Low Frequency Linear Colliders

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Abstract

The various approaches towards a future linear collider with a center-of-mass energy of 300...500 GeV and a luminosity of $10^{33}...10^{34}$ cm^{-2} s^{-1} currently under investigation cover a frequency range from 1.3 GHz to 30 GHz for the accelerating rf. This paper reports on the status of the design for the two approaches at the lower end of this frequency scale, namely the TESLA superconducting L-band (1.3 GHz) accelerator and the approach using conventional S-band (3 GHz) structures. Common to both designs are a high AC-to-beam power transfer efficiency and relaxed tolerances relative to high frequency machines. The general layout, accelerator physic issues, and the potential for energy and luminosity upgrade for the TESLA and S-band linear colliders are discussed.

1. INTRODUCTION

Among the different design studies for a next generation e^+/e^- linear collider, the SBLC and the TESLA approaches both follow the concept of a rather low rf-frequency ω_{rf} and a moderate accelerating gradient g, which allows for a high overall efficiency and relaxed tolerances in combination with reduced wakefield effects in the linac (the wakefields scale approximately as $W_{\parallel} \propto \omega_{rf}^2$, $W_{\perp} \propto \omega_{rf}^3$). In case of the SBLC, it is proposed to use conventional travelling wave accelerating structures at 3 GHz (S-Band) and g=17 MV/m. It is to a certain extend an extrapolation of the existing SLC machine [1] operating at the same frequency, therefore likely being of all designs the one closest to existing technology and able to profit most directly from the experience gathered at the SLC. The TESLA approach uses superconducting Nb accelerating structures operating at 1.3 GHz (L-Band) and is aiming for an accelerating gradient of g=25 MV/m with a quality factor (unloaded) of $Q_0=5\times10^9$ at T=2K. The choice of 1.3 Ghz is mainly a compromise between surface resistance ($\propto\omega_{rf}^2$) on one and R/Q (favoring a high frequency) on the other side. Another argument is the availability of klystrons at this operating frequency. Whereas the advantages of very low wakefields and high acceleration efficiency are obvious, the challenge of TESLA is clearly to demonstrate that stable operation with a gradient of g=25 MV/m can be achieved not only within a laboratory experiment but on a large scale. In addition, the costs of the s.c. structures have to be drastically reduced.

The SBLC and TESLA linear collider studies are pursued at DESY in international collaborations with institutes in China, France, Germany, Italy, Japan, Netherlands, Russia and USA contributing to the technical R&D and/or the design of the 500 GeV collider. In the following, the present status of design is described. After a discussion of general parameters, the layouts of the collider interaction region, the main linac and the injection system are presented. In section 6, the upgrade potential of SBLC and TESLA is discussed. A brief summary of the R&D status is given in section 7.

2. PARAMETERS

The achievable luminosity of a linear collider is determined by the following basic parameters:

- the average power per beam P_b, which is limited by a reasonable AC-power limit and the overall AC-to-beam transfer efficiency η
- the normalized vertical emittance ε_y, limited by tolerances
- the maximum tolerable beamstrahlung energy loss $<\Delta E/E>_{rad}$, limited by background considerations and the energy resolution required by the high energy physics experiment.

Using basic relations for the luminosity and the beamstrahlung and assuming an optimum beta-function β_y^* at the interaction point (IP) equal to the bunchlength σ_z, the luminosity is in good approximation given by:

$$L = const. \times \frac{P_b}{\gamma} \times \frac{< \Delta E / E >_{rad}^{1/2}}{\varepsilon_y^{1/2}}$$

With P_b in MW, $<\Delta E/E>_{rad}$ in % and ε_y in 10^{-6}m, we find *const.*/$\gamma \approx 2.8\times10^{32}$cm^{-2}s^{-1} at E_{cm}=500 GeV. SBLC and TESLA achieve a high efficiency $\eta_{AC\text{-}to\text{-}beam}$ by accelerating long bunchtrains per linac pulse allowing for high P_b, at the same time keeping beamstrahlung at a low level. The required emittances and beam sizes at the IP are close to what has been achieved at the FFTB experiment [2]. A list of the main SBLC and TESLA parameters is given in table 1.

3. INTERACTION REGION, FINAL FOCUS, COLLIMATION

Keeping beamstrahlung at a low level is an essential prerequisite for acceptable background conditions and good energy resolution for the high energy physics experiment. The most important parameters concerning beam-beam effects are summarized in table 2. With the relatively large spacing between bunches (especially for TESLA with $\Delta t_b = 1\mu s$), only the background produced per bunch crossing is relevant. Thus the small numbers of e^+e^- pairs N_{pair} outside a mask with 5cm radius and 100mrad opening angle as well as the hadronic background (N_{hadr}) are handable.

Table1: main parameters of the S-band and TESLA 500 GeV (c.m.) linear colliders

	SBLC	TESLA	
active length	29.4	20	km
t_{pulse}	2	800	μs
n_b/pulse	125	800	
Δt_b	16	1000	ns
f_{rep}	50	10	Hz
N_e/bunch	2.9	5.1	10^{10}
$\varepsilon_x/\varepsilon_y$	10/0.5	20/1	10^{-6} m
β_x^*/β_y^*	22/0.8	25/2	mm
σ_x^*/σ_y^*	670/28	1000/64	nm
σ_z	0.5	1	mm
$<\Delta E/E>_{rad}$	3.2	3.0	%
P_b	7.2	16.5	MW
P_{AC} (2 linacs)	113	137	MW
$\eta_{AC\text{-}to\text{-}beam}$	13	24	%
L (incl H_D)	3.6	6.5	$10^{33}cm^{-2}\,s^{-1}$

In case of the SBLC, beams have to cross at an angle (θ_c=3 mrad) in order to avoid the multibunch kink-instability [3] due to parasitic interactions. A reduction of luminosity caused by an effective increase of the hor. beamsize is avoided by employing a simple crab-crossing scheme with finite dispersion at the IP, making use of a coherent energy spread within the bunch of about σ_E=0.5 % [4]. For TESLA a head-on collision design with electrostatic separation of the beams after the final doublet is possible [5], see fig.1. This allows TESLA to use s.c. quadrupoles which provide a large aperture (a_Q=20 mm) for the exiting disrupted beam and the beamstrahlung γ's emitted at the IP with large angles (SBLC uses conventional quadrupoles with a_Q=4mm).

The magnet lattice between the IR and the main linac consists of the final focus system (FFS) for beamsize demagnification and chromatic corrections, a collimation section to protect the IR quads from large amplitude particles and bending sections for creating a sufficient separation between two beamlines if the collider is to serve two experiments. The bend between collimation and the FFS also helps to reduce background due to muons originating at the collimators.

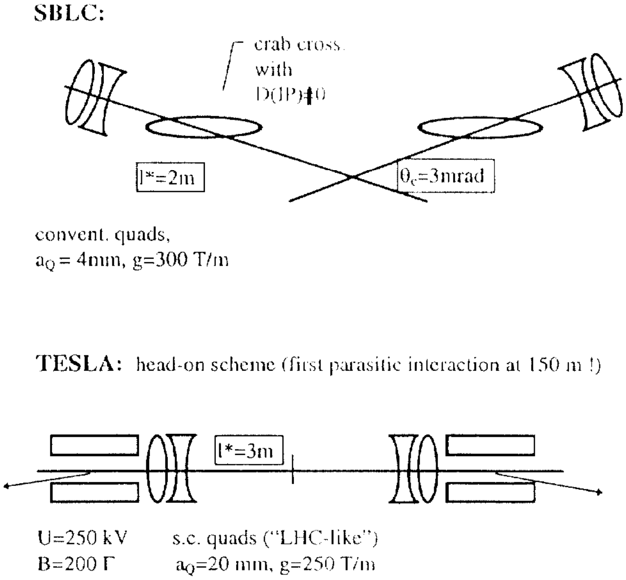

Fig. 1: Basic layouts of the interaction region

Table 2: results of beam-beam simulations for SBLC and TESLA [5,6,7]

	SBLC	TESLA	
$<\delta E/E>_{cm;rms}$	2.7	2.	%
Υ_o	.04	.021	
Disr. D_x/D_y	0.4/8.5	0.4/8.5	
angle $\hat{\theta}_{\gamma x/y}$	1.28/0.55	1.07/0.64	mrad
N_{pair}/bunch	7	14	
N_{hadr}/bunch	0.2	0.3	

The momentum acceptance of the FFS for both designs is far in excess of the beam energy spread. For TESLA, a simple two sextupole family chromatic correction gives a bandwidth of ±0.6 % [5] ($\sigma_{E,beam}$=0.06%) and for SBLC with an optimized sextupole distribution a bandwidth of ±2.0 % is achieved ($\sigma_{E,beam}$=0.5%) [8].

The requirements for beam collimation are determined by the condition that synchrotron radiation generated in the doublet before the IP has to pass freely through the aperture of the final quad on the opposite side. This means that particle amplitudes have to be restricted to $6\sigma_x \times 8\sigma_y$ for SBLC and $12\sigma_x \times 35\sigma_y$ for TESLA. In the latter case, continuous scraping of beam tails may not be necessary, since in the s.c. linac gas scattering is negligeable and wakefields are small so that particle betatron amplitudes should normally not reach the above defined limits. Following concepts developed at SLAC [9], a beam optics design for simultaneous collimation in x,y and dE/E has been worked out , the lattices for SBLC and TESLA being similar. However, an advantage of TESLA is that due to the large bunch spacing the beam can be stopped by a fast dump system, firing a kicker if from the first bunch(es) intolerable high loss rates are detected and sending the beam on an absorber block. The entire lattice from the linac to the IP will require approximately 1.1 km on either side of the IP.

4. MAIN LINAC

The SBLC and TESLA linacs consist of basic units as sketched in fig.2. For the conventional S-band machine, two 6m long travelling wave, constant gradient Cu-structures are powered by a 150 MW (peak power) klystron. For a 2µs flat top current pulse a modulator pulse width of 2.8µs is required. In total 2450 klystrons and modulators are required for the two 250 GeV linacs. A focussing scheme with scaling $\beta \propto \gamma^{1/2}$ and β=18m at the entrance of the linac (E=3 GeV) is foreseen.

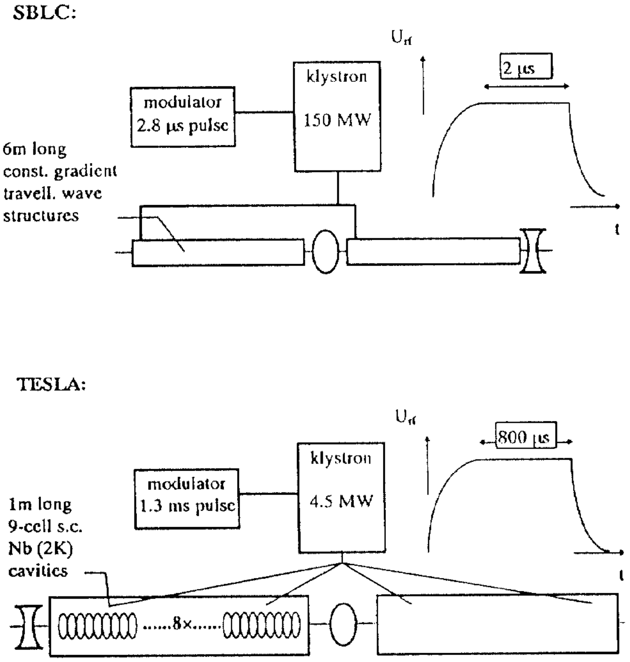

Fig.2: Basic units of the SBLC and TESLA main linac

In case of TESLA, a 4.5 MW klystron delivers rf-power to 16 9-cell 1.3 Ghz s.c. Nb cavities. There are 8 of these 1m long cavities in one kryostat. The modulator provides a 1.3 ms long pulse, yielding a 0.8 ms long accelerating gradient flat top. The two TESLA linacs require in total 1250 klystrons and 20,000 cavities. A focussing scheme using s.c. quadrupoles with constant β=66m is foreseen.

One of the most important accelerator physics issues in a linear collider concerns preservation of a small (especially vertical) emittance in the linac. Emittance dilution caused by chromatic effects (dispersion, filamentation) due to energy spread in the bunch, short range wakefields and long range deflecting modes are investigated for both designs considered here. Recent computer simulation results for SBLC [10] show that single bunch beam break-up can be well suppressed by applying BNS-damping only over the first 30% of the linac length (in the other part of the linac σ_E can be reduced to 0.3% by choosing an rf phase of -12 deg). With a coherent energy spread in this section of σ_E=0.9% the emittance growth due to injection oscillations can be kept small. Taking into account transverse position errors for quadrupoles, accelerating structures and beam position monitors (BPM's) of 0.1 mm (rms), it is shown that after applying different correction algorithms (wakefield-free (WF) orbit correction [11], bumps for dispersion and wakefield compensation), the dilution can be kept as small as $\Delta\varepsilon_y/\varepsilon_y$=3%. In addition to a BPM resolution of 5µm this requires 4 stations distributed along the linac where the emittance can be measured with an accuracy of 3%. The higher order modes (HOM's) induced when bunches pass off-axis through the accelerating structures cause oscillations growing over the entire bunch train (multibunch beam break-up). In order to keep this effect within limits, a frequency spread for the deflecting modes is introduced (the max. variation is assumed to be 40 Mhz). Furthermore, the quality factor of the modes with the strongest coupling to the beam has to be reduced by three HOM-couplers per 6m structure resulting in a Q-profile of typically $\sim 3\times10^3$ [12]. With these assumptions and tolerances as described above, computer simulations yield an effective multibunch emittance dilution of $\Delta\varepsilon_y/\varepsilon_y \sim 20\%$ [13]. This dilution can be further reduced by "beam-based alignment" of the cavities (measure HOM's and move the structures) and/or by using a fast kicker to put all bunches back on the same orbit [14].

Similar studies are performed for TESLA [15]. No BNS-damping is required and the emittance dilution from single bunch effects is small ($\sim$5%) even before optimization with bumps and with a relaxed tolerance of 0.5mm (rms) for cavity position errors. With HOM-damping provided by two couplers per 9-cell cavity ($Q<10^5$), multibunch BBU leads to an effective emittance growth of 22% (for this calculation 1mm rms cavity positon errors were assumed). A drastic reduction of this dilution by improving alignment of cavities with beam or applying the kicker-method should be easy for TESLA.

An important result concerning the stability of emittance with time has been obtained for SBLC [10] by assuming that the linac components are subject to diffusive ground motion following the ATL-rule. Using $A=4\times10^{-6}$ μm^2 m^{-1} s^{-1} as obtained from orbit motion observed at HERA [16], an emittance dilution of only 6% after 1 day is obtained if nothing but the simple one-to-one orbit correction is applied about once per hour. Concerning fast (>5 Hz) ground motion, active stabilization of magnet supports is investigated [17]. For TESLA, vibrations are not considered to be a problem since, thanks to the large bunch spacing, an orbit feedback can be applied within a bunchtrain (measure position of first bunch, correct for all others with a kicker).

5. INJECTION

The emittances required for the SBLC e^- and e^+ beams are provided by two damping rings of 650m circumference operating at 3.15 GeV. A beam optics layout with $\varepsilon_x=5\times10^{-6}$ m (50% of the design value at the IP) has been worked out [18]. The normalized dynamic aperture of 2.4×10^{-2} m is sufficient to accept the beam delivered from the e^+ source. Positrons are produced by converting γ's in a thin (0.4 radiation lengths) target. The required intense photon source is realised by passing the e^- beam after collision through a 30m long wiggler [19]. The method drastically reduces the heat load on the target and opens up the possibility to produce polarized positrons by using a helical undulator. The same scheme for e^+ production is foreseen for TESLA. Here, it is necessary to compress the 0.8ms long bunchtrain in order to fit into a damping ring of reasonable size. Two options are presently discussed: A conventional ring with ~6km circumference (like HERA-e) or a "dog-bone" shaped ring of ~20 km length [20] which fits almost entirely (except for the arcs at the end) into the linac tunnel. One advantage of the latter design is an increased bunch spacing (80 ns instead of 25 ns for the HERA-e like ring), which relaxes bandwidth requirements for the injection/extraction system [21] and the multibunch feedback . For TESLA also the possibility of of achieving the design emittance of the e^- beam by using a rf-photo-gun is being studied, which would allow to save one of the two damping rings.

6 UPGRADE POTENTIAL

With the relaxed tolerances of the low-frequency approach, SBLC and TESLA are very well suited designs if one aims to push the vertical emittance towards a smaller value. After gaining experience with correction and optimization procedures, operation of SBLC and TESLA with ε_y reduced by an order of magnitude seems conceivable. That would allow for higher luminosity and at the same time lower AC-power consumption (parameter sets for such a low emittance option at 500 GeV center-of-mass are given in table 3). A small ε_y becomes very important (if not inevitable) when an energy upgrade to 1TeV is considered. Whereas for TESLA a higher energy requires to increase the linac length, this upgrade could be made for SBLC within the same tunnel by doubling the number of klystrons and compressing the rf-pulse with a SLED system, thus doubling the accelerating gradient to 34 MV/m. Parameter sets for 1TeV are shown in table 4. Beamstrahlung is kept at a low level for both designs. The AC-power for TESLA is close to the 500 GeV version, whereas for SBLC the higher gradient leads to a loss in efficiency so that twice the AC power is required.

Table 3: modified parameters at 500 GeV (c.m.) with reduced vertical emittance

	SBLC	TESLA	
n_b/pulse	180	1200	
f_{rep}	25	5	Hz
N_e/bunch	2.0	3.4	10^{10}
$\varepsilon_x/\varepsilon_y$	5/0.05	10/0.1	10^{-6} m
σ_x^*/σ_y^*	632/6.3	775/12.6	nm
σ_z	0.25	0.5	mm
$<\Delta E/E>_{rad}$	3.0	3.3	%
P_{AC} (2 linacs)	57	70	MW
L (incl. H_D)	5.8	10	10^{33} cm^{-2} s^{-1}

Table 4: parameters at 1000 GeV (c.m.) with reduced vertical emittance

	SBLC	TESLA	
active leng.	29.4	40	km
n_b/pulse	50	4180	
t_{pulse}	0.6	830	μs
f_{rep}	50	5	Hz
N_e/bunch	2.9	0.91	10^{10}
$\varepsilon_x/\varepsilon_y$	5/0.05	5/0.063	10^{-6} m
σ_x^*/σ_y^*	742/6.3	325/8	nm
σ_z	0.50	0.5	mm
$<\Delta E/E>_{rad}$	4.3	2.7	%
P_{AC} (2 linacs)	230	153	MW
L (incl. H_D)	5.9	10.4	10^{33} cm^{-2} s^{-1}

7. R&D, TEST FACILITIES

The goal of the SBLC and TESLA test facilities under construction at DESY is to build and test the basic components required for the 2x250 GeV linear accelerators. For SBLC, the test linac consists of two 150 MW klystrons (built at SLAC) which power two 6m long accelerating structures each. Recently the first klystron gun has reached its full design parameters in a diode test, while rf-tests with the complete device are in preparation at SLAC. Conventional line-type modulators are forseen for pulsing the klystrons. As an alternative, the possibility of using a switch tube modulator is also being studied [22]. The structure design includes symmetric rf-input couplers [23] and additional couplers for HOM damping [24]. Magnet and structure supports and precision movers as well as methods to compensate ground vibrations are investigated [17]. An injector is under construction to deliver the full design pulse current of 300 mA with the nominal bunch spacing of 16 ns for testing the setup with beam.

For TESLA the main objective of the test facility (TTF) is to process and test industrially fabricated Nb cavities and demonstrate that they can be operated with beam stably at a gradient of at least 15 MV/m [25]. The infrastructure includes facilities for high pressure rinsing, heat treatment and high peak power processing of the cavities [26]. The test linac consists of 32 9-cell cavities powered by two 4.5 MW klystrons. The klystron and the modulator (built at FNAL) have been tested successfully at full design parameters. The first cavities are on site and processing is in progress. Recently, with 5-cell 1.3 Ghz structures the g=25 MV/m goal has been reached at Cornell [27]. The injector for the TTF [28] is designed to deliver the full average pulse current, however with reduced bunch charge and higher bunch rep. frequency in its first stage. In a second stage, the bunch structure as designed for TESLA will be available. Furthermore, a low emittance rf-photo-gun for the injector is being investigated.

8. CONCLUSION

The low-frequency approach of SBLC and TESLA is well suited to achieve the performance goals of a next generation linear collider. Which of the two ways to go will have to be decided on the basis of results from the test facilities.

ACKNOWLEDGEMENT

The author would like to express his thanks to the colleagues of the S-band and TESLA collaborations for their support in collecting the information contained in this paper, and for many helpful discussions.

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