Status of the Design for the TESLA Linear Collider

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Abstract

Among the different approaches towards a next generation 500 GeV (c.m.) Linear Collider the TESLA design uses superconducting accelerating structures operating at 1.3 GHz and a gradient of 25 MV/m. The particular features of TESLA are a high AC-to-beam power transfer efficiency and relaxed tolerances compared to the other approaches. This paper gives an update on the machine parameters and the overall design, including a discussion of the potential for an upgrade to higher center-of-mass energies.

I. INTRODUCTION

The different design studies for a next generation e^+/e^- linear collider fall, roughly speaking, in two categories: the high frequency approaches (NLC, JLC, VLEPP, CLIC), which aim at a high accelerating gradient and the low frequency approaches (SBLC, TESLA) operating at a lower gradient, but having the advantage of reduced rf peak power requirements and smaller wakefield effects in their larger aperture accelerating structures [1,2]. The TESLA design, with an rf frequency of 1.3 GHz at the lower end of this frequency scale, has the special feature of using superconducting cavities for the linac, which allows to accelerate many bunches in a long rf-pulse yielding a high rf-to-beam power transfer efficiency. An accelerating gradient of 25 MV/m with a quality factor (unloaded) of $Q_0=5\times10^9$ at T=2K is foreseen. The choice of 1.3 Ghz is a compromise between surface resistance ($\propto\omega_{rf}^2$) and R/Q (favoring a high frequency). 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 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 compared to systems built up to now. In order to demonstrate that these goals can be achieved, a test facility is under construction at DESY [3,4] in international collaboration with institutes in China, Finnland, France, Germany, Italy, Poland, 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 final focus and interaction region, the main linac and the injection system are presented. In section 5, the upgrade potential of TESLA is discussed.

II. PARAMETERS

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

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

where P_b is the average beam power, $<\Delta E/E>_{rad}$ the energy loss due to beamstrahlung and ε_y the normalised vertical emittance. With the extremely small wakefields in the s.c. cavities, the TESLA linac is ideal for preserving a small ε_y without excessively tight tolerances (see section 4). Making use of this fact, the TESLA parameters have recently been slightly modified towards a smaller vertical emittance (see table 1 for a comparison of the new with the original [2] TESLA parameters). The main benefit of the new parameter set is a reduced AC-power consumption which is now below 100 MW for the 500 GeV (center of mass) machine at unchanged luminosity. The tolerances in the linac still remain conservative and the vertical spot size at the interaction point (IP) is a moderate extrapolation of the recent achievement of the FFTB experiment [5] by about a factor of 3.5.

III. INTERACTION REGION, FINAL FOCUS, COLLIMATION

Keeping beamstrahlung at a low level is essential for acceptable background conditions and good energy resolution for the high energy physics experiment. The center-of-mass energy spread in TESLA amounts to $<\delta E/E>_{c.m.} = 1.5\%$. It could be further reduced for a top quark threshold scan to $<\delta E/E>_{c.m.} \approx 0.1\%$ by increasing the horizontal beamsize at the IP, still keeping the luminosity above 10^{33} cm^{-2} s^{-1}. With the relatively large spacing between bunches ($\Delta t_b=0.7\mu s$), the experiment can resolve individual bunch crossings. 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 [6] are easily handable.

For TESLA a head-on collision design with electrostatic separation of the beams after the final doublet is possible [7], see fig.1. This allows to use s.c. quadrupoles which provide a large aperture (a_Q=24 mm) for the disrupted beam and the beamstrahlung γ's emitted at the IP with large angles. A layout for the separation of the outgoing from the incoming beam and for beamstrahlung collimation is under study [8].

Table 1: New parameters of the TESLA 500 GeV (c.m.) linear collider in comparison with the original design.

	NEW	OLD	
total length	32	32	km
t_{pulse}	800	800	μs
n_b/pulse	1130	800	
Δt_b	707	1000	ns
f_{rep}	5	10	Hz
N_e/bunch	3.63	5.1	10^{10}
$\varepsilon_x/\varepsilon_y$	14/0.25	20/1	10^{-6} m
β_x^*/β_y^*	25/0.7	25/2	mm
σ_x^*/σ_y^*	845/19	1000/64	nm
σ_z	0.5	1	mm
$<\Delta E/E>_{rad}$	2.9	2.9	%
Disr. D_x/D_y	0.2/11	0.4/8.5	
P_b (2 beams)	16.3	33	MW
P_{AC} (2 linacs)	88	154	MW
$\eta_{AC\text{-}to\text{-}beam}$	19	21	%
luminosity L	6	6	10^{33} cm^{-2}s^{-1}

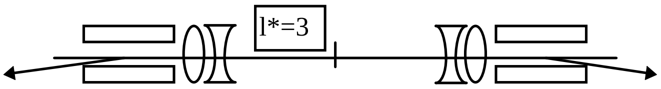

Fig. 1: Basic layout of the interaction region

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 [9]. In total this "beam delivery" system is 1.5 km long (per beam). The momentum acceptance of the FFS (±0.6%) is well in excess of the beam energy spread (σ_E/E=0.1%).

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 $12\sigma_x \times 35\sigma_y$ for TESLA. Continuous scraping of beam tails may not be necessary, since in the s.c. linac gas scattering is negligable and wakefields are small so that particles should normally not reach the above defined limits. Following concepts developed at SLAC [10], a design for simultaneous collimation in x,y and dE/E has been worked out [10].

IV. MAIN LINAC

The TESLA linac consists of basic units with one 9 MW klystron delivering rf-power to 32 9-cell 1.3 Ghz s.c. Nb cavities.

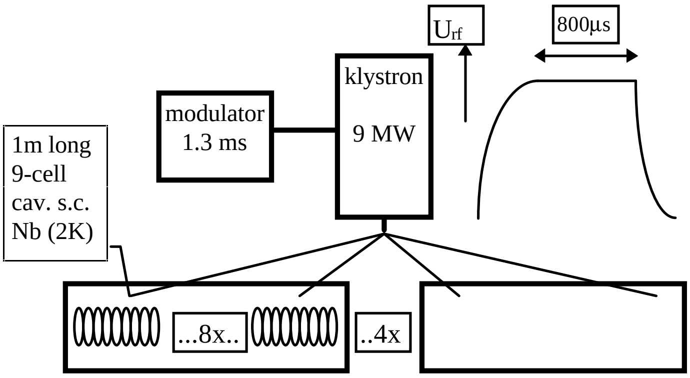

Fig. 2: Basic unit of the TESLA main linac

There are 8 of these 1m long cavities in one kryostat. The modulator produces a 1.3 ms long pulse, yielding a 0.8 ms long flat top accelerating field. The two TESLA linacs require in total 604 klystrons and 19,328 cavities. A focussing scheme using s.c. quadrupoles with scaling $\beta \propto \gamma^{0.2}$ (initial β = 22m) is foreseen [11].

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 have been investigated [11]. With HOM-damping provided by two couplers per 9-cell cavity ($Q<10^5$), multibunch BBU leads to an effective emittance growth of only about 1%, assuming rather relaxed transverse rms position tolerances of 0.5 mm for the cavities and 0.1mm for the quadrupoles and beam position monitors (BPM's). A simple "one-to-one" orbit correction algorithm was applied in this computer simulation. With the same assumptions, the calculated emittance growth due to short-range wakefields and chromatic effects amounts to $\Delta\varepsilon_y/\varepsilon_y$ = 20%. A further reduction of emittance dilution is possible applying additional beam-based correction procedures [12]. With its relaxed tolerances, the TESLA linac will be rather insensitive to ground motion. In addition, the large bunch spacing allows to very effectively eliminate pulse-to-pulse orbit jitter. This is done by measuring the position of the first bunch and correct for the following ones with a kicker. Such devices would be installed at the beginning and the end of the main linac. The fast orbit correction method can also be applied to stabilise the beam position at the IP.

V. INJECTION SYSTEM

For TESLA 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 $\approx$6km circumference (like HERA-e) or a “dog-bone” shaped ring of $\approx$20 km length [13] 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 and the multibunch feedback. Recent beam optics studies for the dogbone ring show that the required emittances can be achieved with reasonable magnet position tolerances [14]. The possibility to use a rf-photo-gun to achieve the design emittance of the electron beam is being studied [15], which would allow to save one of the two damping rings.

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 [16]. The method drastically reduces the heat load on the target and opens up the possibility to produce polarized positrons by using a helical undulator.

VI. UPGRADE POTENTIAL

With the relaxed tolerances of the low-frequency approach, TESLA is a very well suited design if one aims to push the vertical emittance towards a smaller value. A small ε_y becomes very important (if not inevitable) when an energy upgrade to 1TeV or higher is considered. How in detail the energy upgrade of TESLA would be realised depends on the progress on cavity development in the longer term future. Under conservative assumptions, the gradient has to be kept at 25 MV/m implying that a 1 TeV version of TESLA would have to double the length of the linac. However, neither this gradient nor the assumed quality factor of 5×10^9 are fundamental limits. Assuming a gradient of 40 MV/m as a future possibility, the machine with twice the length of the 500 GeV design could reach a center-of-mass energy of 1.6 TeV..The parameters for this machine are shown in table 2. A reduced bunch charge is used to facilitate preservation of the vertical emittance (first results of simulation studies show that this emittance can indeed been achieved with still relatively relaxed tolerances). A luminosity above 2×10^{34} cm^{-2} s^{-1} can be reached with an AC-power consumption increased by about a factor of 2.5 compared to the 500 GeV design.

Table 2: Parameters at 1600 GeV (c.m.) with an accelerating gradient of 40 MV/m at $Q_0 = 5\times 10^9$.

	TESLA 1.6 TeV	
total length	62	km
t_{pulse}	800	μs
n_b/pulse	2825	
Δt_b	283	ns
f_{rep}	3	Hz
N_e/bunch	1.8	10^{10}
$\varepsilon_x/\varepsilon_y$	10 / 0.03	10^{-6} m
β_x^*/β_y^*	35 / 0.7	mm
σ_x^*/σ_y^*	474 / 3.7	nm
σ_z	0.5	mm
$<\Delta E/E>_{rad}$	5.2	%
Disr. D_x/D_y	0.15 / 18.8	
P_b (2 beams)	39.2	MW
P_{AC} (2 linacs)	228	MW
$\eta_{AC\text{-}to\text{-}beam}$	17.2	%
luminosity L	23	10^{33} cm^{-2}s^{-1}

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