DESIGN ISSUES OF TeV LINEAR COLLIDERS

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ABSTRACT

Within the frame work of a world-wide collaboration, various possible approaches for Linear Colliders in the TeV energy range (TLC) and high luminosity (~ 10^{34} cm^{-2} sec^{-1}) are explored in different laboratories and periodically compared in international workshops. The main accelerator physics issues required to meet the requested performance improvement by three orders of magnitude in luminosity and by a factor 10 in beam energy with respect to the unique linear collider presently operational, the SLC at SLAC, are reviewed, pointing out the main challenges common to all designs as well as the possible technological choices. Corresponding designs based on the improvement of present standard or the development of new technologies are presented, emphasizing their main issues and specific challenges. The main goals of ambitious test facilities presently set-up to study the feasibility and cost of the various schemes in the next few years are introduced.

1 INTRODUCTION

In the quest for higher energies, hadron and lepton colliders with a regular and parallel evolution in the past have shown to be very complementary for the discoveries and studies of elementary particles. This is why, now that the construction of a 14 TeV Large Hadron Collider (LHC) has been launched, the study for a Lepton Collider in the TeV range, complementary to LHC with possibly an option for γ-γ collisions, is strongly supported by the physics community.

The usual technology of lepton colliding beams in storage rings reaches its natural economical limit with LEP2 at ~ 200 GeV c.m. Synchrotron losses scaling with the 4th power of the beam energy makes it prohibitively expensive in the TeV range. Instead the Linear Collider technology with a cost increasing linearly with the beam energy is well adapted to extend the lepton energy frontier. The first and only linear collider built so far, the SLC [1] at SLAC successfully demonstrated their feasibility and operation at a remarkable level of performance. Nevertheless, their cost has to be significantly reduced with respect to present standards which corresponds to about 10 MCHF/GeV.

Because of the size of the complex and the large extrapolation in performance with respect to the SLC, a wide range of technical options is being explored before technology and design parameters are chosen. In the last few years new concepts of beam acceleration based on lasers, plasmas or wakefields have been envisaged but it does not look as if any of these exotic schemes would present the required performance and energy conversion efficiency for such a collider. Finally, all the schemes presently studied are based on conventional RF structures with either improved or advanced power sources. A schematic layout of a TLC is presented on fig. 1 which illustrates all the subsystems common to the various designs as well as the areas requesting developments.

An international collaboration for R & D on **T**eV **L**inear **C**olliders (**TLC**), joining the efforts of 24 laboratories from all over the world was created at EPAC94. A Technical Review Committee (TRC) was nominated with a precise mandate, i.e. “examine accelerator designs and technologies suitable for a collider that will initially have centre of mass energy of 500 GeV and luminosity in excess of 10^{33} cm^{-2} sec^{-1} and be built so that it can be expanded in energy and luminosity to reach 1 TeV centre of mass energy with luminosity of 10^{34} cm^{-2} sec^{-1} “. International workshops are regularly organised to monitor the progress of the studies, compare possible performances with physics requests and favour exchanges between experts in the field. The TRC recently described [2] the status of the

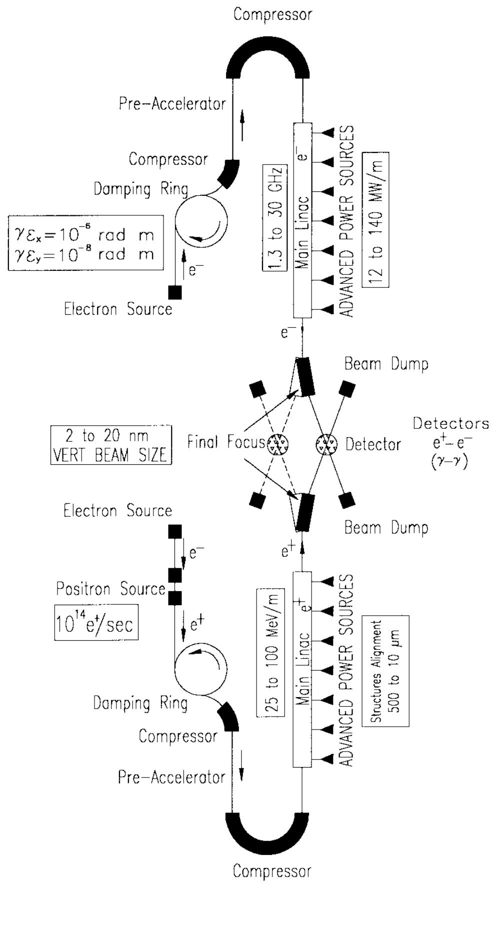

Fig. 1: Schematic layout of a TeV Linear Collider (TLC)

various options from which the updated main parameters are summarized in table 1. Four lines of R & D are intensively studied (as explained in paragraph 5) which mainly differ by the technology and the frequency of the main linac accelerating structures covering a wide range from 1.3 to 30 GHz with:

- a conventional approach in the SBLC study,
- superconducting technology (S.C.) in TESLA
- high frequency klystrons in JLC, NLC and VLEPP,
- a Two Beam Acceleration (TBA) scheme in CLIC and TBNLC.

2 LUMINOSITY

The luminosity is given by the standard formula (see table 1 for definition of parameters):

$$L = \frac{H_D N_b \, N_e^2 \; f_{rep}}{4\pi \, \sigma_x \sigma_y} \qquad (1)$$

The enhancement factor, H_D, takes into account the modification of the beam size by disruption during collision at the Interaction Point (I.P.). The so-called pinch effect helps to increase the integrated luminosity by mutual focusing of the bunches when colliding electrons and positrons. But this effect has to be limited as it generates synchrotron radiation by beamstrahlung which is responsible for average beam energy loss, δ_B [3], broadening of the luminosity spectrum and background, all detrimental for good physics conditions:

$$\delta_B \propto \frac{U_b}{\sigma_z} \frac{{N_e}^2}{\left(\sigma_x^2 + \sigma_y^2\right)} \propto \frac{U_b}{\sigma_z} \frac{N_e^2}{\sigma_x^2} \qquad (2)$$

A flat beam at the I.P. ($\sigma_y << \sigma_x$) makes possible at the same time a high luminosity and a reasonable δ_B. Acceptable average energy loss, typically of the order of a few %, limits the achievable enhancement factor. Adjusting the vertical focusing at the I.P. to the optimum of the “hourglass” effect, the luminosity at a given beam energy U_b and a specified δ_B only depends on the beam power and its normalized vertical emittance:

$$L \propto H_{Dy} \frac{\delta_B^{1/2}}{U_b} \frac{P_b}{\varepsilon_y^{*1/2}} \propto H_{Dy} \frac{\delta_B^{1/2}}{U_b} \frac{\eta_b^{AC} P_{AC}}{\varepsilon_y^{*1/2}} \qquad (3)$$

In order to reach the specified luminosity of $10^{34}\,cm^{-2}\,sec^{-1}$ at 1 TeV c.m., a future TLC will have to collide beams with several MW of power and extremely

			TESLA	SBLC	JLC$_C$	JLC$_X$	NLC	VLEPP	CLIC
Technology			**S.C.**	⇐	**KLYSTRONS**			⇒	**TBA**
Beam parameters at I.P.									
Centre of mass energy	[TeV]	$2U_b$	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Luminosity	$10^{33}cm^{-2}s^{-1}$	L	6.0	5.0	6.6	5.2	5.5	9.3	6.85
Beamstrahlung mom. spread	[%]	δ_B	2.9	3.1	3.9	3.5	3.2	13.3	3.5
Linac repetition rate	[Hz]	f_{rep}	5	50	100	150	180	300	700
Number of particles/bunch	$[10^{10}e^{\pm}]$	N_e	3.63	1.1	1.0	0.63	0.75	20	0.8
Number of bunches/pulse	[-]	N_b	1130	333	72	85	90	1	20
Bunch spacing	[nsec]	Δ_b	708	6	2.8	1.4	1.4	-	1.0
Transverse emittances .	10^{-8} radm	$\gamma\varepsilon_{x,y}$	1400/25	500/25	330/4.5	330/4.8	400/9	2000/7.5	340/10
RMS beam width .	[nm]	$\sigma_{x,y}$	845/19	335/15	318/4.3	260/3.0	294/6.3	2000/4	264/5.1
Bunch length	[µm]	σ_z	700	300	200	90	125	750	160
Enhancement factor	[-]	H_D	2.3	1.8	1.82	1.4	1.4	2.0	1.30
Beam power per beam	[MW]	P_b	16.5	7.25	3.2	3.2	4.8	2.4	4.5
Main Linac									
RF frequency of main linac	[GHz]	$\omega/2\pi$	1.3	3	5.7	11.4	11.4	14	30
Accelerating field (loaded)	[MV/m]	G	25	17	31.9	58	29.4	91	100
Total two linacs length	[km]	l_T	32	36	18.8	10.4	17.6	7	7.5
Length of sections	[m]	l_s	1.04	6	1.8	1.31	1.8	1.0	0.32
Klystron peak power	[MWatts]	P_k	8	150	50.3	135	50	150	159000
Klystron pulse length	[µsec]	Δ_k	1315	2.8	2.44	0.5	1.2	0.5	0.041
RF pulse compression ratio	[-]	-	-	-	5	2	3.6	3.2	-
Number of klystrons	[-]	N_k	604	2517	4184	3320	4528	140	10
AC to RF efficiency	[%]	η_{RF}^{AC}	35	37	22.6	30	28	39	35
AC to beam efficiency	[%]	η_b^{AC}	19	10.7	4.2	5.6	7.9	8.4	9.4
AC power for RF generation	[MW]	P_{AC}	88	136	153	114	121	57	96

Table 1: Main parameters of TLC designs in a first stage at 500 GeV c.m., updated from [2]

small emittances strongly focused to vertical sizes of a few nm at the I.P. (table 1). RMS beam dimensions down to 70 nm have already been demonstrated by an international collaboration in the F.F.T.B. experiment [4] at SLAC and feasibility of a few 10^{-8} rad-m vertical emittances will soon be studied in the Accelerator Test Facility (ATF) [5] at KEK. For an objective comparison between the different designs, a figure of merit, M, is defined as the luminosity at a given beam energy normalized to the AC power consumption and the δ_B momentum spread. In principle, the figure of merit should also be normalised to the cost of the design once better known. Neglecting the enhancement factor, the figure of merit only depends on two parameters:

$$M = \frac{L \quad U_b}{\delta_b^{1/2} \quad P_{AC}} \propto \frac{\eta_b^{AC}}{\varepsilon_y^{1/2}} \qquad (4)$$

The optimisation of the design of a TLC consists of selecting the technology and beam parameters able to accelerate, at a reasonable cost, a high beam power with an optimum AC power to beam conversion efficiency (chapter 3) while preserving a vertical emittance as small as possible (chapter 4). Fig. 2 displays the figures of merit achieved in the different schemes explored (chapter 5).

3 THE AC POWER TO BEAM CONVERSION EFFICIENCY

The AC to beam power conversion is the product of the AC to RF power efficiency and the RF to beam power conversion:

$$\eta_b^{AC} = \eta_{RF}^{AC} \times \eta_b^{RF} \qquad (5)$$

An impressive technological R & D is presently pursued to develop advanced and effective high peak power RF sources. In spite of the large range of frequencies and technologies explored, the AC to RF power conversion is fairly constant around 35% (Table 1). Nevertheless, these are usually target values, with significant improvements with respect to present standards. To demonstrate their feasibility is one of the main goals of the Test Facilities presently under construction [5-10].

The RF to beam conversion efficiency is directly related to the choice of the RF frequency and beam parameters. With normal conducting constant gradient travelling wave accelerating structures:

$$\eta_b^{RF} = \frac{W_b}{W_{RF}} = \frac{N_b\, q_b g(\tau) R'/Q\,\omega}{G_a\left\{1+\frac{(N_b-1)\Delta_b\omega}{2Q\tau}\left(1+\frac{G_d}{G_a}\right)^2\right\}} \qquad (6)$$

where $g(\tau)=[1-\exp(-2\tau)]/(2\tau)$. R', Q, τ and G_d are respectively the shunt impedance per meter in Linac convention, the quality factor, the field attenuation of the section and the beam loading decelerating field.

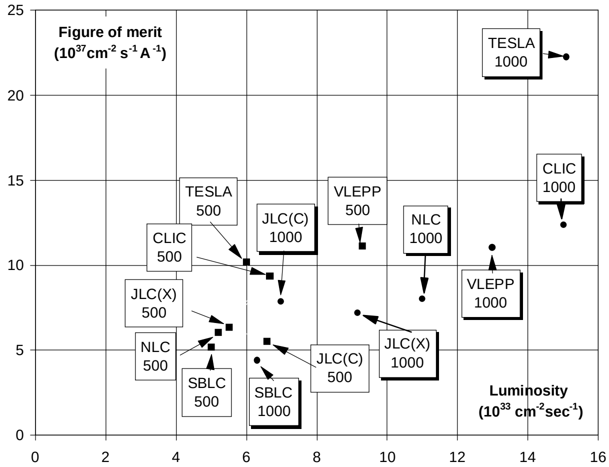

Fig. 2: Luminosity and figure of merit of TLC schemes

Increasing the accelerating gradient, G_a, as desirable for a reasonable linac length, penalizes the conversion efficiency. But all parameters in (6) are inter-related. Assuming the usual scaling, R' ∝ $\omega^{1/2}$, Q ∝ $\omega^{-1/2}$, observing (table 1) that the bunch charge, q_b, scales with $G_a\omega^{-1}$ (as expected from single bunch beam loading compensation) and $\Delta_b \propto \omega^{-1}$, the RF to beam power conversion only depends on the RF frequency and the field attenuation per section independently of the accelerating gradient. It is favoured by high frequency structures as shown in formula (7) and fig. 3 in the extreme cases of single bunch or infinite number of bunches:

$$\eta_b^{RF}(N_b = 1) \propto g(\tau)\omega$$

$$\eta_b^{RF}(N_b = \infty) \propto \frac{\tau g(\tau)\,\omega^{1/2}}{(1+G_d/G_a)^2} \qquad (7)$$

where $G_d/G_a \propto \{1-\exp(-2\tau)/g(\tau)\}\omega^{1/2}$.

The performances obtained in the different studies are compared on fig. 3. They are all based on multi-bunches (except VLEPP) for a good power extraction efficiency. In order to improve the RF to beam power conversion with respect to the present standard as optimized in the SBLC study, the two possible options

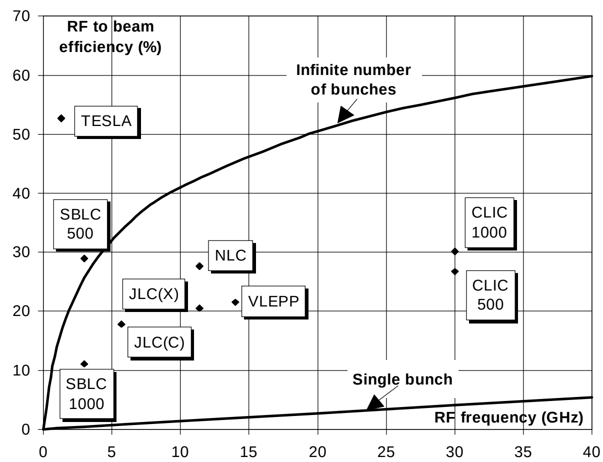

Fig. 3: RF to beam conversion efficiency

are explored:

- superconducting cavities in TESLA with negligible RF losses and an excellent efficiency but with moderate accelerating fields limited by the S.C. technology.

- high frequency structures as developed in all the other studies with the additional advantage to allow large accelerating fields at the limit of dark current capture, scaling with ω (fig. 4).

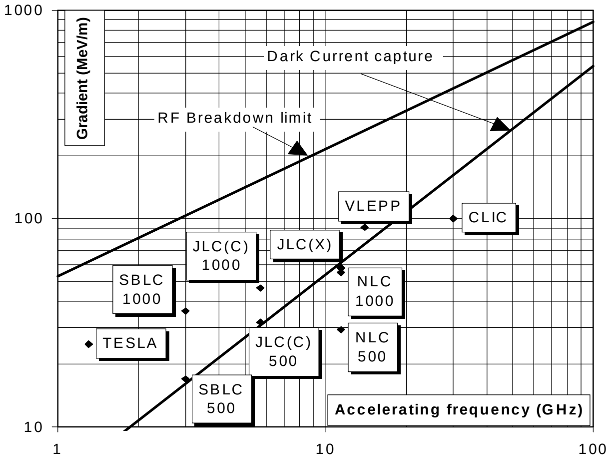

Fig. 4: Accelerating Gradients in TLC Designs

4 BEAM GENERATION AND QUALITY PRESERVATION

Although quite challenging especially for the positrons with a flux one to two orders of magnitude larger than in the SLC, the generation of the main beams with the required quality is not so much the main concern but rather the preservation of this quality during acceleration in the main linacs several km long. Indeed, wakefields are generated by interaction of particles with the RF structures with possible detrimental effects on the following particles of the same bunch (short range) or of the following bunches (long range). These effects are specially strong with high frequency structures as longitudinal and transverse wakefields scale with the second and the third power of the frequency respectively. In the longitudinal plane, they create momentum spread and in the transverse plane emittance blow-up especially critical in the vertical plane because of the very small beam emittance.

An overall beam energy spread and jitter limited to a fraction of a % by both physics requirements and Final Focus acceptance necessitates accurate beam loading compensation. The transverse degradation of the beam ultimately comes from the misalignment or vibration of the linac components through three main mechanisms:

• **the dispersive effect** of the optics when steering the beam along the trajectory defined by position monitors with a random misalignment. Sophisticated beam based alignment techniques relying on the resolution of the beam position monitors rather than their absolute position, have been developed such as the dispersion free and wake-free methods [11] to limit this effect.

• **the short range transverse wakefields** induced by misalignment of the beam or of the RF structures, δy_s, responsible for the so-called single bunch Beam Break-Up (BBU). Assuming the same scaling of parameters with frequency as in chapter 2 and a bunch length, $\sigma_z \propto \omega$, the corresponding blow-up is estimated [12].

$$\Delta\varepsilon_w^s \propto \frac{N_e^2\;\omega^6\sigma_z\;\delta y_s^2\langle\beta_i\rangle}{G_a^2} \propto \omega^3\delta y_s^2 < \beta_i > \qquad (8)$$

The ω^3 dependence is partially compensated in high frequency designs by a better pre-alignment of the structures, δy_s, and a stronger focusing optics $<\beta_i>$. The effect is further reduced by the Balakin, Novokhatsky and Smirnov (BNS) damping. An increase of the betatron focusing along the bunch is introduced by RF quadrupoles or by an energy correlation along the bunch accelerated off-crest of the RF wave, which compensates for the defocusing effect of the transverse wakefields and breaks the resonant condition between head and tail of the bunch.

• **the long range transverse wakefields** generating a multibunch BBU. Several methods are being developed to damp the wakes created by each bunch before the next bunch arrives. Damping by two orders of magnitude with “lossy” irises [6] or by the so-called “detuned” (decohe-rence of the excited fields) [5] or “damped” (coupling of High Order Modes) or “detuned and damped (DDS)” [8] techniques has been shown on simulations to be sufficient to enable the acceleration of long trains of bunches without significant additional blow-up.

The last two effects are the most important in high frequency structures because of the strength of the transverse wakes whereas the first one is usually dominant in low frequency structures where the accelerating gradients are lower. Nevertheless, with a precise pre-alignment of the structures ranging from 500 to 10 µm and sophisticated beam corrections, the overall blow-up is limited to reasonable values of a few tens %.

5 THE TECHNOLOGICAL CHOICES

Apart from common challenges to all designs like a high positron flux, damping to extremely small emittances in the injector complex and strong focusing to nanometer beam sizes at the Interaction Point, four main lines of development are followed-up which mainly concern the main linac acceleration scheme.

5.1. The conventional approach of the SBLC study at the DESY laboratory develops to its limit the present standard technology (room temperature 3 GHz travelling wave sections fed by high power klystrons) taking advantage of the extensive experience accumulated in the SLC [1]. It serves as a reference to compare possible improvements expected from new technologies. A test facility [6] is under construction to demonstrate the high charge multibunch operation and the efficiency of high RF power generation. As an extension of the conventional approach, a study based on C-band klystrons at 5.7 Ghz has been started at KEK [13]. A test facility is under preparation to demonstrate its performance and reliability.

5.2 The superconducting option studied by the international TESLA collaboration coordinated by DESY is based on low frequency standing wave cavities made super-conducting to minimize the RF losses and favour the RF to beam power conversion. The RF losses would not be worth mentioning if they would not be at a cryogenic temperature. It makes possible the acceleration of a long train of bunches widely spaced which eases the design of the Final Focus and is favourable for the detector. The small wakefields inherent to the low frequency structures strongly relax the alignment tolerances, but in a cryogenic environment. A test facility [7] is being prepared to develop the superconducting technology with the ambitious challenges to improve the accelerating fields up to 15 to 25 MeV/m, greater than the dark current capture and well above the present state of the art, together with a reduction of the cost per MeV by a factor 20. The energy upgrade of TESLA above 500 GeV c.m. relies on further improvement of the accelerating fields (40 MeV/m?) to limit the overall extension of the complex.

5.3 High frequency RF structures with reduced stored energy and peak power requirements is the other approach to improve the RF to beam efficiency (fig. 3). Moreover, it makes possible high accelerating gradients as the dark current capture and the breakdown limit both scale with ω (fig. 4). As a consequence, the linacs can be made shorter with smaller structures which should reduce the capital cost. How high can be the frequency depends on the availability of RF power sources and on the ability to preserve the beam quality. Indeed, the wakefields rapidly increasing with frequency bring about sophisticated alignment and beam correction techniques. Developments of high peak power RF sources follow two approaches:

- X-band klystrons at 11.4 GHz for NLC at SLAC, JLC at KEK and at 14 GHz for VLEPP at BINP made excellent progress in the last few years. Tests facilities [5,8] will operate soon to test the X-band technology as well as efficient modulator/klystron stations with RF pulse compression and to demonstrate the multibunch operation under strong wake-field conditions.

- The Two Beam Acceleration Scheme in which the energy from a high intensity low momentum drive beam running all along the linac is transformed into RF power which in turn is used to feed the accelerating structures of the main linacs. This new acceleration scheme [14] is potentially very effective with a simple mechanical arrangement avoiding the need for a large number of powerful klystron/modulator stations in a separate tunnel all along the linac. Two technologies are presently under development from which the feasibility is being studied in test facilities [9,10]. One at LBL for the NLC at 1 TeV based on induction linacs continuously reaccelerating a 10 MeV drive beam to compensate for the energy transformed in X-band RF power and one for CLIC at an even higher frequency of 30 GHz using low frequency superconducting cavities to pre-accelerate the drive beam with a good efficiency.

CONCLUSION

In the past few years, tremendous progress has been realized towards the conceptual design of a performing and effective TLC. A wide range of technical options is being explored and will soon be tested in challenging test facilities, a necessary step before technology and design parameters are chosen based on performance, operability and realistic costing. Imagination and international collaboration in a stimulating and constructive atmosphere have been and will be the key of success towards the final design hopefully followed by the approval, construction and operation of such a facility in the near future.

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