The TESLA Linear Collider

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Abstract

In this paper the present status of the overall design and of the technical R&D for the TESLA linear collider is summarized.

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1 Introduction

The feasibility of a linear collider has been demonstrated by the successful operation of the SLC, the only existing facility of this kind. Nevertheless, meeting the requirements for a next generation linear collider is by no means an easy task. In particular, high beam powers and very small spot sizes at the collision point are needed in order to obtain a sufficiently high luminosity. Several groups worldwide are pursuing different linear collider design efforts [2]. The fundamental difference of the TESLA approach compared to other designs is the choice of superconducting accelerating structures. The challenge of pushing the superconducting linac technology to a high accelerating gradient and at the same time reducing the cost per unit length, both necessary in order to be competitive with conventional approaches, is considerable, but the advantages connected with this technology (as summarized below) are significant and we are convinced that the potential for the machine performance is unrivaled by other concepts. The R&D for the superconducting linac technology as well as the overall design of the TESLA facility by an international collaboration, centered at DESY, in which more than 30 institutes from Armenia, China, Finland, France, Germany, Italy, Poland, Russia and the USA participate.

TESLA uses 9-cell Niobium cavities (Fig. 1) cooled by superfluid Helium to T=2K and operating at L-band frequency (1.3 GHz). This technology provides several important advantages for the design of a linear collider. The power dissipation in the cavity walls is extremely small which allows to produce the accelerating field with long, low peak power RF-pulses and yields a high transfer efficiency of RF-power to the beam. The long RF-pulse allows for a large bunch spacing (see Table 1), making it easy for the experiment to resolve single bunch crossings. In addition, a fast bunch-to-bunch feedback can be used to stabilise the orbit within one beam pulse, which makes TESLA practically immune to mechanical vibrations which could otherwise lead to serious luminosity reduction via dilution of the spot size and separation of the beams at the IP. Further benefits of the long pulse are the possibility to use a head-on collision scheme with large-aperture super-

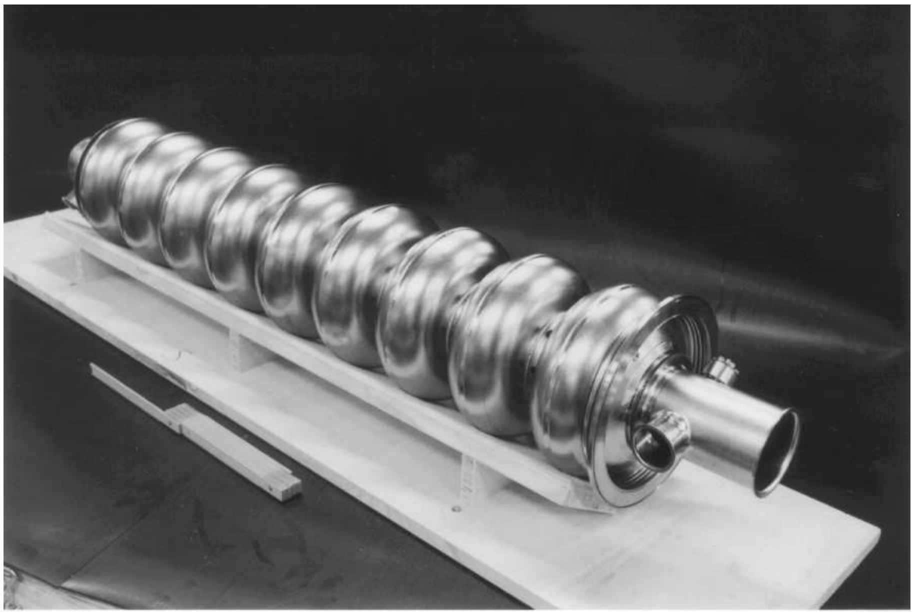

Figure 1: The 9-cell Niobium cavity for TESLA.

conducting quadrupoles in the interaction region and to employ a safety system which can “turn off” the beam within one pulse in case an emergency is indicated by enhanced loss rates. The choice of a low drive frequency for TESLA results in very small transverse and longitudinal wakefields in the accelerating structures. This leads to relatively relaxed alignment tolerances for the linac components required for the transportation of a low emittance beam. The high efficiency, very low emittance dilution and good beam stability make TESLA the ideal approach for a high-performance next generation linear collider.

2 Overview and Machine Parameters

The overall layout of TESLA is sketched in Fig. 2. The total site length is about 32 km, including the beam delivery system (which provides beam collimation and spot size demagnification).

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

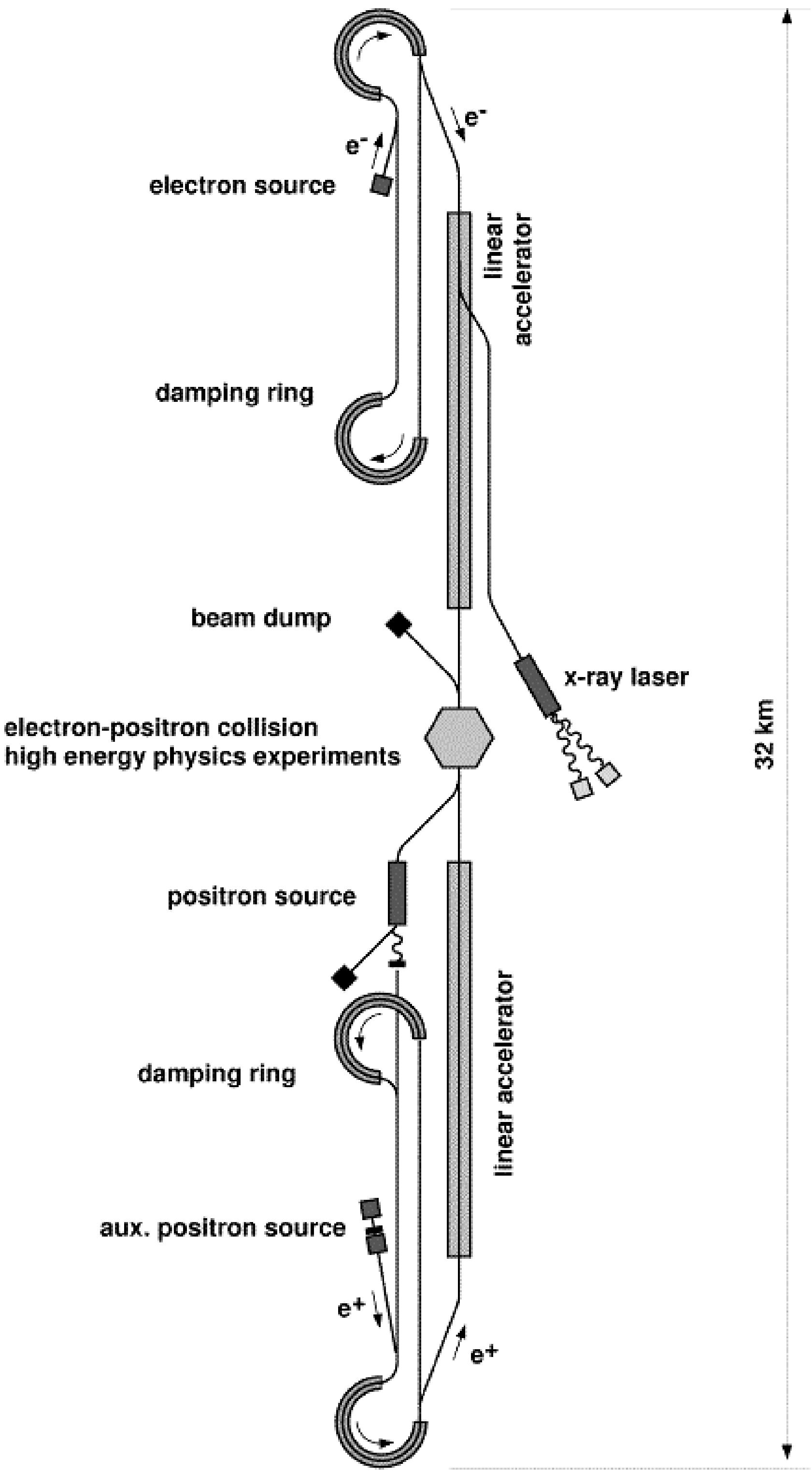

Figure 2: Schematic layout of the TESLA facility.

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

	TESLA (ref.)	TESLA (new)
site length [km]	32.6	32.6
active length [km]	20	23
acc. gradient [MV/m]	25	22
quality factor Q_0 [10^{10}]	0.5	1
t_{pulse} [μs]	800	950
no. of bunches per pulse n_b	1130	2820
bunch spacing Δt_b [ns]	708	337
rep. rate f_{rep} [Hz]	5	5
N_e per bunch [10^{10}]	3.6	2
norm. emittances ϵ_x/ϵ_y [10^{-6}m]	14 / 0.25	10 / 0.03
beta functions at IP β_x^*/β_y^* [mm]	25 / 0.7	15 / 0.4
spot size at IP 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
AC power (2 linacs) [MW]	95	95
efficiency $\eta_{AC-to-beam}$ [%]	17	23
luminosity [10^{34} cm^{-2}s^{-1}]	0.68	3

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.

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 below 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 and recently a 9-cell TESLA cavity reached above 30 MV/m. 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 22 MV/m. Including a further reduction of vertical emittance to $\epsilon_y = 10^{-8}$ m, a luminosity of $5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ can be reached at low beamstrahlung ($\delta_B < 5\,\%$) 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 $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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, 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 offset and crossing angle 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. In order to limit the decrease in luminosity to less than 10%, the orbit offset and crossing angle must be kept within one tenth of the beam size and angular spread, respectively. This accuracy of orbit stabilisation seems feasible with a fast IP feedback [3] which removes pulse-to-pulse orbit jitter on a time scale short w.r.t. the length of a beam pulse.

The original beam delivery system lattice design allows for the foreseen decrease of the spot size without significant modifications. The stability of the spot size has been studied with the MERLIN simulation code[4] using an ATL-like diffusive ground motion model with a conservative assumption of $A = 4 \cdot 10^{-6}\mu\mathrm{m}^2\mathrm{s}^{-1}\mathrm{m}^{-1}$ derived from HERA orbit drift data [5]. 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 10 s 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 [6].

With reduced beam emittances, the layout of the beam collimation system becomes a more critical issue. A method to protect the collimators in case of accidental beam loss using non-linear elements to blow up the beam size has been worked out. We assume here that large energy errors occur more frequently than large transverse mis-steerings. By arranging a non-linear magnet lattice at a position of large energy dispersion, the off-energy beam experiences a strong betatron-coupling which increases its spot size on the collimator by an order of magnitude. This is safely sufficient to guarantee survival of the collimator, taking also into account that the beam would be switched off and directed to an emergency beam dump by a fast (few μs reaction time) extraction system. Being able to install an active safety dump system is another benefit of the large bunch spacing in TESLA. Further new developments concern an improved scheme for extracting the spent beam after the IP and transport it to the dump with a minimum of beam and beamstrahlung losses in the extraction channel (see also section 5). This will reduce neutron background in the detector, reduce radiation safety problems and make installation of spent beam diagnostics (in particular a spectrometer to determine the energy distribution) easier.

4 Main Linac

The layout of the linear accelerator described in ref. [1] assumed an arrangement with groups of eight 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 been proposed [7], where groups of four 7-cell resonators form an rf-superstructure fed with power from a single input coupler. This scheme not only improves η_{fill} from 66% to about 76%, but also strongly reduces the number of input couplers and simplifies the rf-distribution system. With unchanged site length, the required gradient at E_{cm}=500 GeV goes down to 22 MV/m. We also assume that at this gradient the quality factor can be higher than the original design value ($Q_0 = 10^{10}$ instead of $5 \cdot 10^9$). 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%. Per linac, 3600 superstructures are fed with rf-power by 300 klystrons of 8.3 MW each, 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%. Installation of a 10 MW klystron at the test facility is planned for early 2000 and will allow to gain operational experience with this new RF power source at the test linac.

5 Injection System

The TESLA positron source is based on the concept of high-energy photon conversion into e^+e^- pairs in a thin target (this concept was first proposed at INP Novosibirsk for the VLEPP project). The photons are generated by the high-energy electron beam which 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. In the reference design, the spent electron beam after the IP has been used to drive the positron source. However, the beam exhibits a large energy spread due to beamstrahlung which makes chromatic correction difficult and collimation of the low-energy tail (about 10% of beam power) necessary. We have therefore investigated the possibility to move the positron production to a position in the beam line upstream from the IP. The resulting beam energy loss and spread of 1.6% and 0.18%, respectively, are considered acceptable. The implications for the beam line geometry (separation of electron and photon beams, transport of the positrons to the other side of the IP) are under study. Main advantages of this concept are the de-coupling of positron production and beam-beam interaction and the elimination of the complicated spent-beam line with large amounts of beam loss in the collimators. Furthermore, when replacing the wiggler in the e^+ source by a helical undulator, polarised positrons can be generated with the tighter demands for the electron beam quality being easily fulfilled by using the incoming beam. Since there is definite interest in positron polarisation from the Particle Physics point of view and the option for polarised positrons would be ruled out when using the spent beam, the upstream version of the source has become our baseline design. This will also facilitate machine commissioning, since it is not necessary to send the high energy electron beam through the interaction region for operating the positron source.

Another benefit is that the spent beam extraction line can now be optimised for minimum beam losses on the way to the dump, without having to take into account the restrictions to the spent beam quality needed previously for positron production. By concentrating all beam losses (including the beamstrahlung absober) in a common underground hall about 250 m downstream from the IP, radiation shielding requirements are easier to meet than in case of large amounts of losses distributed over a longer section.

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 90% of the 17 km long ring in the linac tunnel, thus saving considerable civil construction cost. The beam-optical design of the ring has been improved in context with a critical point concerning the space charge tune shift. The latter could be reduced by a factor of two by going from 3.2 to 5 GeV beam energy, at the same time optimising the lattice in the arcs to maintain the horizontal emittance. An additional way to cure the space charge 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 horizontal emittance into the vertical plane. This can be done by a closed vertical skew quad coupling-bump. First calculations based on linear theory show that the space charge limitation can be very efficiently removed. More detailed studies involving particle tracking including space charge have started.

New ideas have been developed in the field of flat-beam electron sources, which may eliminate the need for an electron damping ring [8]. Further studies are under way and an experimental test of the new concept will be possible at the existing rf-photocathode gun test stand at FNAL or at the gun test facility which is in the planning state at DESY-Zeuthen.

6 Results from the TTF

The s.c. cavity development program was launched by the TESLA collaboration in 1992 [9]. 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 eight 9- cell cavities. A summary of cavity performance in the vertical test stand over the past years is given in Fig. 3. Many cavities from the more recent production series have reached gradients of 20...30 MV/m already in the first test, i.e. after having passed through the standard preparation procedure, a very important result in view of future mass production. Defining a succes rate for cavities by setting a lower cut on the gradient at 20 MV/m in first test yields 48% for 1998 data and 68% for 1999 (mid-August) data (see Fig. 4). The average gradient and quality factor for these cavities are 25 MV/m and $8 \cdot 10^9$, respectively, for the 1999 results.

Several of the cavities also went through the pulsed-rf horizontal test and have shown no systematic reduction in the achieved gradients. The best test result 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. While this is an important proof-of-principle, it is also clear that further improvements in cavity

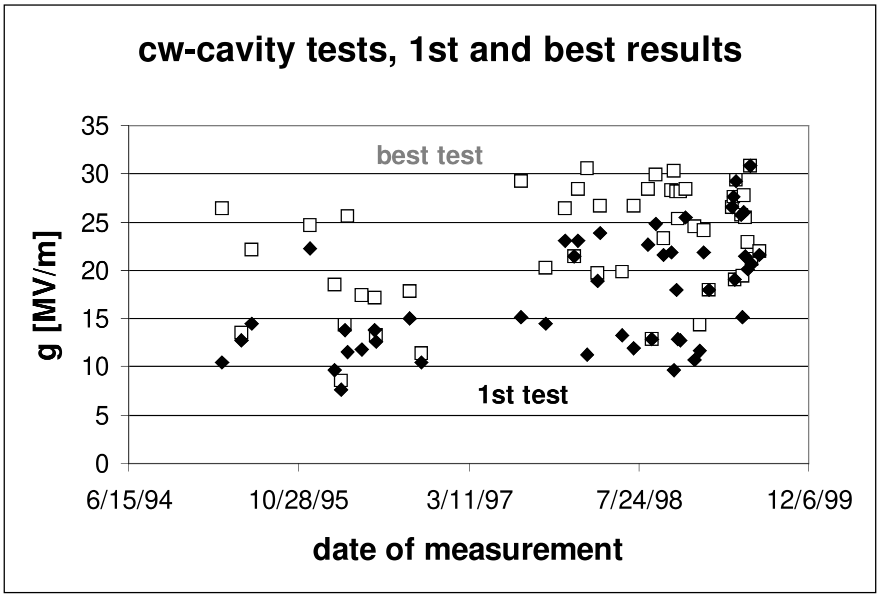

Figure 3: Accelerating gradient of TESLA cavities on the vertical test stand achieved at first test (diamonds) and after additional processing (squares).

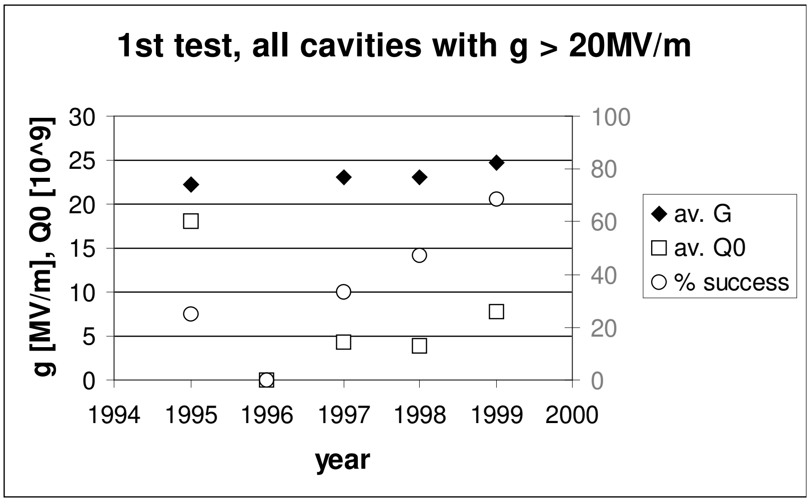

Figure 4: Average cavity performance in first cw-test over the last years, taking into account only those resonators which reached at least 20 MV/m. Shown are the average gradient and quality factor (diamonds and squares, left scale) and the succes rate (percentage of cavities above 20 MV/m, circles, right scale).

fabrication are necessary to obtain gradients above 30 MV/m on average. One possible method may be electro-polishing, which has proven to improve the gradient to values around 35 MV/m in tests with several single-cell resonators [10]. In a recent test at TTF of a single-cell resonator electro-polished at CERN, a gradient of 39 MV/m was achieved.

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. The second module was commissioned early this year and yielded beam acceleration with an average gradient of 18.6 MV/m. In summer, the first module was exchanged with a third one which has recently come into operation. During the TTF linac run in August-September 1999 the two modules were operated at a gradient of about 14 MV/m to deliver beam for commissioning of the new installations for the SASE Free Electron Laser test facility. High-gradient tests of module #3 have started in October and are presently ongoing.

7 Site Considerations

From our point of view it is strongly beneficial for both the construction time and cost to build the next generation Linear Collider close to an existing HEP laboratory. DESY as the co-ordinating institute of the TESLA collaboration has taken over the task to investigate in detail a possible site for the future facility nearby the existing DESY site in Hamburg [1]. The geographical boundary conditions suggest to construct the linac to the north-west direction (see Fig. 5). We also assume that the beginning of the linac

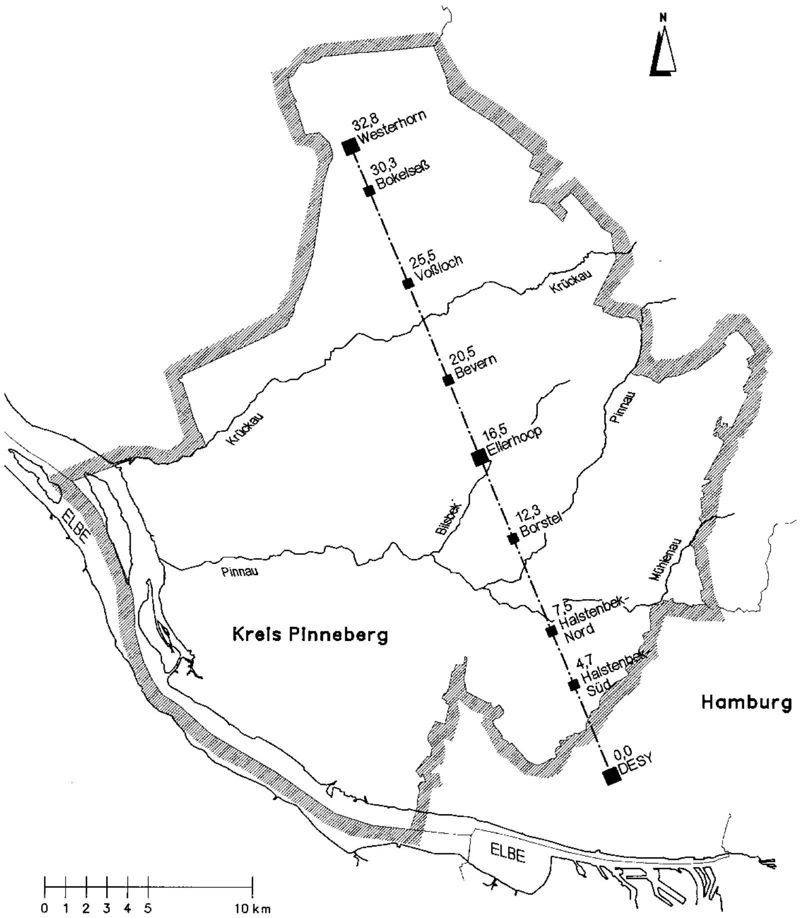

Figure 5: Sketch of the TESLA site north-west from the existing DESY site.

[1] This does, of course, not rule out other possibilities. In fact, in the design report [1] also FNAL has been discussed as a possible site for TESLA

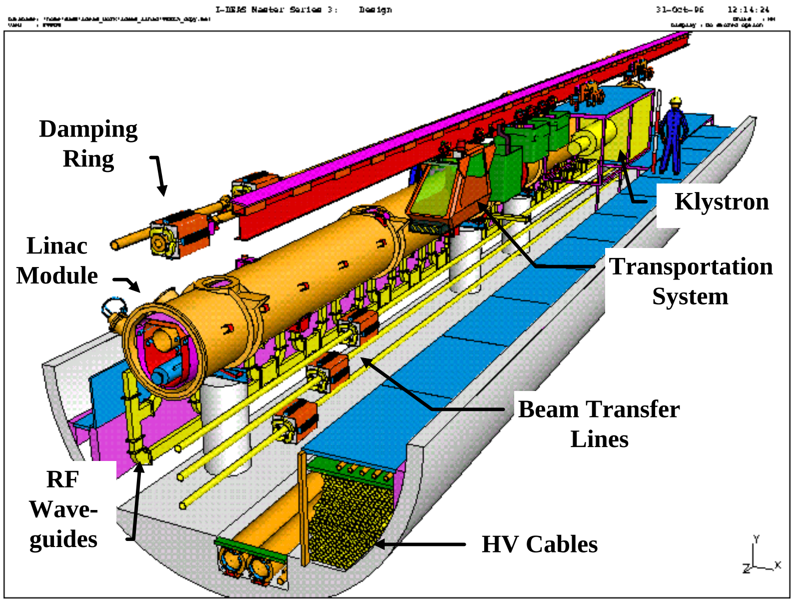

Figure 6: CAD drawing of the TESLA tunnel.

should be on the DESY site to make optimum use of existing infrastructure and to have it tangential to the straight section of HERA in order to include the possibility of electron-hadron collisions using a beam stored in the 900 GeV proton ring as a future option. The linac will be installed in a tunnel about 15...20 m underground with a diameter of 5 m (Fig. 6). The country north-west of Hamburg is very flat so that the depth of access shafts can be reduced to a minimum. A well suited central area which accomodates both the colliding beam experiments and the X-ray FEL user facility has been found. The basic layout for adding a 2nd interaction region has also been worked out. At the 2nd IP the beams cross at an angle of about 30 mrad which is necessary to for the $\gamma\gamma$-collider option (see Appendix A in ref. [1]). The possibility to operate the 2nd experiment also in e+e- mode is not ruled out by this geometry.

8 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.

Within the next 1.5 years a technical proposal for the TESLA facility will be prepared, including the cost estimate and construction schedule. In parallel, the preparations for the legal procedure required by the authorities for getting the permission to construct the machine will continue so as to be ready for offering a site for the facility.

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