LINEAR COLLIDER PROJECTS AT DESY

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Abstract

At DESY, in international collaboration with many institutes, plans for a next generation e+e- Linear Collider with a cms energy of 0.5 - 1 TeV are being developed. The preferred technical solution for the accelerator (TESLA) is based on superconducting rf-technology operating at 1.3 GHz with a gradient of 25 MV/m. A second approach using conventional S-band technology is investigated as a backup solution. This paper summarises the present status of the TESLA design and discusses the perspectives for reaching a very high luminosity (close to 10^{35} cm^{-2} s^{-1}). A brief overview of the progress on the TESLA and S-band test facilities will also be given.

1 Introduction

Studies towards a next generation e+e- Linear Collider in the 0.5 - 1 TeV centre-of-mass energy range are being pursued world-wide by several High Energy Physics laboratories. In the international TESLA collaboration, centred at DESY, more than 30 institutes from China, Finland, France, Germany, Italy, Poland, Russia and USA participate in the design work and technical R&D for a linear collider based on superconducting accelerating structures. The combination of high AC-to-beam power transfer efficiency $\eta_{AC \rightarrow b}$ with small emittance dilution in the low-frequency (1.3 GHz) linac makes this choice of technology ideally suited for an optimum performance in terms of the achievable luminosity.

A considerable challenge results from the need to reduce the cost per unit accelerating voltage by a large factor compared to existing large-scale installations of superconducting cavities (e.g. at LEP and CEBAF). Our aim is to increase the accelerating gradient by about a factor of five to 25 MV/m and simultaneously the cost per unit length by a factor of four.

In the following, the progress on the design of the TESLA Linear Collider facility and the status of the R&D programme at the TESLA Test Facility (TTF) will be summarised. The status of R&D for the conventional S-Band version of a Linear Collider, which is investigated as a backup solution, will also be briefly reported.

2 TESLA Overview and Parameters

The overall layout of TESLA is sketched in Fig. 1. The total site length is about 32 km, including the beam delivery system (which provides beam collimation and spot size demagnification).

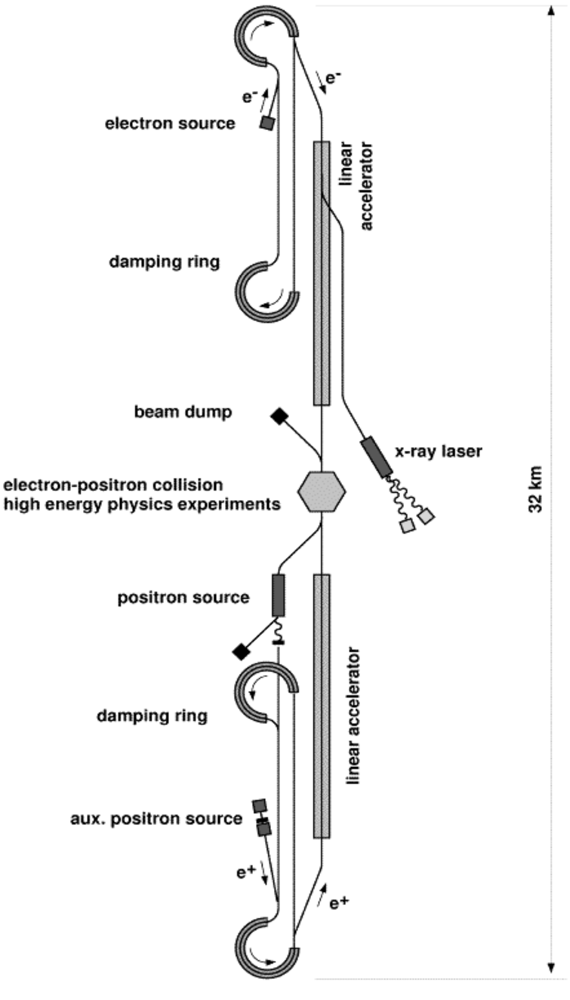

Fig.1: Overall layout of TESLA

A complete description of the machine, including all sub-systems such as cryogenic plants, damping rings, particle sources, etc. is given in the design report published in spring 1997 [1]. The report includes chapters on the Particle Physics and the layout of the Detector, which were prepared in a joint study of DESY and ECFA. The integration of an X-ray coherent light source user facility into the

TESLA project is also part of this design study. Furthermore, the possibility to use part of the TESLA linac as an injector for a continuous electron beam source for Nuclear Physics using HERA as a stretcher ring is discussed as a possible option.

In this first detailed design study of TESLA, a reference parameter set was used as a basis, which yields values for the beamstrahlung energy loss δ_B and the luminosity L comparable to those of the other Linear Collider designs [2]. For that parameter set the requirements for the alignment and stability of the linac and Final Focus components turn out to be quite relaxed. While this is considered very beneficial in particular for an early stage of machine operation, it also leaves room for improved machine performance if one allows to reduce the large safety margin with regard to beam dynamics. This aspect, discussed only to some extend in ref. [1], is being studied in more detail since completion of the design report. As a result of these studies, we have been led to an improved parameter set shown in Table 1 in comparison with the reference parameters for a centre-of-mass energy of 500 GeV.

Table 1: Updated parameters at E_{cm}=500GeV in comparison with the original reference parameters [1].

	TESLA (ref.)	TESLA (new)
site length [km]	32.6	32.6
active length [km]	20	23
acc. Gradient [MV/m]	25	21.7
quality factor Q_0 [10^{10}]	0.5	1
t_{pulse} [μs]	800	950
# bunches n_b/pulse	1130	2820
bunch spacing Δt_b [ns]	708	337
rep. rate f_{rep} [Hz]	5	5
N_e/bunch [10^{10}]	3.6	2
ε_x / ε_y (@ IP) [10^{-6}m]	14 / 0.25	10 / 0.03
beta at IP $\beta_{x/y}^*$ [mm]	25 / 0.7	15 / 0.4
spot size σ_x^*/σ_y^* [nm]	845 / 19	553 / 5
bunch length σ_z [mm]	0.7	0.4
beamstrahlung δ_B [%]	2.5	2.8
Disruption D_y	17	33
P_{AC} (2 linacs) [MW]	95	95
efficiency $\eta_{AC \to b}$ [%]	17	23
lumin. L [10^{34} cm^{-2}s^{-1}]	0.68	3

Besides a smaller beam emittance, an improvement in the overall efficiency is taken into account, which results from a reduced accelerating gradient possible due to a higher fill-factor in the linac. The improvement in luminosity amounts to more than a factor of four. The steps which led to this new parameter set and the impact on the individual sub-systems of the collider are described in sections 3-6 in more detail.

2.1 Energy Upgrade

The theoretical limit for the gradient in s.c. Nb structures is well above 50 MV/m. Single-cell L-band resonators have reached up to 40 MV/m [3,4] and recently a 9-cell TESLA cavity reached above 30 MV/m (section 7). We assume therefore that the energy reach of TESLA (within the site length specified in Table 1) goes well beyond 500 GeV. All sub-systems of the machine have been layed out to accommodate an energy upgrade to 800 GeV. This would require an accelerating gradient of 34 MV/m. The number of klystron is doubled and the rep. rate reduced from 5 Hz to 3 Hz to limit the heat load at 2K to a level compatible with the present layout of the cryogenic plants, assuming a quality factor $Q_0 = 5 \cdot 10^9$, half the value at 21.7 MV/m. Including a further reduction of vertical emittance to $\varepsilon_y = 10^{-8}$ m, a luminosity of $5 \cdot 10^{34}$ cm^{-2} s^{-1} can be reached at low beamstrahlung (δ_B<5%) and only moderately increased power consumption ($P_{AC} \approx$ 130 MW). An upgrade of the cryogenic system would allow to go back to 5 Hz operation at a luminosity close to the 10^{35} cm^{-2} s^{-1} level.

3 Delivery System and Beam-Beam Effects

One potential problem arising from the reduced vertical emittance and spot size is due to the kink instability at large disruption parameter,

$$D_y = \frac{2 N_e r_e \sigma_z}{\gamma \cdot \sigma_x^* \sigma_y^*} \qquad (1)$$

which for a given beam energy and average beam power is simply proportional to the product of luminosity and bunch length. The effect of the kink instability is an enhanced sensitivity of the luminosity with respect to vertical beam orbit offsets at the IP. We have therefore combined the smaller σ_y^* with a reduction of σ_z, thus limiting the increase of D_y to about a factor of two compared to the previous design parameters. A further decrease of σ_z is possible in principle, but not without problems regarding the damping ring and bunch compressor systems (for a more detailed discussion of parameter scaling towards high luminosity in TESLA, see [5]).

The decrease in luminosity as a function of relative beam separation is shown in Fig. 2. A beam offset of $0.1\sigma_y^*$ leads to a luminosity reduction of 7%. This accuracy of orbit stabilisation seems feasible with a fast IP feedback [6] which removes pulse-to-pulse orbit jitter on a time scale short w.r.t. the length of a beam pulse.

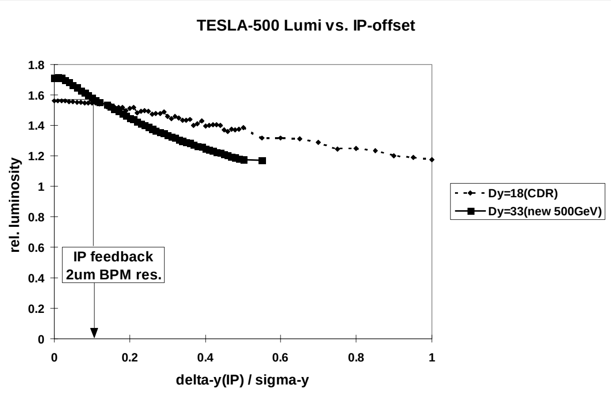

Fig.2: Simulation results [7] for the luminosity vs. vertical beam separation for the new parameters with D_y=33 compared to the reference design.

The original beam delivery system lattice design allows for the foreseen decrease of $\beta_{x,y}^*$ without significant modifications. The momentum bandwidth can still safely accommodate the full energy spread of the beam (±0.18% peak-to-peak, σ_E=0.05%). The stability of the spot size has been studied with the MERLIN simulation code [8] using an ATL-like diffusive ground motion model with a conservative assumption of $A=4\cdot10^{-6}\ \mu m^2\ s^{-1}\ m^{-1}$ derived from HERA orbit drift data [9]. The average increase of the vertical beam size from spurious dispersion and betatron coupling can be limited to a few percent with a one-to-one steering algorithm applied every 10s assuming a BPM resolution of 1μm. A concept for fast luminosity monitoring with a relative accuracy of 1 percent within one beam pulse has been worked out [10].

4 Main Linac

The layout of the linear accelerator described in [1] assumed an arrangement with groups of 8 9-cell superconducting resonators per cryogenic module very similar to the ones built for the TTF. One drawback of this scheme is a rather low filling factor (η_{fill} = ratio of active length to total length), partly due to the large spacing of 1.5 wavelength between resonators. A new scheme with reduced spacing between cavities has bee proposed [11], where groups of 4 resonators form an rf-"superstructure" fed with power from a single input coupler. This scheme not only improves η_{fill} from 66% to 76…80%, but also strongly reduces the number of input couplers and simplifies the rf-distribution system. For η_{fill} = 76% and an unchanged total site length, the required gradient at E_{cm} = 500 GeV goes down to 21.7 MV/m. This leads to a reduction of power for the cryogenic plants which can be invested into rf-power and an improvement of beam pulse to rf-pulse length due to a lower loaded quality factor Q_{ext}. As a result, the overall power transfer efficiency goes from 17% to 23%. The required power per klystron rises from 6.8 MW to 8.3 MW, which still leaves a safety margin of 20% w.r.t. to the design power of 10 MW per klystron. A multi-beam, high efficiency 10 MW klystron is under development in industry. Tests with a first prototype showed a maximum power according to design (at reduced pulse length, limited by the modulator) and an efficiency of 65%, compared to the design value of 70%.

Beam dynamics in the main linac, which were shown to be very uncritical in the reference design, become more of an issue with the beam emittance reduced by an order of magnitude. Tracking simulations [12] have been performed assuming transverse alignment tolerances of 500 μm for the cavities and 10 μm for the BPM's relative to quadrupole axis (obtained by beam-based alignment). The resulting vertical emittance growth amounts to 23% from single-bunch and to 17% from multi-bunch effects. Especially for the latter case, this can not be simply interpreted as incoherent spot size dilution when determining the impact on the luminosity. Rather, the centroids of the bunches in a train are at different positions in phase space at the end of the linac with the result of vertical offsets at the IP. Since these offsets are critical (see section 3), a further reduction of multi-bunch effects is desirable. Fortunately, most of the multi-bunch effect is "static" (i.e. reproducable from pulse to pulse), because it results from HOM excitation in the displaced cavities and a slow variation of bunch energy over the length of the pulse from Lorentz-force detuning (most, but not all of which is removed by the rf-feedback system). We therefore expect that the multi-bunch emittance dilution can be strongly reduced with the help of fast kickers, which are present in any case as part of the foreseen fast (i.e. bunch-to-bunch) orbit feedback system. An accurate determination of the remaining multi-bunch effects needs further investigations.

5 Damping Ring

The damping ring design represents a compromise between a reasonable upper limit for the circumference and a lower limit for the injection/extraction system bandwidth. The “dogbone” design chosen here accomodates 95% of the 17 km long ring in the linac tunnel, thus saving considerable civil construction cost. The beam-optical design of the ring presents no serious problem, but a critical point resulting from an unusually large ratio of circumference over beam energy (3.2 GeV) concerns the space charge tune shift. We find an incoherent shift of $\Delta Q_{incoh} = -0.18$ in the vertical plane for the reference parameters, already close to a tolerable limit. Further reduction of emittance and bunch length pushes this value further up. The proposed way to cure this problem is to increase the beam cross section in the long straight sections of the ring (occupying more than 90% of the circumference) by coupling longitudinal or horizontal emittance into the vertical plane. This can be done by a closed vertical dispersion- or skew quad coupling-bump. First calculations based on linear theory show that the space charge limitation can be very efficiently removed. Furthermore, intrabeam scattering remains uncritical unless an emittance below $\varepsilon_y = 10^{-8}$ m is required. Further studies taking higher-order effects of the lattice and the space charge forces into account are necessary.

6 Positron Source

The TESLA positron source is based on the concept of high-energy photon conversion into e+e- pairs in a thin target. The photons are generated by the spent high-energy electron beam after the IP which, after being captured by a large-bandwidth “inverse Final Focus” system, is sent through a wiggler. Advantages of this concept are a low heat load on the target and a higher capture efficiency for the e+ beam behind the target. However, the spent electron beam exhibits a large energy spread due to beamstrahlung which makes chromatic correction difficult and collimation of the low-energy tail necessary. With the new TESLA parameters, the situation is improved because of a smaller horizontal emittance of the spent beam after the IP. The fraction of spent beam usable for e+ production goes up from 86% to 93%, which in addition to a slightly higher e+ rate reduces the load on the beam collimators by a factor of two.

When replacing the wiggler in the e+ source by a helical undulator, polarised positrons can be generated, however with tighter demands for the spent electron beam quality. The latter depends strongly on the IP-parameters. As an example, increasing the horizontal spot size at the IP by a factor of three yields a luminosity of 10^{34} cm^{-2} s^{-1} at only 0.4% beamstrahlung. The spent beam can in this case almost entirely (>97%) [13] be used for production of *polarised positrons*.

7 Results from the TTF

The s.c. cavity development program was launched by the TESLA collaboration in 1992 [14]. The test facility built at DESY includes clean rooms for preparation and assembly, chemical treatment, ultra-pure high-pressure water rinsing and heat treatment of Nb cavities. Single cavities undergo tests in a vertical cryostat and in a horizontal test stand ("CHECHIA"), before they are installed in a cryo-module which houses 8 9-cell cavities. A summary of cavity performance in the vertical test stand is given in Fig. 3. All cavities are included, except those where fabrication errors were clearly identified (e.g. several resonators from one production line which showed systematically bad performance due to a fault in the welding procedure. After correcting the procedure, the problem disappeared). The TESLA500 goal of 21.7 MV/m at $Q_0 = 10^{10}$ is reached by these cavities *on average*. The most recent test of a TESLA cavity in CHECHIA, equipped with input and HOM couplers, showed a gradient of 33 MV/m at $Q_0 = 4 \cdot 10^9$, close to the performance goal for the energy upgrade to 800 GeV. Further improvements in cavity fabrication are underway. The Nb sheets are checked for impurities with an eddy-current method before being used for resonator production. Two methods are being tested which would allow to produce multi-cell cavities without welding seems: spinning [15] and hydroforming [16]. For more details on the s.c. cavity R&D, see [17].

A full integrated system test with beam is done at the TTF linac. The linac went into operation with beam in May 1997 and the first TESLA module could demonstrate stable acceleration with a gradient above 16 MV/m, thus surpassing the initial TTF goal of 15 MV/m. A description of the linac and further results are given in [18]. Two more modules will be installed in the linac in autumn 1998 and early 1999, respectively. We expect an improved performance of these modules to reach g = 20…25 MV/m, thus yielding a maximum beam energy close to 500 MeV. The linac will then also be used to test the SASE Free Electron Laser concept in the VUV wavelength regime [19].

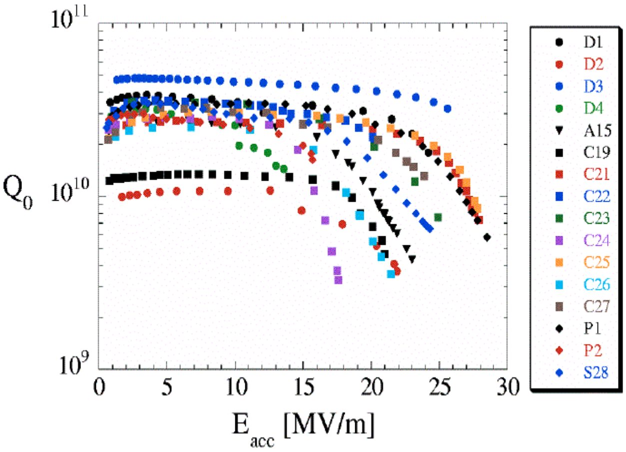

Fig. 3: Quality factor vs. acc. gradient in the vertical test stand (CW-operation mode) for all TESLA cavities, excluding those with well identified fabrication errors.

8 S-Band Test Facility

A linear collider concept based on conventional S-Band technology has been worked out as a backup solution (see ref. [1]). For the development of the main accelerator components, a test facility has been set up at DESY. Two high-power klystrons were developed at SLAC in co-operation with DESY and TU Darmstadt. Both devices reached there design power of 150 MW at design pulse length of 3µs and rep. rate of 50Hz. With shorter pulses, up to 210 MW could be achieved. An economic and fast brazing technique for accelerating structures using inductive heating was developed. The measured straightness of 1m long sections is 30µm (rms). Accelerating structures of 5.2m and 6m lengths have been built at DESY and installed in the test linac. Coating of the irises for HOM damping was successfully tested. Beam operation started in autumn 1996. The injector delivers the design beam current (300mA), time structure and pulse length (2µs). Further investigations will include HOM measurement and precision alignment of structures using the HOM signals. The experimental studies at the S-Band test facility will be continued until the end of 1998.

9 Conclusions

With the completion of the overall design of the TESLA facility as documented in ref. [1] and the successful commissioning of the TTF important milestones have been reached by the TESLA collaboration. The studies towards an optimisation of the luminosity confirm the high potential of the superconducting linac approach for a next generation e+e- machine. This high potential justifies the effort going into the R&D of s.c. cavities and the progress obtained at the TTF justifies the optimism that the ambitious performance goals for the s.c. cavities can be reached.

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