A 5-TeV-c.m. Linear Collider on the NLC Site *

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ABSTRACT

We present parameters for a 5-TeV-c.m. linear collider that would fit on the proposed Next Linear Collider (NLC) [1] site and use 34-GHz accelerator structures. Supporting arguments are given for the choice of important parameters, and changes required for each machine section are described. This work should be considered preliminary, as a full 5-TeV upgrade would require extensive study.

I. INTRODUCTION

The luminosity formula for a linear collider may be written

$$L = \frac{1}{4\pi}\frac{P_W \eta_{W\to B}}{E_{cm}}\frac{N}{\sigma_x}\frac{H_D}{\sigma_y}. \qquad (1)$$

Scaling from the NLC luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by the square of energy, one would ideally like a luminosity of $25 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at a c.m. energy of 5 TeV. We have decided to allow the linac wall plug power, P_W, to increase from the 200 MW of the NLC design to 300 MW. We believe that by improving the NLC pulse compression scheme and developing an efficient high-power klystron that we should be able to obtain wall-plug-to-beam efficiencies close to 17% at 34 GHz. The higher 34-GHz rf frequency was chosen in order to obtain higher accelerating gradients, keeping the main linac length the same as the NLC 1.5-TeV upgrade. The IP spot height determines vibration and stability tolerances, and, according to the Oide limit [2], smaller spot sizes imply smaller vertical nomalized emittances. We will argue it is possible to achieve and operate with a spot size of 0.3 nm and a corresponding normalized vertical emittance of 0.5×10^{-8} m-rad. The vertical Beta function, β_y, would be about 100 μm.

The value of the ratio N/σ_x is fixed by the goal of keeping the number of beamstrahlung photons per electron, n_γ, less than about 1.5, and the normalized field strength of the beam-beam interaction, Υ, less than about 10. N must be chosen consistent with beam-loading requirements of the rf structure, thus fixing σ_x. The horizontal emittance and horizontal β_x are then chosen so that $\sigma_{x'} \approx \sigma_{y'}$. The result for all of these parameters is shown in Table I. The bunch length σ_z is reduced to 50 μm so that it is compatible with the accelerating structure rf bucket length.

In the following section we present a more detailed justification of these parameter choices. And in the section subsequent to that, we descibe the changes that would be required to upgrade the NLC systems to these 5-TeV-c.m. parameters.

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II. JUSTIFICATION OF PARAMETER CHOICES

A. Beam Height

We believe that σ_y = 0.3 nm is an achievable IP spot height because ground motion measurements [3] at SLAC show a high degree of correlation at wavelengths between 1 Hz and 0.1 Hz where the ground spectrum is large. As a result, calculations for the NLC final focus system show that at quiet sites the beam separation at the IP will satisfy [4]

$$\Delta y_{IP,rms} \leq 0.3 \text{ nm}. \qquad (2)$$

Most of the contribution to this value comes from frequencies in the neighborhood of 10 Hz driving a π mode of the final doublets. This contribution can be reduced by active stabilization methods [4]. The Streckeisen STS-2 instrument used to measure ground motion at SLAC has a resolution in the 1 Hz region of about 30 ppm, illustrating that measurements, corrections and compensations can be carried out with remarkable precision.

After the vibration tolerance, which is addressed above, the most difficult tolerance to achieve is the stabilization of the final focus system between tunings of important aberrations, such as waist, skew and dispersion. This stabilization can be accomplished with high resolution, stable BPMs. The demonstration at the FFTB of a 40-nm resolution rf BPM [5] exceeds requirements for stabilization by a factor of two for these 5-TeV parameters.

The Oide limit requires a vertical normalized emittance of 0.5×10^{-8}m-rad to achieve this 0.3-nm spot height. The NLC damping ring is designed for $\gamma\epsilon_y = 2.2 \times 10^{-8}$. If the 50-$\mu$m vertical alignment tolerance of the sextupoles were reduced to 25 μm one would expect a vertical emittance of 0.5×10^{-8} m-rad. Such a tolerance would be achievable with beam-based alignment techniques and good BPM resolution. Also, as we shall see later, $\gamma\epsilon_x$ should be reduced by about a factor of three. We will argue in the next section that a modified lattice of the NLC damping ring, in the same vault, can achieve the required vertical and horizontal emittance.

The vertical spot size of 0.3 nm and normalized emittance of 0.5×10^{-8}m-rad imply a vertical IP beta function of β_y = 100 μm. This will mean that $\sigma_z \leq 100$ μm. We will insist on $\sigma_z = 50$ μm to keep the beam length to rf bucket size ratio about the same as for the NLC.

B. Beam Width and Bunch Population

The number of particles per bunch, N, must be chosen with attention to the rf beam loading to get a good rf-to-beam transfer efficiency. A beam loading of about 25% is thought optimum.

Table I: A list of parameters for a 5-TeV-c.m. linear collider that would fit on the NLC site.

Parameter	Symbol	Units	Value
Energy (c.m.)	E_{cm}	TeV	5.0
Luminosity	L	cm^{-2}s^{-1}	2.5×10^{35}
Wall Plug Power	P_W	MW	300
IP spot height	σ_y	nm	0.3
IP spot width	σ_x	nm	30
Vert. Emittance	$(\gamma\epsilon_y)_{IP}$	m-rad	0.5×10^{-8}
Hor. Emittance	$(\gamma\epsilon_x)_{IP}$	m-rad	0.5×10^{-6}
Vert. beta IP	β_y	μm	100
Hor. beta IP	β_x	mm	8
Bunch Length	σ_z	μm	50
Vert. Divergence	$\sigma_{y'}$	μr	3.2
Hor. Divergence	$\sigma_{x'}$	μr	3.6
Particles/bunch	N		2.4×10^9
Bunches/pulse	n_b		225
Pulses/sec.	f	Hz	120
Vert. Disruption	D_y		15
Hor. Disruption	D_x		0.17
Enhancement	H_D		1.8
Upsilon	Υ		7.5
Energy Spread	δ_b		0.38
Photons/electron	n_γ		1.6
Had. Events/Crossing	n_{had}		4.3
rf Frequency	ν_{rf}	GHz	34
Unloaded Acc. Voltage	G_0	MV	250
Loaded Acc. Voltage	G_b	MV	190
Structure Length	L_{st}	m	0.6
Wall-to-Beam-Eff.	$\eta_{W\rightarrow B}$		0.17
Beam Power	P_B	MW	26

At 34 GHz this occurs for an average current during the pulse train of about 2 amps. For $N \sim 3 \times 10^9$ we find a bunch separation of a little over six wavelengths. To achieve exactly $6\lambda_{rf}$ separation we reduce the particles per bunch to $N = 2.4 \times 10^9$. (At 34 GHz, $6\lambda_{rf} = 2\lambda_{X-band} = 1\lambda_{C-band}$).

A first guess at a reasonable σ_x would be 100 times σ_y or about $\sigma_x \approx 30$ nm. With this σ_x, the beam-beam interaction constraints appear to be met. The number of beamstrahlung photons per electron n_γ is 1.6 and the beamstrahlung parameter Υ is about 7.5. In this case, the number of hadronic events per crossing, n_{had}, is approximately 4.3, and the beamstrahlung energy spread is $\delta_b \approx 0.38$. The fractional luminosity that suffers no beamstrahlung energy loss is 24%.

C. Beam Power

The spot size parameters we have chosen above give a pinch enhancement of $H_D = 1.8$. This gives us a luminosity of $L = 2.5 \times 10^{35}$ cm^{-2}s^{-1} and a beam power of $P_B = 26$ MW.

We expect that a binary pulse compression scheme, together with efficiency improvements in the klystrons and other NLC rf system components, could lead to an overall wall plug to beam rf efficiency near 17%. The required AC power would then be about 300 MW.

D. Repetition Rate and Number of Bunches Per Train

The pulse structure can be determined from the relationship

$$N f n_b E_{cm} = 2P_B \quad (3)$$

which can now be solved for $fn_b = 2.7 \times 10^4$. Since we desire f to be a multiple of 60 Hz, we find the combinations (f, n_b) = (180, 150), (120, 225), or (60, 450), with pulse train lengths of 20 ns, 40 ns, and 80 ns. Since the expected fill time for the structure is about 20 ns (for a 0.6-m structure), the 180 Hz $n_b = 150$ is too small. We have settled on 120 Hz and $n_b = 225$.

E. RF Parameters

As indicated above, we have chosen a rf system with frequency $\nu_{rf} = 34$ GHz. The unloaded gradient is about $G_0 = 250$ MV and the loaded gradient is about $G_b = 190$ MV. For a 2.5-TeV beam energy the active rf length will be about 14 km. This length is very similar to the length of the NLC upgrade to 1.5 TeV c.m.

The input power to a structure is about 800 MW/m. With a structure length of 0.6 m, and a group velocity of $v_g = 0.095c$, the filling time is $\tau_{fill} = 20$ ns.

The pulse compression is imagined to be a 16 $\times$ binary compression scheme, with 4 rf accelerating structures being filled by each klystron. This implies a klystron power of 150 MW. This would have to be a multiple-beam or sheet-beam klystron [6]. This component of the system is not now in hand and would require a serious R&D program in the intervening years. The total number of klystrons would be 12,000, very similar to the 1.5-TeV design parameters.

These rf components are imagined to yield an AC-to-rf efficiency (at the entrance to the rf accelerating structure) of $\eta_{AC\rightarrow rf} = 0.55$ from which we then derive $\eta_{W\rightarrow B} = 0.17$.

III. SYSTEM UPGRADE REQUIREMENTS

A. Injector

We need about 30% more intensity at the output of the preinjector than at the IP, thus the parameters we have chosen imply a current of 2.9 Amp during the pulse train, with 3.1×10^9 electrons in each bucket of 5.712 GHz (C-band) rf after the preinjector at about 80 MeV. We would generate the pulse train by using a 40 ns long pulse from the cathode then bunch it with C-band standing wave bunchers and accelerators to achieve the desired bunch train. This makes for an easier laser system than the 1.5 TeV NLC design[7] since we do not have to produce the pulse train from the laser itself.

This injector would be just like the existing injector for the Next Linear Collider Test Accelerator (NLCTA) [8] in operation at SLAC, except that the rf system would halve the frequency. The X-band NLCTA injector was designed for 3.3 Amp during the pulse, filling every X-band bucket. The charge per bunch for NLCTA is 1.8×10^9 electrons. Since the rf wavelength for C-band is twice as long as for X-band, we expect to be able to capture twice as much charge in the C-band bucket as in the X-band bucket.

Larger apertures in the C-band injector would make it an easier injector to construct and operate than the X-band injector. However, C-band klystrons and accelerator structures would have to be developed and contructed, but this should be easier to do than it was for X-band.

B. Damping Ring

We have chosen $\sigma_x/\sigma_y \approx 100$. To get $\sigma_{x'} \approx \sigma_{y'}$ we will need $\epsilon_x/\epsilon_y \simeq 100$, or $\gamma\epsilon_x = 0.5 \times 10^{-6}$ m-rad. The present ring has an exit horizontal emittance design of $\gamma\epsilon_x = 3 \times 10^{-6}$ m-rad. The present ring is sized to contain four trains separated by 60 ns for the injection and extraction kickers with a train length equal to 126 ns. For a train length of 40 ns, as conceived for the 5-TeV parameter set, the same ring diameter could contain between 7 and 8 trains. Therefore we can have less damping, which means less quantum excitation and a smaller equilibrium emittance. Thus we expect we can use the same vault, with perhaps a change of lattice to one with longer weaker bends and stronger quadrupole focusing.

The rf will have to be C-band, which means that the longitudinal impedence could be problematic. We suggest the use of a storage ("Aires") cavity as proposed [9] for the KEK B-factory. The transverse feedback system will also have to be more aggressive than for the NLC design because of the increased impedence.

The exit bunch length will now be smaller, by more than a factor of 2, since $\lambda_{734MHz}/\lambda_{C-band} = 8$. Fortunately, the peak current decreases and so single bunch instabilities and intra-beam scattering are probably less of a concern.

C. Bunch Compressor

If indeed the exit bunch from the damping ring is a factor of two smaller, then the compression factor for the 5-TeV parameters will be the same as for the NLC parameters. The pre-linacs in the bunch compressor would have frequencies corresponding to C-band (instead of the NLC L-band pre-linac [10]) and X-band (instead of the NLC S-band pre-linac).

D. Linac Dynamics

There are many factors to consider in linac dynamics, such as quad strengths, β functions and structure wakes. From our experience of going from S-band to X-band, where the cell length is smaller by a factor of four, we would predict that in going from X-band to 34 GHz, where the cell length is smaller by a factor of three, the single-bunch wake effects, for the same charge per bucket, would be worse by a factor of about two to three. Since the charge per bucket is smaller by a factor of five, we would predict that this would not be a problem. Also the iris being opened to achieve $v_g = 0.095c$ will help.

While these numbers are suggestive, further detailed studies are necessary.

E. Collimator

The collimated aperture at any location down stream of the collimation system, assuming the beta function there has remained unchanged, scales as $\sqrt{N/(\sigma_z\gamma)}$, hence will be smaller by a factor of 2.5.

However to retain the passive protection of the existing collimation system will not be possible because of the higher beam power, and because of the longer bends that would be required to keep the emittance growth under control.

An actively protected system could be employed, which at 5-TeV-c.m. could probably be less than half the length of the existing ZDR collimation system length.

F. Big Bend

To retain the same crossing angle of 20 mr, and the separated-function magnet scheme of the NLC big-bend design, which is designed to go up to 1.5-TeV c.m., the big bend would necessarily get longer by a factor of $\gamma^{3/2}$, or about six. There is the possibility to go to a combined function design to keep the length more similar.

G. Final Focus

Because the energy has increased by a factor of three from the NLC 1.5 TeV design, the same final doublet lengths and same L^* could be retained if the aperture were reduced by a factor of three. As seen above, the collimated aperture can be reduced by a factor of 2.5. Thus, to maintain clearance for particle backgrounds, the quadrupole apertures can only be reduced by this amount. The scaling of the resistive wall wake, which goes as the inverse of the aperture cube, is also OK for this aperture change because of the reduced bunch charge and reduced jitter, assuming it is proportional to beam size. But it is not possible to reduce the aperture any further, and so the chromaticity will remain about the same, or in fact increase somewhat. With the same chromaticity but an energy increase of a factor of three, experience and formulae for minimum final focus system lengths, indicate that the final focus system length would increase by a factor of three.

Hence we conclude that if one wanted to leave open the option for this upgrade, significant additional length would have to be provided for the final focus system.

H. Interaction Region

With the closer bunch spacing, we have checked the multi-bunch crossing instability threshold. It is at 1 mr, so the 20 mr is plenty large to avoid this potential problem.

The Υ parameter has gone from 0.3 to 7.5, dramatically changing the production rate of coherent pairs from the beamstrahlung photons. These pairs are soft (as compared, for example, to Bethe-Heitler pairs, where some large angle pairs are expected), and as a result should be well curled by the solenoid and contained within the mask. Simulations will be required to exactly determine the import of these pairs, but it is expected that modifications could be made along the solenoid axis to respond to the high pair densities which are expected there.

IV. CONCLUSION

We have presented the parameters for an upgrade of the NLC design to a 5-TeV-c.m. linear collider. This is a major upgrade, requiring complete replacement of 28 km of rf systems: klystrons, pulse compression, and rf accelerating structures.

According to the parameter set we have presented, we believe that if the beam delivery system tunnels were sized according to the requirements of a 5 TeV upgrade scenario, then a 5-TeV-c.m. collider could fit onto the NLC site and could use its conventional facilities with only minor modification. Of course this brief study should be taken as a tentative indicator of the possible, and not the solid conclusion of a detailed study. Furthermore, the 34-GHz klystron power source has yet to be designed. We have made an agressive assumption on the efficiency of this device.

V. REFERENCES

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