of 6∼8 smaller than those from the NLC rings. To do this, one could use a pre-damping ring (similar to the present NLC rings) to perform most of the damping and then a ring with half the bending field but twice as many cells to obtain the final emittances. In this case, the alignment tolerances and the effect of intrabeam scattering will be similar to that in the NLC rings.

Finally, attaining the bunch length of 35 μm will require compressing the bunch length by two orders of magnitude. This is thought to be possible but care must be taken to minimize the longitudinal nonlinearities and the emittance growth due to coherent synchrotron radiation.

4.3 Linac Dynamics

There are three primary issues in the linacs which are described in greater detail in Ref. [12]. First, the bunch spacing is limited by the multi-bunch beam break-up as described earlier. Next, we have assumed alignment tolerances of 10 μm on the accelerator structures and 2 μm on the BPM-to-quadrupole alignment which are similar to the values in the NLC and CLIC designs and are thought to be attainable using beam-based techniques. With these tolerances, the vertical emittance dilution is about 200% after 1-to-1 trajectory correction. Emittance bumps, like those used very effectively in the SLC to reduce the vertical emittance dilution from roughly 1000% to 100%, should reduce the dilution to roughly 50%; this is half of the 100% that is budgeted. Finally, because of the very small beam emittances, the linac and beam delivery systems are sensitive to motion of the quadrupoles. This limits the strength of the focusing system in the linac and requires the use of slow cycling trajectory correction feedback[12].

4.4 Final Focus and Interaction Region

In the final focus and interaction region, we have assumed parameters similar to those of the NLC and CLIC final focus systems, leading to a $\beta_y^\star$ that is significantly larger than the limit imposed by the bunch length. This choice was made for two reasons. First, with the emittances determined by the Oide limit, these beta functions lead to spots that are consistent with the limits from the measured ground motion. Second, for a given optics and tolerances, the length of the final focus system scales linearly with the beam energy[13] which, for the same tolerances, already implies a length of 3 to 5 km per side.

The other difficulty that arises with these high energy parameters is the large number of coherent e^+e^- pairs that are produced when $\Upsilon \gtrsim 1$. Fortunately, these pairs are emitted with small transverse momenta and thus can be removed from the IP with a strong solenoidal field. In addition, by adding a small toroidal component to the solenoidal field, the particles can be directed out the beam exit ports, preventing the pairs from interacting with any material until well outside the detector.

5 CONCLUSION

In this paper, we have studied the feasibility of a 3 to 5 TeV e^+e^- linear collider. Although much work is still required before completing a design and experience gained with a 0.5 to 1 TeV linear collider will further optimize the parameters, this preliminary study shows that a 'conventional' e^+e^- linear collider is a viable candidate for a multi-TeV experimental physics facility.

6 ACKNOWLEDGEMENTS

Work supported in part by the Department of Energy, contract DE-AC03-76SF00515.

7 REFERENCES

[1] G.A. Loew *et al.*, "International Linear Collider Technical Review Report", SLAC Report–471 (1996).

[2] R.B. Palmer "Prospects for High Energy e^+e^- Linear Colliders", *Annu. Rev. Nucl. Part. Sci.,* **40:** 529 (1990).

[3] S. Chattopadhyay et al., "Advanced Accelerator Technologies: A Snowmass '96 Subgroup Summary," *Proc. of 1996 DPF/DPB Snowmass Meeting,* (1996).

[4] P. Chen *et al.*, "A 5 TeV Linear Collider on the NLC Site", *Proc. of 1996 DPF/DPB Snowmass Meeting,* (1996).

[5] J.P. Delahaye *et al.*, "Scaling Laws for e^+e^- Linear Colliders", Clic–Note–333 (1997).

[6] $\mu^+\mu^-$ Collider Collaboration, "$\mu^+\mu^-$ Collider: A Feasibility Study", BNL–52503 (1996).

[7] P. Chen, "Differential Luminosity under Multi-Photon Beamstrahlung", *Phys. Rev. D,* **46:** 1186 (1992).

[8] NLC ZDR Design Group, "A Zeroth Order Design Report for the Next Linear Collider", SLAC Report–474 (1996).

[9] M. Dehler *et al.*, "CLIC Waveguide Damped Accelerator Structure Studies", *Proc. of the 1996 Linac Conf.,* Geneva, Switzerland (1996) p. 734.

[10] See Appendix A of Ref. [8].

[11] P.B. Wilson *et al.*, "RF System for a 30 GHz 5 TeV Linear Collider Based on Conventional Technology", *submitted to these proceedings*.

[12] G. Guignard *et al.*, "Emittance Dilution in 1 and 5 TeV 30 GHz Linear Colliders", *submitted to these proceedings*.

[13] F. Zimmermann *et al.*, "Optimization of the NLC Final Focus System", *Proc. of the 1995 Part. Acc. Conf.,* Dallas, TX.