Options and Trade-Offs in Linear Collider Design

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Abstract

Four markedly different concepts of linear colliders are presently under investigation. They may be characterised by the keywords 'X-band, S-band, two-beam, and superconducting'. Both the essential differences and the common problems are pointed out in this paper. As a basis of discussion, parameter sets of six collider study groups working on JLC/KEK, NLC/SLAC, VLEPP/BINP, CLIC/CERN, SBLC/DESY, and TESLA will be used.

1. INTRODUCTION

This paper deals with the concepts of linear colliders (LC) in the 300 GeV to 1 TeV center-of-mass energy range as they are presently under discussion. They are based on four distinct approaches: the conventional S-band (3 GHz) approach, the X-band (11 to 14 GHz) approach, the two-beam accelerator approach, and the superconducting L-band approach. Except for the X-band approach, each of them is represented by a single linear collider study group. This does not mean of course, that important R&D work is not done elsewhere. These groups are TESLA as an international effort for the superconducting cavity concept, CLIC(CERN) for the two-beam approach, and SBLC(DESY) putting forward the S-band based design. Use of X-band cavities is proposed by three studies named NLC(SLAC), VLEPP(BINP), and JLC(KEK). Note that JLC also considers an S-band and a C-band version of their collider. The main parameters of these six linear collider studies are compiled in table 1.

The information on the status of the respective activities lies beyond the scope of this paper. It may be useful, nevertheless, to point out some problems which are common to all of the designs, and to compare the different ways proposed to solve them. This comparison is all the more possible since an international committee has been founded to work out a detailed comparison of the various linear collider schemes [1]. The emphasis in the following discussion will be on the optimisation of beam power and vertical beam size. The reason is that, in order to get the desired luminosity, one unavoidably needs very high average beam power, so that power efficiency becomes an essential parameter. Depending on what one feels to be the optimum assumption on these parameters, the choice of rf frequency will have to be different. In addition, since the achievable gradient is connected with the rf frequency, the energy upgrade scenario maybe considered an issue, especially if the total length of the collider will be strictly limited.

2. HOW TO GET THE LUMINOSITY

Due to the small cross-sections of the processes of interest, high energy electron-positron linear colliders need a luminosity L of the order of 10^{33} to 10^{34} cm^{-2} s^{-1}. It is instructive to realize that L can be represented by

$$L = \frac{f_{rep} n N^2}{4\pi\sigma^*_x \sigma^*_y} = \frac{P_b \cdot N}{4\pi E \sigma^*_x \sigma^*_y} \qquad (1)$$

For the meaning of symbols, see Table 1.

Apparently, there are only three free parameters at a given collision energy: P_b, N, and the beam size at the interaction point (IP) $\sigma^*_x \cdot \sigma^*_y$.

The bunch population N cannot be increased beyond the 10^{11} level because of wakefields acting on the tail of each bunch and because of excessive beam disruption caused by the interaction with the large Coulomb-field of the opposing bunch. The vertical disruption parameter D_y scales as

$$D_y = \frac{N \cdot \sigma_s}{\sigma^*_y \left(\sigma^*_x + \sigma^*_y\right)} \qquad (2)$$

Thus, one could - at least in principle - compensate the effect of a large N on beam-beam interaction by a large beam size and a short bunch length. This would be favourable only if one operates at a small rf frequency, because only then are both the longitudinal and transverse wakefields tolerable even at large N. In fact, as is seen from Table 1, all high f_{rf} designs except VLEPP use bunch population numbers below 10^{10}. With VLEPP, one intentionally puts up with both wakefields and a large disruption factor D_y = 215, because the BNS damping with 'autophasing' [4] and the 'travelling focus' [5] techniques are considered powerful enough to manage the respective effects. Also, VLEPP considers the γ-γ collision option in the first place, where disruption and beamstrahlung is not an issue. In this scheme[6], two electron beams are collided with very intense laser beams just before interaction thus transferring most of the electron momentum to Compton gammas. These are collided then instead of the electron beams, which are separated by an external magnetic field before collision. Discussion of the challenge of generating the required intense laser beams is beyond the scope of this paper.

A further restriction on parameters is due to the intense synchrotron radiation called beamstrahlung which accompanies the beam disruption. It is characterized by the parameter ϒ which scales as $\Upsilon \propto D_y \sigma^*_y / \sigma^2_s$. This limits the possible reduction of σ_s, besides technical aspects, in the bunch compressor. Since, for a flat beam, Υ depends only on σ_x and not on σ_y , β^*_x is decreased so far that the rms collision energy is smeared by beamstrahlung by just a tolerable amount (say $\delta p/p$ a few %, see Table 1). Afterwards, β^*_y is decreased as far as possible. The limit is given by the bunch length, because a beta function smaller than the bunch length does not increase luminosity (hour-glass effect). In fact, as seen from Table 1, all LC schemes use β^*_y close to σ_s . Another limit on β^*_y that comes into play at very high beam energies is due to the synchrotron

General parameters	Units	Symbol	TESLA	SBLC	JLC(X)	NLC	VLEPP	CLIC
Initial c.m. energy	GeV	E	500	500	500	500	500	500
Luminosity	10^{33} cm $^{-2}$ s $^{-1}$		3.6	2.2	5.1	5.3	12	0.7-3.4
total two-linac length	km	l_{tot}	31	36	15	20	10	12.4
rf frequency of main linac	GHz	f_{rf}	1.3	3	11.4	11.4	14	30
Linac repetition rate	Hz	f_{rep}	5	50	150	180	300	2530-1210
Number of particles/bunch	10^{10}	N	3.6	2.9	0.63	0.65	20	0.8
Number of bunches/pulse		n	1130	125	85	90	1	1-10
Damping ring energy	GeV	E_d	4	3.15	1.98	2	3	2.15
Main Linac			**TESLA**	**SBLC**	**JLC**	**NLC**	**VLEPP**	**CLIC**
Avg. beam power/beam	MW	P_b	8.2	7.26	3.2	4.2	2.4	0.8-3.9
Bunch spacing	ns	τ_b	708	16	1.4	1.4	--	0.66
Bunch train length	ns	τ_p	$8{\cdot}10^5$	1984	118	125	--	0 - 6
Unloaded Gradient	MV/m	g_0	25	21	73	50	100	80
Loaded Gradient	MV/m	g_l	25	17	53	38	91	78-73
Length of sections	m	l_s	1.04	6	1.3	1.8	1.0	0.27
a/λ range		a/λ	0.30	0.16-0.11	0.20-0.14	0.22-0.15	0.14	0.2
Section filling time	ns	τ_f	$5{\cdot}10^5$	790	110	100	110	11.6
rf pulse length at cavity	µs	τ_p	1315	2.8	0.23	.24	0.11	0.0116
Pulse compression ratio			--	--	2	3.6	4.5	--
Number of klystrons		n_k	604	2517	3400	3940	1300	‘2’
Peak rf power from klystron	MW	P_k	7.1	150	135	50	150	700
Avg. total AC power for rf generation (both linacs)	MW	P_{tot}	88*	142	114	102	57	100*)**)
Beam parameters at interaction			**TESLA**	**SBLC**	**JLC**	**NLC**	**VLEPP**	**CLIC**
Horizontal invariant emittance	10^{-8} πm	ε^n_x	1400	1000	330	500	2000	300
Vertical inv. emittance	10^{-8} πm	ε^n_y	25	50	4.8	5	7.5	15
Horizontal β at IP	mm	β^*_x	25	22	10	10	100	10
Vertical β at IP	mm	β^*_y	0.7	0.8	0.1	0.1	0.1	0.18
rms beam width at IP	nm	σ^*_x	845	670	260	320	2000	247
rms beam height at IP	nm	σ^*_y	19	28	3	3.2	4	7.4
Bunch length	mm	σ_s	0.5	0.5	0.09	0.1	0.75	0.2
eff.beamstrahlung parameter		Υ_{eff}	0.03	0.04	0.12	0.09	0.07	0.07
rms $\delta p/p$ from beamstrahlg.	%	$\sigma_{\delta p/p}$	2.9	2.8	3.2	2.4	13.3	3.5
vertical disruption		D_y	11	8.5	8.2	7.3	215	9.7
Crossing angle	mrad		0	3	6.1	20	0	1

Table 1: Main parameters of linear collider studies at a c.m. energy of 500 GeV [1-3]. For the JLC, there is also a C-band (5.7 Ghz) and an S-band (2.8 GHz) version under consideration. The choice will depend on the maximum beam energy desired in the final stage of upgrade, given a fixed total length of the tunnel. Also, a change of frequency during a later upgrade stage is possible. The luminosity is calculated in accordance to eq. (1). No enhancement due to the pinch effect has been taken into account, and no loss due to the crossing angle. For flat beams, the combination of both effects yields a luminosity enhancement factor of typically 1.5.

*) *For TESLA and for CLIC (drive beam) the cryogenic power is included.* **) *For the single bunch version.*

radiation in the final focus quadrupole magnets [7]. The increasing difficulty with chromatic errors when reducing β^*_y is less a problem since the development of a broad-band final focus optics [8].

If one combines all these scalings and restrictions with eq. (1), it now reads

$$L = A \frac{P_b}{\gamma} \cdot \sqrt{\frac{\langle \delta p / p \rangle}{\varepsilon_y^n}} \quad (3)$$

with $A \approx 10^{36}\, cm^{-2}\, s^{-1}$, if P_b is measured in MW and ε^n_y in rad·m. As $\delta p/p$ is limited by the experiment's requirements, there are only two free parameters left in the luminosity formular: the average beam power P_b and the normalized vertical emittance ε^n_y .

In principle, ε^n_y is determined in the damping ring by misalignment tolerances or, ultimately, by intra-beam scattering. In practice, however, it could be in vain to achieve, with big technical effort, a very small ε^n_y at the exit of the damping ring because it will eventually grow in the linac due to wakefield effects if its value was chosen unreasonably small.

One concludes that, with reasonable numbers on ε^n_y and $\delta p/p$, Megawatts of average beam power are needed to keep L above the $10^{33}\, cm^{-2}\, s^{-1}$ level. Thus, the efficiency of beam power generation from wall plug power becomes an important issue. Facing the fact that there is surely an upper limit of tolerable power consumption, it is a non-trivial statement that the parameter optimization and even the choice of fundamental technical parameters like the rf frequency could have a very much different outcome if the required luminosity would be smaller by say a factor of ten.

2. THE CHALLENGE OF HIGH BEAM POWER

Realization of high beam power involves two problems:

1.
2. One has to generate a large amount of rf power with high power efficiency. Then, again with high efficiency, this rf power must be transmitted to the electron/positron beam.
3. When the beam extracts this large electric power from the accelerating cavities, there will be longitudinal and transverse field distortions induced, called wakefields. They will, in turn, act on the tail of each bunch and may still be present to some extent when the next bunch arrives, thereby causing both single bunch beam break-up and multi-bunch instabilities.

The design net efficiency η_{rf} for production of rf power for the various schemes is listed in Table 2. It is seen that all of these values lie close by in the 25 - 40 % range. It should be noted, however, that the respective values are much closer to the present-day state of the art for the lower rf frequency schemes TESLA and SBLC than for the high frequency ones. The machines differ over a wider range concerning the efficiency η_{AC} of converting ac power to beam power, see Table 2. The reason is, that the efficiency of rf power transmission to the beam is best if the rf pulse is much longer than the cavity filling time, i.e. acceleration of a long bunch train is favoured. In this case, power transmission is in a quasi steady-state. While now most collider schemes foresee the multi-bunch mode, it leads to severe difficulties with CLIC. One concludes from all that, that it is harder for high frequency machines to achieve high beam power.

	TESLA	SBLC	JLC	NLC	VLEPP	CLIC
η_{rf} /%	35	36	30	30	39	26
η_{AC} /%	19	10	5.6	8.2	8.4	1.6

Table 2: Net rf system efficiency for production of rf power [1]. For TESLA and for CLIC (drive beam) the cryogenic power is included. For CLIC, the single bunch version is meant.

With respect to wakefields, the difference is much bigger. The short-range longitudinal wake field causes an energy spread within the bunch, which is undesirable due to the chromatic effects of focusing along the linac. For scaled accelerating structures this spread is proportional to the square of the frequency f_{rf}. This is plausible if one considers the fact that for fixed gradient the stored energy per unit length in an accelerating cavity is inversely proportional to f_{rf}^2. The easiest cure foreseen for this higher order mode excitation is to increase the aperture-to-wavelength ratio a/λ when increasing the rf frequency. Unfortunately, this measure also injures the shunt impedance, i.e. one needs more power to generate the accelerating field (a superconducting linac like TESLA does not have this problem, so it can use a large a/λ value, anyway). Thus one cannot go too far in that direction. What also helps is just to increase the accelerating gradient g_0, because the stored energy scales with g_0^2 while the extracted power only scales linearly with g_0. This is of cause the most favourable way, but it is limited by efficiency considerations. Thus, one has to conclude that low frequencies are preferable also with respect to longitudinal wakefields [9].

The frequency scaling behaviour of transverse wakefields is even more pronounced as they increase with the third power of f_{rf} and linearly with the bunch population N. This is illustrated in Figure 1, where $N \cdot f_{rf}^3$ is plotted in arbitrary units versus N for those frequencies which are considered by the respective linear collider schemes. Note that a logarithmic scale is used. Although TESLA and

SBLC use N considerably larger than the X-band designs and CLIC do (again except for VLEPP), the transverse wakefields would be still smaller by up to two orders of magnitude if the other parameters were unchanged. However, $\vec{E}_\perp$ scales with $\sigma_s^{1/2}$, and the beams suffer on a

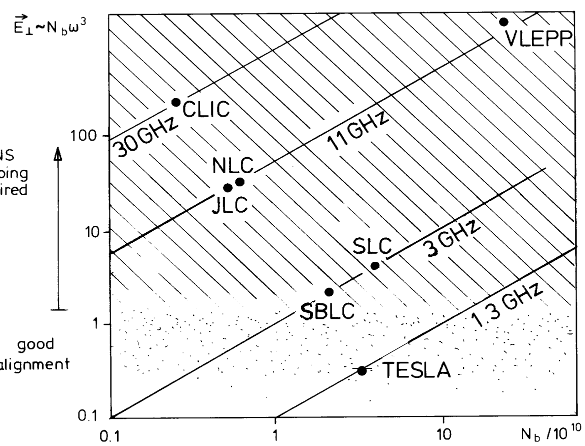

Figure 1: Transverse wakefield $\vec{E}_\perp$ as a function of bunch population N for scaled structures with frequencies as considered by the respective linear collider schemes. The hatched area indicates the region where BNS damping techniques will be indispensable, while for the dotted region good alignment of quadrupole lenses and cavities (in the 10 to 500 μm range) may be sufficient.

longer way if the accelerating gradient is smaller. Also, the cavity shape and the average β function enter. If all these effects are taken into account, the relative transverse emittance growth scales roughly as [10]

$$\Delta\varepsilon/\varepsilon \propto [N^2 \sigma_z ((f_{rf}\, \lambda/a)^3/g_l)^2/\varepsilon]\, \beta\, \Delta y^2_{cav}$$

if cavities are misaligned by Δy_{cav}. Figure 2 illustrates, that the relative vertical emittance growth in fact differs by orders of magnitude between various machines if no counter-measures like BNS damping are taken. The hatched area in Figure 1 indicates the region where BNS damping will be indispensable.

Besides short range wakefields there are also long range effects that can lead to multi-bunch instabilities. These long-lasting distortions are driven by Higher Order Modes (HOM) which are excited by bunches in the front of the bunch train and act on subsequent bunches. A significant reduction of HOMs has been achieved with the development of the 'Choke Mode Cavity'[11], which allows the HOMs to propagate out of the cavity while only the accelerating mode is trapped. Recently a method has been proposed to damp HOMs by stainless steel coating the iris [12].

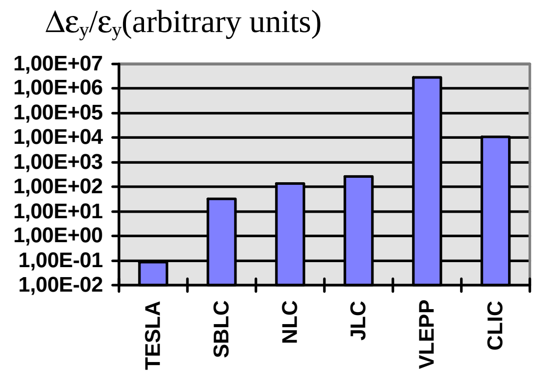

Figure 2: Relative vertical emittance growth (in arbitrary units) from transverse wakefields if cavities are misaligned by Δy_{cav}.and if no BNS damping is applied.

To summarize this paragraph, it is seen that low frequency linacs can more easily achieve high beam power while still suffering much less from wakefields. In other words, in spite of higher beam power and significantly relaxed cavity alignment tolerances they can preserve smaller beam emittances. Additional advantages are

- only one stage of bunch length compressor is required
- in case of SBLC, the existing SLC in Stanford/USA, with all its experience, may be considered an existing 20 % prototype of an S-band collider.

There are, however, serious drawbacks if one concentrates on the technology for high beam power alone:

- For accelerating gradients above some 30 MV/m, the power efficiency of a normal conducting low frequency collider drops, because rf pulse compression is required (i.e. η_{rf} gets smaller and the bunch train will be shorter). Thus, an optimized high beam power collider will be very long. This might be, if not an economical, at least a political disadvantage.
- Concerning TESLA, considerable progress has been made with achieving the design accelerating field of 25 MV/m in 5-cell cavities [13], and recently in a TESLA Test Facility series production 9-cell cavity [14]. However, it remains still to be seen if even higher gradients (although not excluded from basic physics) can be supplied routinely in a long linac and if costs can be reduced sufficiently.
- It seems likely that dark currents are more serious at lower frequencies, since they have a higher probability to get trapped there.
- Multi-bunch operation is essential for high beam power operation, and it involves all the complications of multibunch-instabilities. Meanwhile no scheme except VLEPP (and maybe CLIC) is completely free of this complication, but one should be aware that it has ist roots in the requirements of high power efficiency.

3. SMALL VERTICAL EMITTANCE

The vertical beam size achieved with the Final Focus Test Beam installation at SLAC [15] was σ^*_y = 70 nm at ε^n_y = $200 \cdot 10^{-8}\pi$ rad·m and N = $0.65 \cdot 10^{10}$. Comparing with the respect values of the LC plans (see Table 1), one readily sees that all of them need ‘small’ vertical beam size at the IP. Some go, however, more than one order of magnitude below the present state of the art. Interestingly, this does not necessarily mean, that alignment tolerances in the respective damping rings are much different, because the TESLA and SBLC damping rings have to be much longer due to the longer bunch train, i.e. more focusing elements are involved.

Techniques beyond well-proven ways of alignment and orbit correction will be needed. As a means of improving the effective beam position monitor alignment, the ‘beam based alignment’ technique has been devised [16]. To improve cavity alignment, mechanical micro-movers, controlled by signals from HOM antennas, are under construction [17]. All beam-based correction techniques are applicable only for misalignments changing slowly compared to f_{rep}. In this respect, the low f_{rf} , low f_{rep} machines have clearly a disadvantage. On the other hand, especially TESLA can tolerate a much worse cavity misalignment (few tenths of a mm compared to less than 10 µm for X-band) and position monitor resolution because the wakefields are weak enough. Also, its large bunch spacing allows using the first bunch in a train to correct the subsequent ones.

Name	upgrade scenario	l_{tot} for 1 TeV c.m.
TESLA	double the length can still very much reduce ε^n_y	60 km
SBLC	rf pulse compression (reduces η_{AC})	30 km
JLC	start with S-band (?), upgrade with X-band	22 km
NLC	increase both length and gradient	20 km
VLEPP	double the length?	20 km?
CLIC	double the length	14 km

Table 3: Energy upgrade scenarios of LC schemes

4. UPGRADE POTENTIAL

The most essential upgrade of a 500 GeV c.m. linear collider will be a program to increase the collision energy. Table 3 illustrates the various energy upgrade scenarios proposed [1]. It is seen that most groups plan to increase the total length, not only the low f_{rf} schemes. Only the high f_{rf} machines, however, can stay within 20 km for a 1 TeV collider. Also, they have the potential to even further increase the gradient, at the expense though of further reducing η_{AC}. By learning from operational experience how to preserve extremely small ε^n_y, they might then still be able to provide the required luminosity. It is unclear yet if this is realistic and if saving total length pays off compared to the higher power efficiency of, say, a long TESLA collider.

5. CONCLUSION

It is the lesson from many theoretical as well as experimental studies performed over the last two decades, that a linear collider providing the required high luminosity can be built. It remains to be learned, however, from the various test facilities under construction now, what the most economical way and the most reliable technique will be.

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