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Bird's IP View of Limits of Conventional e^+e^- Linear Collider Technology*‡

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Abstract

This paper examines the scaling laws appropriate to future e^+e^- linear colliders in the high upsilon regime assuming that the luminosity must scale with the square of the energy. It then seeks to identify the limits on achievable energy for these colliders under the assumption that no exotica such as energy recovery, superdisruption, or four-beam charge compensation are employed, and all technology is forseeable and has an apparent cost within the bounds of a large international collaboration. Following these guidelines we find an apparent energy limit around 15 TeV in the center-of-mass because the requirements on normalized emittances, required to produce ever smaller vertical spot sizes, become unattainable with conventional damping ring technology.

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Introduction

This paper is an attempt to look into the future and so one should view these results with a large amount of scepticism. On the other hand, as we sit on the verge of choosing a technology for the next linear collider, it seems important that each technology be assessed as regards its possiblilites for expansion to higher energies. The current linear collider design projects have settled on an initial energy of 500 GeV in the center-of-mass (c.m.), with expansion to 1 TeV c.m., and in some cases expansion to 1.5 TeV c.m. is contemplated. This paper takes the point of view that a subsequent project would have at least 5 times this energy, namely be able to achieve at least 5 TeV in the center-of-mass. A third generation machine would be envisioned to have a center-of-mass energy of 25 TeV.

This investigation is based on five premises that:

(i) no known physics be violated,

(ii) luminosity must scale as energy squared and be equal to 10^{34} cm^{-2} sec^{-1} at 1 TeV c.m.,

(iii) the technologies employed must be known and conceivably extrapolated to the limits assumed,

(iv) no exotica like energy recovery, charge compensation with four beams, or superdisruption be invoked, and

(v) the "first glance" total cost must lay within bounds that might be imagined for a large international project.

The perspective of this study is heavily weighted on IP dynamics, and indeed a second motivation for this study is the investigation of the IP scaling laws at very large upsilon parameters. When designing a complete machine, trade-offs between optimal parameters derived from any single perspective are invariably balanced, and this usually drives parameters into a “corner” of the natural parameter space as viewed from any one perspective. Thus the results of this study should not be expected to match one-to-one with the outcome of a more complete design process.

We will often refer to the prameters quoted for the next linear project (NLC) at SLAC. Figure 1 shows the schematic layout of this project, and Table 1 and Table 2 give the general and IP parameters, respectively.

Luminosity Scaling Law

We start with the well known luminosity formula

$$L = 1/4\pi\ (N^2 f n_b)/\langle\sigma_x\rangle\langle\sigma_y\rangle \qquad (1)$$

where $\langle\sigma_x\rangle$ and $\langle\sigma_y\rangle$ indicate the average size of the spot during the collision including disruption effects. In fact $\langle\sigma_x\rangle$ is usually very close to the linear σ_x for acceptable parameters, wheareas $\langle\sigma_y\rangle$ is usually somewhat smaller, about two-thirds of, σ_y.

If in this formula the beam power, P_B, and wall-plug power, P_W, and the energy in the center-of-mass, $E_{c.m.}$, are inserted through the relationships $E_{c.m.}=2E_B$, $N f n_b E_B = P_B$, and $2P_B = \eta_{w->B} P_W$ where $\eta_{w->B}$ is the wall-plug-to-beam-power efficiency, one obtains

$$L = 1/4\pi\ (P_W/E_{c.m.})\ \eta_{w->B}\ (N/\langle\sigma_x\rangle)\ (1/\langle\sigma_y\rangle) \qquad (2)$$

We will show that the factor $N/<\sigma_x>$ is defined by a desire to have a clean interaction, where by clean we mean not too much energy spread in the final center-of-mass energy of colliding primary particles, low numbers of background hadrons per bunch collision and good polarization retention throughout the collision. One will of course seek to maximize the efficiency, but there are limits to what we can do with presently concievable technology. The only remaining free factor, $1/<\sigma_y>$, will be limited by stability considerations and normalized emittance limits.

If we require the luminosity to scale as the square of the energy and equal 10^{34} cm^{-2} s^{-1} then L must equal

$$L = 10^{26} \gamma^2 \, m^{-2} \, s^{-1} \quad (3)$$

Putting this together with the luminosity formula (Eq. 2) one arrives at

$$\gamma^3 = 0.5\ 10^{-14}\ P_W \eta_{w->B} (N/<\sigma_x>) (1/<\sigma_y>) \quad (4)$$

The product of four factors must increase as the cube of the energy to achieve an acceptable design for a higher energy machine. These factors are: i) the wall-plug power, ii) the efficiency, iii) N/σ_x, which we show to be related to collision quality, and iv) the inverse of the vertical spot size.

For the NLC 1 TeV parameter set ($\gamma^3 = 10^{18}$, L=1.7 10^{34} cm^{-2} sec^{-1})

$P_W = 1.4\ 10^8$, $\eta_{w->B} = 0.12$, $N/<\sigma_x> = 3\ 10^{16}$, and $1/<\sigma_y> = 0.7\ 10^9$.

Limits on Luminosity Factors

The $P_W\ \eta_{w->B}$ ($=2P_B$) Limit

The wall-plug-to-beam efficiency achievable with present conventional RF technology is about 6%. The 1 TeV technology efficiency is projected to be 12%. This gain is achieved by going to a gridded klystron thereby eliminating the need for a modulator. We take as a “forseeable” technology an efficiency of 19% which would be acheved by eliminating the SLED pulse compression unit, using instead something like the cluster klystron now under development by SLAC and BNL (R. Palmer....)

The component efficiencies associated with present technology, the projection for 1 TeV, and the “forseeable” technologies are indicated in Table 3 (P. Wilson).

Table 3

->	Power prep	RF source	Pulse comp.	Power Transm.	RF-to-Beam	Wall-to-Beam
0.5 TeV	**.75**	**.6**	**.76**	**.95**	**.27**	**.09**
1.0 TeV	**.95**	**.65**	**.82**	**.95**	**.25**	**.12**
Forseeable	**.95**	**.70**	**1.0**	**.95**	**.3**	**.19**

The total wall-plug power that might be available for a future linear collider is difficult to predict. It does not seem unreasonable to assume that one would locate such a facility near a large source of cheap power (hydroelectric?) or that one would build a power plant dedicated to providing energy to the collider as needed, and otherwise feeding a power grid. Under such assumptions a power in the range of 1 or 2 gigawatts would seem to be a maximum limit.

Assuming the availablility of 2 gigawatts of power, one achieves a factor of 25 improvement in the $P_W \eta_{W->B}$ (=$2P_B$) product as compared to the NLC 1 TeV parameters. Since we will be contemplating 2 future collider generations with a factor or 5 increase in center-of-mass energy each, this assumption on available beam power corresponds roughly to a linear increase of beam power with center-of-mass energy. Thus for the purposes of this paper we will assume

$$P_W \eta_{W->B} = 2P_B = 16\ E_{c.m.}(\mathrm{TeV})\ \mathrm{MW}.$$

$$= 80\ 10^6\ (\gamma/\gamma_5)\ \mathrm{Watts}$$

Here we have introduced the notation $\gamma_5 = 5\ 10^6$ for the value of γ at 5 TeV c.m. We will be scaling our results from a 5 TeVc.m. platform which lies within the high upsilon regime.

$N/<\sigma_x>$ **Limits**

In the large upsilon limit (note ref) there is a rather simple relationship between n_γ, the number of photons produced per electron during the beam-beam collision, and the quantity N/σ_x(ref. yokoya and chen).

$$N/\sigma_x = c_1\ (\gamma/\sigma_z)^{1/2}\ n_\gamma^{3/2} \qquad (5)$$

where C_1=1.4 10^{11} $m^{-1/2}$. (For orientation, if one inserts the 1 TeV c.m. parameters, which are not yet in the large upsilon regime, into the RHS of eq. (5) one obtains an N/σ_x about 1/2 its value in the 1 TeV design). Additionally in the large upsilon limit one finds the simple relationship

$$\delta_B = 2/9\ n_\gamma \qquad (6)$$

where δ_B is the beamstrahlung energy spread. The polarization loss, $<\Delta P>$, during the beam-beam collision has been shown to be (ref):

$$<\Delta P> = .04\ n_\gamma \qquad (7)$$

and the distribution function for the crossing-averaged number of electron-positron collisions as a function of electron energy has a delta-function spike at the initial electron beam energy given by (ref)

$$\Psi_{AV}(E) = ((1-e^{-n\gamma})/n_\gamma)\ \delta(E-E_0) + ... \qquad (8)$$

The expressions for δ_B, $<\Delta P>$, and $\Psi_{AV}(E)$ indicate the value of n_γ must lie between 1/2 and 1. The coefficient of the delta function spike at n_γ=0.5 is .79 while at n_γ=1.0 it is .63.

If relation (5) is inserted into the luminosity formula of Eq. (4) one obtains:

$$\gamma^{5/2} = 0.7\ 10^{-3}\ n_\gamma^{3/2}\ 2P_B\ (1/\sigma_z)^{1/2}\ (1/<\sigma_y>)$$

(9)

We see here that except for a mild $(1/\sigma_z)^{1/2}$ dependence one must rely on increased beam power and a small vertical spot size to achieve the $\gamma^{5/2}$ scaling.

The choice for n_γ also has an important impact on the number of hadronic background events per crossing. The number of hadronic events per crossing, N_{Had}, is well represented by (ref. Peskin barklow, and chen)

$$N_{Had} = L_X\ n_\gamma^2\ \sigma_{\gamma\gamma\text{–>}Had}$$

(10)

where the luminosity per crossing, L_X, is given by

$$L_X = 1/4\pi\, N^2/(\sigma_x <\sigma_y>) = 1/4\pi\, (N/\sigma_x)^2\, (\sigma_x/<\sigma_y>) \qquad (11)$$

Figure 2 shows the predicted $\sigma_{\gamma\gamma\to Had}$ cross-section as a function of energy. It grows very slowly as the function $\ln(s)^2$. Hence hadronic backgrounds of future colliders will be no worse than the design value, $N_{Had} = 0.3$, for the NLC 1 TeV collider, if $L_X\, n_\gamma^2$ is held constant. Thus

$$c_2 = (4\pi\, N_{Had}/\sigma_{\gamma\gamma\to Had})^{1/2} = (N/\sigma_x)\, n_\gamma\, (\sigma_x/<\sigma_y>)^{1/2} \qquad (12)$$

must remain approximatedly equal to its value at 1 TeV: $c_2 = 3\ 10^{17}\ m^{-1}$.

At this point one can use relation (5) and (12) to solve for n_γ or N/σ_x in terms of the aspect ratio, $\sigma_x/<\sigma_y>$, and σ_z/γ with the result:

$$n_\gamma = (c_2 /c_1)^{2/5}\, (\sigma_z/\gamma)^{1/5}\, (<\sigma_y>/\sigma_x)^{1/5} \qquad (13)$$

or

$$N/\sigma_x = c_2^{3/5}\, c_1^{2/5}\, (\gamma/\sigma_z)^{1/5}\, (<\sigma_y>/\sigma_x)^{3/10} \qquad (14)$$

If the NLC 1 TeV aspect ratio and σ_z are inserted into the RHS of eq. (13) a value of n_γ =1.0, is achieved at $\gamma = 4.6\ 10^6$, nearly 5 TeV in the center-of-mass. For these parameters eq. (5) or (14) evaluates, as it must, to its value at 1 TeV: $N/\sigma_x = 3\ 10^{16}$.

Interestingly, for higher energies, the condition of equation (13) allows for aspect ratios closer to unity. In other words, σ_x can be allowed to decrease faster than σ_y. However this is not easy to achieve. The beta ratio at the IP tends to be very close to the emitance ratio, for when this is true the horizontal and vertical divergent angles are equal. If one trys to further reduce β_x at the IP then the horizontal divergent angle increases and the vertical spot size is degraded by additional synchrotron radiation emitted in the horizontal focusing element of the final doublet.

The other option, reducing the horizontal emittance, is also difficult if this is accomplished in a damping ring, because, as we shall see below, the intrabeam scattering conditions become quite severe. Assuming then that the aspect ratio is constant, eq. (14) sets the condition for the growth of N/σ_x, namely as $\gamma^{1/5}$. n_γ will fall below unity as $\gamma^{-1/5}$ implying that the beam quality will improve with energy! Instead of eq. (9) we get

$$\gamma^{14/5} = 0.9\ 10^{-20}\ 2P_B\ (1/\sigma_z)^{1/5}\ (\langle\sigma_y\rangle/\sigma_x)^{3/10}\ 1/\langle\sigma_y\rangle$$

(15)

If we assume, as suggested in the section on beam power, that beam power scales linearly with energy, and assume σ_z and $\langle\sigma_y\rangle/\sigma_x$ are almost constant, then eq(15).requires that the luminosity be achieved by a $\gamma^{9/5}$ reduction of σ_y .

Since by eq. (14) N/σ_x grows as $\gamma^{1/5}$, assuming again that $\langle\sigma_y\rangle/\sigma_x = 10^{-2}$ is almost constant, N must be decreasing as $\gamma^{-8/5}$ and will satisfy

$$N = 3\ 10^8\ (\gamma_5/\gamma)^{8/5}$$

(16)

This will be helpful for wakefield considerations and will allow smaller RF structures. It implies however that, to put more average power into the beam, the number of bunches per second must be increasing dramatically. One can expect longer bunch trains and higher repetition rates.

The σ_y Oide Limit

The vertical beam size is limited by considerations of machine stability and conditions set by the Oide limit. Following the scaling laws proposed in the previous paragraph, eq(15). leads to the vertical beam heights presented in Table 4 (based on $<\sigma_y>/\sigma_x = 10^{-2}$ and $\sigma_z = 10^{-4}$ m):

Table 4

	P_B (MW)	$<\sigma_y>$ (nm)
5 TeV c.m.	**40**	**0.1**
Beyond 5 TeV	**40** (γ/γ_5)	**0.1** $(\gamma_5/\gamma)^{9/5}$

The Oide limit (ref), based on a calculation of the effects of synchrotron radiation emitted in the final doublet, requires that

$$\sigma_{y,\,min} = 2.6\ 10^{-4}\ F^{1/7}\ \varepsilon_{Ny}^{5/7} \qquad (17)$$

at

$$\beta_y = 5/7\ \sigma_{y,\,min}^{\ 2}/(\varepsilon_{Ny}/\gamma) \qquad (18)$$

where F is a slowly varying function of the final doublet design parameters. For typical doublets, including the effects of horizontal motion, F ≈100 and

$F^{1/7} \approx 1.9$. (Oide note ref). This limit can be improved by a factor of about 3 by observing that the distribution from the synchrotron radiation is not Gaussian, as assumed in Oide's first note (ref Hirata, Oide, Zotter). These considerations lead to a minimum

$$\sigma_{y,\,min} = 1.7\ 10^{-4}\ \varepsilon_{Ny}^{5/7} \tag{19}$$

Assuming an enhancement $\sigma_y / \langle \sigma_y \rangle = 1.5$, the normalized emittance corresponding to the 5 TeV c.m. parameters is $\varepsilon_{Ny} = 3.3\ 10^{-9}$ m.rad., a factor of 16 smaller than the normalized vertical emittance for the 1 TeV design. For smaller energies, according to Table 4 and equation (19), the scaling law must be $(\gamma^{-9/5})^{7/5} = \gamma^{-63/25} \sim \gamma^{-5/2}$, which may be written

$$\varepsilon_{Ny} = 3.3\ 10^{-9}\ (\gamma_5 / \gamma)^{5/2} \tag{20}$$

For $E_{cm} = 25$ TeV $\varepsilon_{Ny} = 6.0\ 10^{-11}$ m.rad., almost three orders of magnitude smaller than its value for the 1 TeV NLC parameters.

The scaling for β_y which now may be deduced from eqs. (18) and (20) is $\beta_y \sim \gamma^{-1/10}$, very close to independent of energy. This result is welcome, as the chromaticity of the final doublet, and the tolerances of the final focus system, scale with β_y .

ε_{Ny} Limits

A quantum mechanical limit on emittance was noted by J. Seeman (ref)

$$\Delta y\ \Delta p_y = p\ \Delta y\ \Delta y' = \gamma\, mc\ \Delta y\ \Delta y' > h_{bar} \tag{21}$$

implying

$$\gamma\, \varepsilon_y = \varepsilon_{Ny} > h_{bar}/mc = \lambda_{bar,e} = 4\ 10^{-13}\ \text{m-rad.} \quad (22)$$

This quantum limit is comfortably small. Indeed it yields, through eq. (19), a limit on the energy of E_{cm}=180 TeV at σ_y = 0.25 pm.

The real barrier to smaller normalized emittances comes from consideration of damping ring beam dynamics. The intrabeam scattering growth rate (Piwinski ref) scales as

$$\tau^{-1} \sim N/(\gamma^{1/2}\ \sigma_z\ \varepsilon_{Nx}{}^{5/2})$$

(23)

Using the scaling law for N from the paragraph following eq. (15), namely $N{\sim}\gamma^{-8/5}$, and the emittance scaling of eq. (19), we get

$$\tau^{-1} \sim \gamma^{4.15} \qquad (24)$$

This is a very severe scaling law. This growth rate must be balanced by a rapidly increasing damping rate. A preliminary damping ring design for the 5 TeV parameters has been proposed by Tor Raubenheimer (ref) that would achieve $\varepsilon_{Ny} = 10^{-9}$ m.rad.. It consists of a dogbone design with a 1 km hybrid wiggler. The wiggler period λ_W would be 4 cm. and have a field strength of 1.5 Tesla. The energy of the ring would be 3 GeV. Raubenheimer estimates that the limit of this technology, is perhaps a factor of 4 smaller yet than this, at $\varepsilon_{Ny} = 2.5\ 10^{-10}$. If that is true, equation (19) can be used to estimate a maximum achievable energy.

$$E_{max,\ cm} = 14.0\ \text{TeV}$$

(25)

Eq. (24) implies that the maximum achievable energy varies only weakly (the 1/4 power) with the maximum growth rate that can be overcome with additional damping. In this sense one would expect the result quoted in equation (25) to be reliable.

The minimum emittance, $\varepsilon_{Ny} = 2.5\ 10^{-10}$, corresponds to a vertical beam size at the IP of $\sigma_y = 0.04$ nm.

The σ_y Stability Limit

Figure 3 shows a frequency scale with 4 significant frequencies present in the design and operation of a linear collider. From right to left we have: 1) the repetition frequency, which is contemplated to be 120 Hz for the 1 TeV NLC, ii) the effective frequency of feedback, about one-tenth of the repetition frequency, iii) the frequency at which the aberrations contributing to spot size growth are tuned, perhaps once every 15 minutes, and iv) the frequency at which the overall machine alignment is checked with beam-based procedures, perhaps every few days.

The repetion frequency for higher energy can be estimated by rewriting $P_B = Nfn_b E_B$ as

$$fn_b = P_B/(E_B N) \qquad (26)$$

Becasue of our assumption that P_B scales linearly with energy $P_B/E_B=10^{14}$ is a constant.. Using eq. (16), which shows that N scales as energy to the 8/5 power we have

$$fn_b = 3.3\ 10^5\ (\gamma/\gamma_5)^{8/5} \qquad (27)$$

Details of RF design would be required to determine f and n_b separately, but a first guess would be to take the square root for each, giving:

$$f = 600\ (\gamma/\gamma_5)^{4/5} \quad \text{and} \qquad n_b = 550\ (\gamma/\gamma_5)^{4/5} \tag{28}$$

Since feedback is unable to cope with motion at frequencies higher than the feedback frequency (Recall the feedback frequency is estimated to be one-tenth the repetition frequency, and hence by eq. (28) estimated to be 60 Hz.), jitter must be suppressed at and above this frequency by either passive elements that filter the jitter, or active elements that measure element jitter directly and remove it. Typcially the jitter tolerance of the final doublet is somewhat smaller than the spot size, and the jitter tolerance on all other quadrupoles is about10 times the spot size.

A rather simple-to-execute idea which has been used in Beijing (ref) to reduce quadrupole jitter, is sketched in figure 4. A seismometer placed on the quadrupole measures the vibration. The signal is amplified and fed to a steering coil mounted within or next to the quadrupole so that the steering compensates for the steering of the quadrupole center offset. Effectively one keeps the magnetic center of the quadrupole fixed although the quadrupole itself is moving. The <u>Beijing ref</u>. claims they have been able to reduce quadrupole motion by a factor of 100 in this way.

The disadvantage of the above method is that it is a dead-reckoning method which ultimately depends on the accuracy of the seismometer and the gain and stability of the amplifier. This idea may be improved upon (Gordon Bowden ref) by inertially suspending a coil in the quadrupole (see figure 5), and measuring the quadrupole field motion directly. The correction coil is mounted on the same quadrupole, and is driven to balance out the motion of the quadrupole field. Thus the system is now a feedback device. The limitation is the ability to inertially suspend the measuring coil. Preliminary estimates by S. Smith (ref) on the sensitivity of this device, based on the assumption of 150 turn coil with resistance of 2.6 kOhm, indicate an ability to detect 12 pm motion at 1 Hz and 1pm at 10 Hz. This of course assumes that the coil is suspended inertially.

Figure 6 indicates the range of typical ground motion as measured at “noisy” and “quiet” sites. The collider would be optimally located at a quiet site, but the presence of humans would immediately make the site somewhat noisy. Let us assume an average site. At 1 Hz the ground motion is indicated to be 1.6 nm. This is somewhat quiter than SLAC which is measured to haveup about10 nm, depeding on specific location. However no sitewide precautions have been taken to preserve “quiet”. And weekends and nights are indeed quieter. Also to be reckoned is that the motion of quadrupoles which are mounted on stands above the ground is inevitably somewhat larger than the ground.

Neverthelss, the factor of 100 achieved by the Beijing method is enough to more than meet stability requirements for all quadrupoles other than the final doublet quadrupole. Let us assume these have motion in the 20nm range (ref Ash measurements). To obtain 40 pm stability requires a factor of 500. In figure 7 we plot suppresion functions associated with various feedback strategies, taking into account the suspension of the inertial coil. Inertial quad plus deadbeat at 360 Hz achieves a suppression of 2000 at 1 Hz and 300 at 10 Hz. We conclude that the 40pm stability can be achieved, even quite economically, and that one can even do better, considering the high repetition rate of these machines.

Conclusions

IP considerations give clear indications of how future conventional linear collider parameters must scale with energy. The resulting scaling laws are achievable only if the vertical spot size decreases as the $9/5^{th}$ power of the energy. The Oide limit, based on synchrotron radiation in the final doublet, requires that the normalized emittance scale as the 5/2 power of the energy. If the normalized emittance is achieved conventionally within a damping ring, this requirement on normalized emittance translates into an increase of the intrabeam scattering growth rate as roughly the 4th power of the final energy. Inevitably, at some energy, methods introduced to create radiation damping can no longer overpower this intrabeam growth rate. We believe this limitation sets a maximum energy achievable in conventional colliders somewhere in the vicinity of 15 TeV c.m.. This would suggest an search for better ways to achieve small normalized emittances. There is a quantum limit on normalized emittance, but the quantum limit would allow energies up to E_{cm} = 180 TeV.

References

R. Palmer, Cluster Klystrons

P. Wilson, Forseeable Efficiencies

Large upsilon note: The upsilon parameter grows quite dramatically if one trys to achieve the luminosity scaling laws. It was thought at one time that this might be a limitation because of the large coherent conversion of beamstrahlung to electron-postiron pairs. However, if initial beamstrahlung production is kept small, coherent conversion will only result in the complete conversion of these photons into pairs, which are not problematic large-angle pairs because the coherent production process has low momentum transfer. Cascade production of further beamstrahlung will not be large again because of the limits on beamstrahlung production. The limits on beamstrahlung enter through a parameter n_γ the number of photons produced during the collision per incident electron.

K. Yokoya and P. Chen, summary of beam-beam equations

Polarization ref.

Electron-positron distr. ref

Peskin, Barklow, and Chen

K. Oide, Oide limit

Oide note: If one include the horizontal motion in the doublet, then for usual situation with equal divergent angles at the IP, the synchrotorn emission effects are dominated by emission along the large horizontal trajectories in

the horizontally focussing member of the doublet. The formula is the same as derived by Oide (above ref) but the value of F is almost a factor of 100 larger than that which is found from consideration of the vertical motion only).

Hirata, Oide, Zotter

T. Raubenheimer, 5 TeV damping ring

Piwinski ref

J. Seeman, emittance limit, SLAC-PUB-5646

Beijing ref

Gordon Bowden ref

Steve Smith, (10/92) private communicatiAsh measurement