An Overview of Linear Collider Plans

Jörg Rossbach
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85
2000 Hamburg 52, Germany

Abstract

Four markedly different concepts of linear colliders are presently under investigation. They may be characterized by the keywords "X-band, S-band, two-beam, and superconductivity". Both the essential differences and the common problems are pointed out in this paper.
In addition, an overview is given on the six collider parameter sets which are used by the study groups working on JLC/KEK, NLC/SLAC, VLEPP/BINP, CLIC/CERN, DESY/THD, and TESLA.

1 Introduction

This paper deals with the concepts of linear colliders in the 300 GeV to 1 TeV center-of-mass energy range as they are presently under discussion. These 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 (1.3 GHz) 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 on components relevant to the respective approaches is not also done elsewhere. These groups are TESLA for the superconducting cavity concept, CLIC(CERN) for the two-beam approach, and DESY/ Technische Hochschule Darmstadt putting forward the S-band based design. Use of X-band cavities is proposed by three studies named JLC(KEK), NLC(SLAC), and VLEPP(BINP). The main parameters of this total of 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. This information can be found in the respective status reports and was the basis of table 1 [1–7] . 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 at the 1992 Linear Collider Workshop in Garmisch-Partenkirchen many experts put considerable effort into the task of identifying the advantages and disadvantages of their approaches. The emphasis in the following discussion will be on the optimization of beam power and beam size. It will be seen that the choice of rf frequency is (besides other arguments) intimately connected to what one feels to be the optimum and/or realistic assumption for these parameters.

2 How to get the luminosity

It is the exclusive purpose of a linear collider to supply electron-positron collisions with 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.
Obviously, there are only three free parameters which can be optimized 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

$$D_y \sim \frac{N\sigma_s}{\sigma_y^*(\sigma_x^* + \sigma_y^*)} \qquad (2)$$

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

General parameters	Symbol	TESLA	DESY/THD	JLC	NLC	VLEPP	CLIC
Initial c.m. energy .... [GeV]	E	500	500	500	500	500	500
Luminosity .... $[10^{33} cm^{-2} s^{-1}]$	L	2.6	2.4	3.5	5.7	12	0.7-2.7
Two-linac active length ..... [km]	l_{rf}	20	30	17	14	6.4	6.6
rf freq. of main linac ...... [GHz]	f_{rf}	1.3	3	11.4	11.4	14	30
Linac repetition rate .... [Hz]	f_{rep}	10	50	150	180	300	1700
Number of particles/bunch$[10^{10}]$	N	5.1	2.1	0.7	0.65	20	0.6
Number of bunches per pulse	n	800	172	90	90	1	1-4
Damping ring energy ...... [GeV]	E_d	14	3.25	1.98	1.8	3	3

Main Linac		TESLA	DESY/THD	JLC	NLC	VLEPP	CLIC
Avg. beam power per beam [MW]	P_b	16.5	7.2	3.8	4.2	2.4	0.4-1.6
Bunch spacing .... [ns]	τ_b	1000	10.7	1.4	1.4	–	0.33
Bunch train length .... [ns]	τ_p	$8 \cdot 10^5$	1835	126	126	–	1
Unloaded gradient .... [MV/m]	g_0	25	21	40	50	108	80
Loaded gradient .... [MV/m]	g_l	25	17	28	38	96	73 - 78
Length of sections .... [m]	l_s	1.04	6	1.22	1.8	1.01	0.27
a/λ range	a/λ	0.15	0.15 - 0.11	0.24 - 0.12	0.21 - 0.15	0.14	0.2
Section filling time .... [ns]	τ_f	$5 \cdot 10^5$	825	75	100	107	11.2
Klystron pulse length .... [μs]	τ_p	1300	2.8	1.5	1.5	0.7	0.011
Pulse compression ratio		–	–	4	6	6.5	–
Number of klystrons	n_k	1264	2450	3424	1945	1300	2
Peak rf power from klystron .... [MW]	P_k	3.3	150	70	94	150	700
Avg. total AC power for rf generation (both linacs) .... [MW]	P_{tot}	137	110	≈ 200	150	91	175

Beam parameters at interaction:		TESLA	DESY/THD	JLC	NLC	VLEPP	CLIC
Horizontal invariant emittance .... $[10^{-8} \pi m]$	ϵ_x^N	2000	500	550	500	2000	180
Vertical inv. emittance . $[10^{-8} \pi m]$	ϵ_y^N	100	50	7.5	5	7.5	20
Horizontal β at IP .... [mm]	β_x^*	10	16	10	10	100	2.2
Vertical β at IP .... [mm]	β_y^*	5	1	0.13	0.1	0.15	0.16
rms beam width at IP ...... [nm]	σ_x^*	640	400	335	320	2000	90
rms beam height at IP ...... [nm]	σ_y^*	101	32	4.5	3	4	8
Bunch length .... [mm]	σ_s	1	0.5	0.08	0.1	0.75	0.17
Beamstrahlung parameter	$<\Upsilon>$	0.07	0.06	0.11	0.1	0.06	0.15
rms $\delta p/p$ from beamstrahlung[%]	$\sigma_{\delta p/p}$	3	5	6	3	9	6
Vertical disruption	D_y	7.9	8.6	15	8.3	200	15
Crossing angle at IP ...... [mrad]		1-2	2	7.2	3	?	1

Table 1: Main parameters of linear collider studies at a c.m. energy of 500 GeV [1 – 7] . For the JLC, there is also a C-band (5.7 GHz) and a S-band (2.9 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. The luminosity L 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.

bunch population numbers below 10^{10}. With VLEPP, one intentionally puts up with both strong wakefields and a large disruption factor $D_y = 200$, because the BNS damping with "autophasing" [9] and the "travelling focus" [8] techniques are considered powerful enough to manage the respective effects.
(It should be noted that the beam disruption is accompanied by intense synchrotron radiation called beamstrahlung. It is characterized by the parameter Υ which scales as $\Upsilon \sim D_y\sigma_y^*/\sigma_s^2$. This limits –besides technical aspects– the possible reduction of σ_s.)

One concludes that large N has at least a tendency to favour lower acceleration frequencies. This is in parallel with the high beam power approach, as will be seen in the next section.

The beam size $\sigma_x^* \cdot \sigma_y^*$. cannot be reduced below the 1000 nm^2 level, because the generation of very small (normalized) beam emittances and emittance preservation during acceleration both impose extraordinarily tight tolerances on the alignment and stability of optics and accelerating components [10].

When keeping clear of these ultimate numbers for N and $\sigma_x^*\sigma_y^*$, one easily calculates beam powers of Megawatts 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. It might be instructive to divide the present day linear collider studies into two groups: those who accept the challenge of high power efficiency (high beam power approach, TESLA, DESY/THD), and those who prefer to aim at very small beam sizes in order to gain some freedom in the choice of rf parameters. This freedom is used to go to higher rf frequencies, which are considered to allow larger field gradients and, consequently, a comparatively short overall tunnel length (X-band, two-beam).

3 The high beam power approach

The average beam power per beam is 16.5 MW with TESLA and 7.5 MW with DESY/THD, respectively (see table 1). When this large electric power is extracted 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 short-range longitudinal wake field causes an energy spread within the bunch, which is undesirable due to the limited momentum acceptance of the final focus optics. 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 gra-

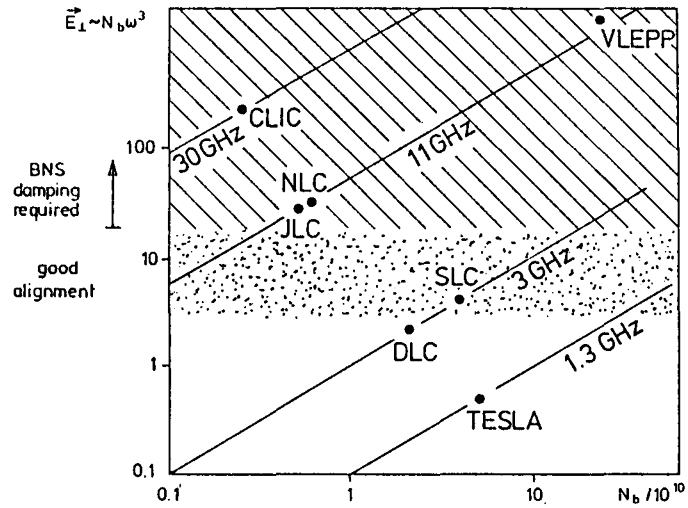

Figure 1: Transverse wakefield $\vec{E}_\perp$ as a function of bunch population N for scaled structures with frequencies as considered by the respective linear collider schemes. The hatched area indicates the region where BNS damping techniques will be indispensable, while for the dotted region good alignment of quadrupole lenses and cavities (in the 10 to 100 μm range) may be sufficient.

dient the stored power 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. Thus one cannot go too far in that direction and one has to conclude that low frequencies are preferable if high beam power is desired [13].

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 DESY/THD use N nearly one order of magnitude larger than the X-band designs and CLIC do (again except for VLEPP), the transverse wakefields are still smaller by up to two orders of magnitude. This means that beam stabilisation like BNS damping –if required at all– will not have to operate much above the instability threshold if low frequencies are used. This threshold also depends on the transverse alignment tolerances of quadrupole lenses and cavities and can be improved using beam based alignment techniques [10]. The hatched area indicates the region where BNS damping will be indispensable for any reasonable alignment tolerance.

Again, one concludes from this paragraph, that high beam power colliders might prefer lower rf frequencies, and one faces the at the first glance paradoxical result that high beam power colliders will suffer much *less* from wakefields than low beam power/high f_{rf} schemes.

One of the most important parameters of a high beam power collider is the efficiency η of beam power generation from wall plug power. In order to optimize this parameter it is useful to consider *that* part of the klystron pulse which definitely cannot be used for acceleration, namely the filling time τ_f of the accelerating structure. During this time lots of electric power is dissipated but no bunch can be accelerated as the full accelerating field is not yet achieved. As the bunch length is much shorter than the filling time of any structure, η of a single bunch linac cannot exceed some 1–2 %.

If a long bunch train $\tau_p >> \tau_f$ is to be accelerated, the situation may become much more advantageous, because the structure is operated in a steady state like mode. Therefore, η is some 13 % at DESY/THD, and in the extreme case of TESLA, with pulses of 0.8 msec duration, the efficiency may exceed 24 %. Dissipative losses in the superconducting structure would not be worth mentioning at all if they would not occur at Helium temperature (approx. 1 W/m at 2 K [2]). Cooling at this temperature is quite power consuming. This additional power requirement by the superconducting design (as well as the power required to cool the static heat loss of some 0.4 W/m) has not been allowed for in the above efficiency number. It is also the limiting factor prohibiting CW operation of TESLA.

The importance of high power efficiency has also seriously affected the high frequency schemes, although they do not play the high beam power card in the first place (by now, only the VLEPP design still considers n = 1). They cannot go as far as the low frequency colliders, however, because high power klystrons for long pulses are technically much more challenging than those at low frequencies.

To summarize this section, the advantages of the low frequency/high beam power approach are obvious:

- significantly relaxed tolerances
- drastically reduced wakefields in spite of large N
- only one stage (and the less demanding one, see below) of bunch length compressor required
- in case of DESY/THD, the existing SLC in Stanford/USA, with all its experience, may be considered as an existing 20 % prototype of a S-band collider.

There are, however, serious drawbacks of this approach, namely:

- For accelerating gradients above some 30 MV/m, the power consumption of a low frequency collider becomes unreasonably large. Thus, a high beam power collider will be very long. This might be, if not an economical, at least a political disadvantage.
- Concerning TESLA, the present state of the art of some 10 MV/m [2] has to be improved at least by a factor of two, and the component costs must be reduced considerably.
- Dark currents have not been investigated sufficiently so far, but it seems likely that they are more serious at lower frequencies, since they have a higher probability to be trapped there.
- Multibunch operation is essential for high beam power operation, and it involves all the complications of multibunch-instabilities [12]. Meanwhile no scheme except VLEPP (and maybe CLIC) is completely free of this complication, but one should be aware that it has its roots in the requirement of high power efficiency.

4 The small beam size approach

If one compares the beam sizes routinely achieved at SLC [11] with the respective values of all of the linear collider plans, one readily realizes that all of them need "small" beam sizes at the interaction point, see table 2. Some, however, use σ_y^* values well below the 10 nm level (VLEPP, JLC, NLC, CLIC). This is called the "small beam size approach" within this paper. With such small beam sizes, one can reach the $10^{33} cm^{-2} s^{-1}$luminosity level at an average beam power below one Megawatt. This allows application of X-band rf technology or the

	σ_s/mm	σ_x^*/nm	σ_y^*/nm	$\epsilon_{x/y}^N/10^{-6}\pi m$
SLC	1	2000	1500	30/30
TESLA	1	640	100	20/1
DESY/THD	0.5	400	33	5/0.5
VLEPP	0.75	2000	4	20/0.08
JLC	0.08	300	3	5/0.05
NLC	0.1	300	3	5/0.05
CLIC	0.17	90	8	2/0.2

Table 2: beam size of linear collider schemes in comparison with parameters routinely achieved at SLC.

even more ambitious two-beam concept, which both promise larger accelerating fields.
Remark: Historically, the development was vice versa: high frequencies had been considered because they permit larger accelerating fields, and, realizing that large beam power would hardly be possible, one had to cope with very small beam dimensions to get the luminosity.

The most important consequence is that there is a 1 TeV c.m. option within a total length of 15 km.

What are the objectives of the small beam size approach?

- one has to generate small beam emittances
- one has to preserve the small invariant beam emittance on the whole course along the accelerator

Generally, *no* linear collider scheme can cope with emittances as delivered from electron or positron sources. But damping rings and bunch length compressors for small emittance colliders are much more ambitious: The bunch compressor must come in two stages (the second one at some 15 GeV and over 500m long), and the vertical orbit stability and beam position monitor (BPM) resolution in the damping ring must be below 1 μm.

Emittance dilution in the main linac may be due to three different error sources [10]:

- limited BPM precision and misalignment, causing dispersive dilution
- quadrupole misalignment, causing dispersive dilution as well as wakefields (as a consequence of orbit errors in the accelerating structures)
- accelerating structure misalignment, causing wakefields and rf deflection of the whole beam

The tolerances can be relaxed by about 3 orders of magnitude if beam-based correction techniques are applicable. This is the case only for misalignments changing slowly compared to the repetition frequency ("quasi-static" regime). Table 3 gives an idea of the stability requirements. None of these numbers is easy to achieve. To meet the tighter tolerances for the small beam size designs, considerable technical effort will be required.

type of misalignment		high beam power approach	small beam size approach
quasi-static	BPM, quads	$\approx 50\mu m$	7 μm
	acc.structure	15 μm	4 μm
jitter	low cut off	$> 1Hz$	$> 3Hz$
	quadrupoles	30 nm	5 nm

Table 3: approximate misalignment tolerances in case of the high beam power approach and in case of small beam size schemes. The numbers are rough estimates only, mainly based on NLC [10] and DESY/THD [7] numbers. TESLA numbers will be even larger.

Finally, the question of rf power sources should be mentioned. The status of X-band klystron development (100 MW during at least 1 μs will be required) is given in ref.[14]. rf pulse compression by a factor of 4 to 6.5 will be necessary. This is under active development. Ref[5] describes the challenges of the drive beam acceleration for CLIC.

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