THE TESLA LINEAR COLLIDER AND X-RAY FEL

K. Floettmann (for the TESLA Collaboration)
DESY, D-22603 Hamburg, Germany

Abstract

The superconducting linac technology combines a high power transfer efficiency with excellent beam quality, yielding optimum performance for a next generation e^+e^--Linear Collider and for short wavelength FELs. This paper summarizes the overall design and the present status of R&D for the TESLA 500-800 GeV Linear Collider facility with integrated X-ray FEL.

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 40 institutes from Armenia, China, Finland, France, Germany, Great Britain, Italy, Poland, Russia, Switzerland and USA participate in the design work and technical R&D for a linear collider based on superconducting Niobium accelerating structures (figure 1) operated at 2K. The combination of high AC-to-beam power transfer efficiency 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 and operation stability, of a linear collider as well as for short wavelength FELs.

In the last decade a remarkable progress has been achieved in the average accelerating gradient of superconducting cavities. In addition a significant cost reduction has been realized by an optimized linac design and streamlined production procedures, so that the realisation of a linear collider based on superconducting technology is competitive today.

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.

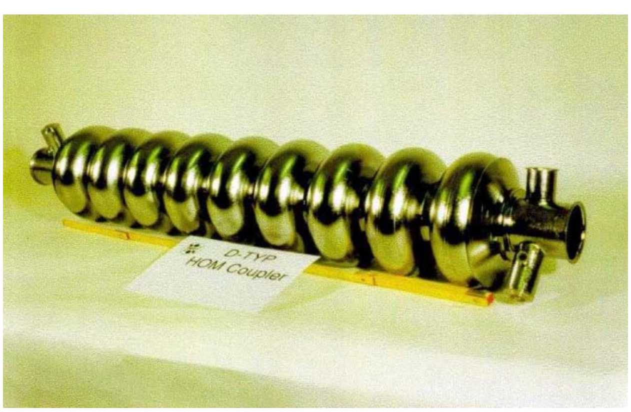

Figure 1: The TESLA 9-cell Niobium cavity

2 OVERALL LAYOUT AND PARAMETERS

The layout of TESLA is sketched in figure 2. The total site length is about 33 km, including the beam delivery system (which provides beam collimation and spot size demagnification). A complete description of the machine, including all sub-systems, infrastructure requirements, site layout and cost estimate is given in the technical design report presented to the public at a colloquium in spring 2001 [1].

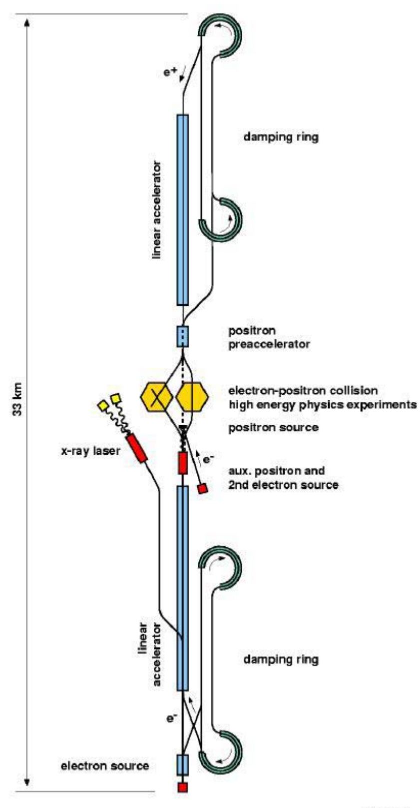

Figure 2: Overall layout of TESLA

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 and chapters on the physics potential of the X-ray coherent light source user facility which is integrated into the TESLA project.

In order to drive the X-ray FEL is was envisaged to run the first part of the linac at doubled repetition rate and to accelerate electron pulses for the linear collider and the FEL in an alternating mode. The study of a separate linac for the FEL has recently started on the recommendation of the German Science Council. The aim is to understand the technical, operational and cost implications of a decoupled linac. Moreover it is conceivable to realize the FEL on a shorter time scale than the linear collider.

3 LINEAR COLLIDER

The main machine parameters at a centre-of-mass energy of E_{cm} = 500 GeV are shown in table 1. The progress on superconducting cavity R&D (Section 5) indicates that the accelerating gradient can be pushed beyond the value of 23.4 MV/m required for E_{cm} = 500 GeV. The sub-systems of the facility (in particular the beam delivery system) have been designed to accommodate an energy upgrade to E_{cm} = 800 GeV. The gradient required for this energy within the given site length for the 500 GeV facility is 35 MV/m, well below the theoretical limit for the Niobium resonators (>50 MV/m). The machine parameters at 800 GeV, which assume an upgrade of the cryogenic plants and of the RF-system (doubling the number of klystrons) are shown in table 1. The assumed higher filling factor can be realized with the so-called superstructure concept, which will be explained below.

Table 1: TESLA parameters at E_{cm}= 500 and 800 GeV.

	500 GeV	800 GeV
site length [km]	32.8	32.8
acc. Gradient [MV/m]	23.4	35
filling factor	79%	85%*
quality factor Q_0 [10^{10}]	1	0.5
t_{pulse} [μs]	950	860
# bunches n_b/pulse	2820	4886
bunch spacing Δt_b [ns]	337	176
rep. rate f_{rep} [Hz]	5	4
N_e/bunch [10^{10}]	2	1.4
ε_x / ε_y at IP [10^{-6}m]	10 / 0.03	8 / 0.015
spot size σ_x/σ_y [nm]	553 / 5	391 / 2.8
bunch length σ_z [mm]	0.3	0.3
beamstrahlung δ_B [%]	3.2	4.3
P_{AC} (2 linacs) [MW]	97	150
luminosity L [10^{34} cm^{-2}s^{-1}]	3.4	5.8

* assuming superstructures for increased fill factor

With cavities achieving gradients beyond 23.4 MV/m installed from the beginning, energies well above 500 GeV can be realised at reduced luminosity without upgrade of the cryogenic plants or the RF system as shown in figure 3, since a superconducting linac allows a trade-off of beam energy and current.

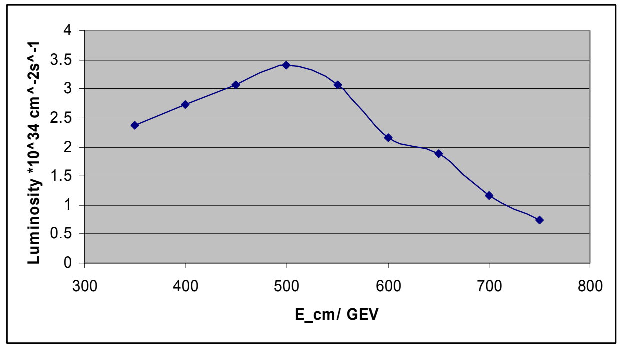

Figure 3: Luminosity versus centre-of-mass energy without upgrade of RF and cryogenic plants.

A brief description of the major subsystems will be given in the following.

The electron beam is generated in a polarized laser driven gun and then pre-accelerated to 5 GeV before injection into the damping ring

The positron source has to provide $5.6{\cdot}10^{13}$ positrons per pulse. It is based on the concept of high-energy photon conversion into pairs in a thin target. The photons are generated by the high-energy (250 GeV) electron beam which is sent through a planar permanent magnet undulator before the interaction point. This layout avoids collimation problems of the spent beam and facilitates the generation of polarized positrons, since the emittance requirements for that option are easily met by the incoming electron beam. To achieve 45% to 60% polarization the planar undulator has to be replaced by a superconducting, helical undulator.

The damping ring has to accommodate the full TESLA bunch train of 2820 bunches, which is ~300 km long for the nominal bunch spacing. To keep the ring length reasonable the bunches are stored in a compressed mode in a 17 km long ring. The "dog-bone" design accommodates 90% of the ring in the linac tunnel with short return loops at either end.

The two main linear accelerators are constructed from roughly ten-thousand 9-cell cavities each. The layout of the linear accelerator described in [1] assumed an arrangement with groups of 12 9-cell superconducting resonators and a superconducting quadrupole package per cryogenic module. The quadrupole package is centred in the module and contains besides the quadrupole vertical and horizontal correction coils and a beam position monitor. A somewhat higher filling factor (6%) can be realised with the so-called superstructure concept. Here two cavities separated only by half a wavelength are fed by a common input coupler. In addition to the higher filling factor a cost reduction is achieved with this concept due to the reduced number of power couplers, waveguide elements and HOM couplers. A module containing two superstructures is presently under test at the Tesla Test Facility (TTF).

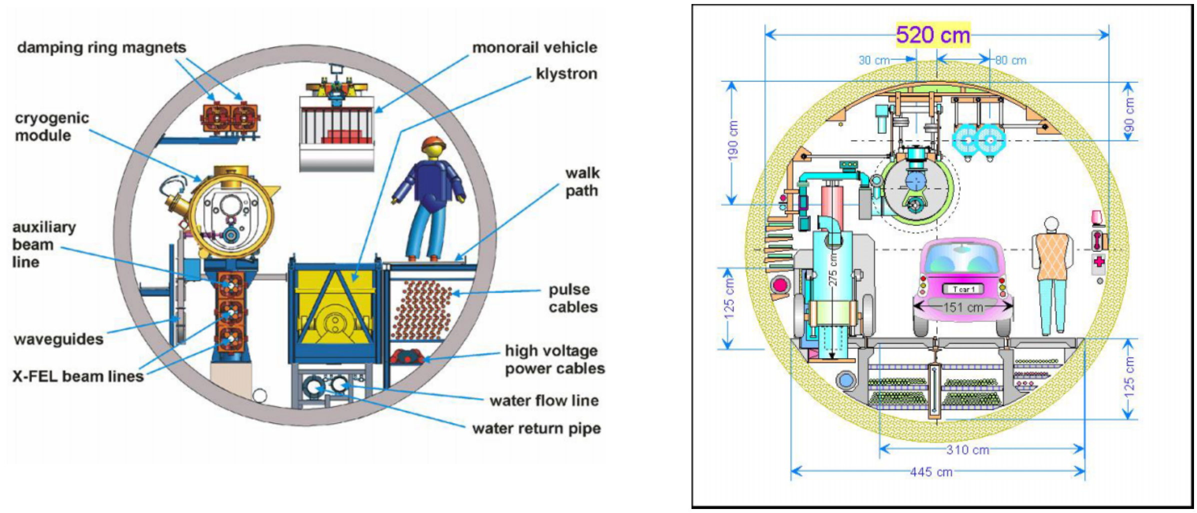

Figure 4: Comparison of the old (left) and the new (right) tunnel layout.

Each linac is powered by ~300 klystrons, each serving 36 cavities. High efficient multi-beam klystrons have been developed by industry. 10 MW of rf-power over 1.5 ms pulse length and an efficiency of 65% have been achieved, according to design.

The cryogenic system is comparable in size to the one currently under construction for the LHC. Seven cryogenic plants are foreseen, each serving a 5 km long section of the linac.

The two 1.6 km long beam delivery systems comprise a beam switch yard to serve the optional second interaction region, a collimation section to remove the beam halo, which could otherwise cause background at the experiment, and the final focus section.

The large bunch spacing allows for head-on collisions in the first interaction region. The optional second interaction region will have a crossing angle of ≈34 mrad and is therefore suitable for the gamma-gamma option.

The luminosity is very sensitive to relative offsets of the colliding beams in vertical position or angle at the IP. A fast orbit feedback system has been designed which, thanks to the large spacing between bunches, can operate on a bunch-to-bunch basis and maintains head-on collision accurate to one tenth of a standard deviation in orbit and angle.

The linear accelerator and beam delivery system will be installed in an underground tunnel of 5.2 m diameter. A new layout of the tunnel has been proposed, with the linac hanging at the tunnel ceiling (figure 4). The new layout makes better use of the available space and has advantages concerning safety aspects (better separation of power cables, more space for the escape route). It also allows to install vertical klystrons, which was not possible in the old design.

For the detector a ~2000 m^2 experimental hall is foreseen. The seven cryogenic plants are located in additional surface halls with a spacing of roughly 5 km.

4 THE X-RAY FEL

For the X-ray FEL low emittance, high peak current electron beams at energies between 10 and 35 GeV are required. Electron bunches of ~1 nC charge are produced in a laser driven rf gun, accelerated and longitudinally compressed in 3 magnetic bunch compression chicanes. The final bunch length is 25 µm, yielding a current of 5kA. Based on user requirements a variable pulse pattern will be provided, with up to 11500 electron bunches per train, the maximum a linac based on TESLA technology can deliver. The electron bunches will be distributed among several users by means of a switchyard, which guides the bunches to four different FEL undulators operating at different wavelength. The FEL undulators are followed either by another FEL undulator operating at longer wavelength or by undulators for the generation of spontaneous radiation. Therefore 10 photon beam lines can be supplied quasi simultaneously.

5 R&D STATUS

5.1 Cavity development

For the Tesla Test Facility (TTF) 80 Cavities have been produced by different companies in three production series. The average gradient has been increased from ~18 MV/m in the first series to above 25 MV/m in the third production series (figure 5). Simultaneously the spread in the gradients has been reduced. Six modules are equipped with cavities up to now. Besides experience and a better control of the treatment procedures the improvement is due to the eddy scanning of the niobium sheets prior to welding and a better specification of the e-beam welding parameters. The eddy scanning allows to discard single niobium sheets with clustered inclusions of foreign materials like tantalum.

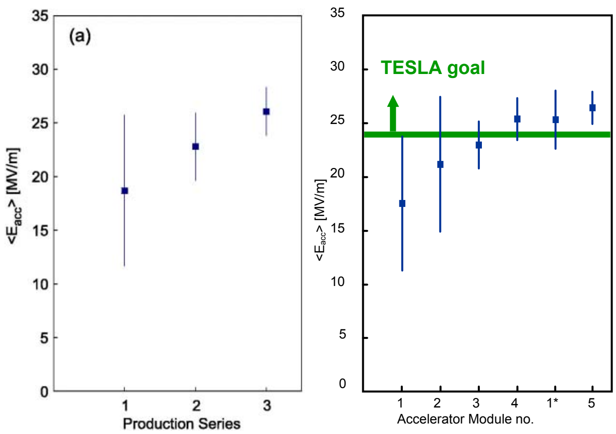

Figure 5: Average gradients measured in the vertical test cryostat of the three production series (left); and of cavities installed in the first six cryogenic modules for the TTF linac (right).

The ongoing R&D program focuses on possible simplifications in the cavity production and treatment and on pushing the performance towards higher gradients. Recent developments in electro-polishing [2] have yielded very high accelerating gradients up to 42 MV/m in single cell resonators. In a collaboration between KEK and DESY the technology is extended to multi-cell cavities. As of writing two TESLA type cavities have reached gradients of ≥ 35 MV/m, required to reach 800 GeV. A third cavity shows promising results before the bake-out (figure 6).

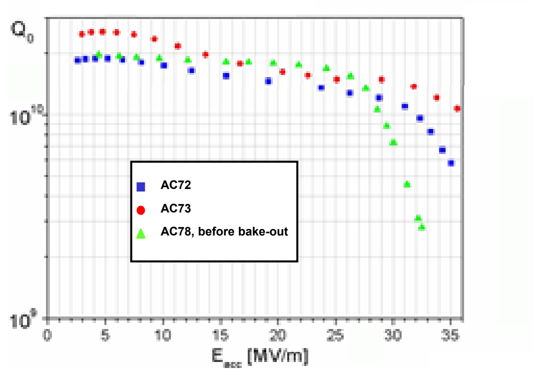

Figure 6: Electro-polished cavities for TESLA.

These cavities have been polished at KEK and received the final clean room treatment at DESY. In future electro-polishing of multi-cell cavities will also be possible at DESY; the required infrastructure is under commissioning.

5.2 HOM couplers

During one of the first long bunch train runs at TTF a potentially dangerous higher order mode with unexpected high Q-factor and R/Q value has been observed [3]. The mode was found in the third dipole passband at 2.58 GHz with an intensity modulated beam with position offset. A detailed theoretical investigation [4] revealed that the low damping is due to the polarization dependent coupling of the higher order mode couplers in the TESLA cavities and that a simple rearrangement of the HOM couplers (one coupler needs to be mirrored) would cure this problem.

Meanwhile cold test measurements support these results and show that the new arrangement gives also sufficient damping for modes in the other passbands [5].

5.3 TTF operation

A full integrated system test with beam has been done at the TTF linac. The linac went into operation in May 1997 and up to date three accelerator modules have been tested (the 3rd one replaced module #1). The maximum accelerating gradient was 14 MV/m, 19 MV/m and 22.7 MV/m, for modules #1, 2 and 3, respectively. These measurements are based on energy gain measurements of the electron beam. For extended periods the linac is in operation 7 days a week, 24 h a day. Approximately 50% of the time is allocated to FEL operation, including beam delivery for two user experiments. Most of the time the linac is operated at modest gradients of ~14 MV/m due to user requests. The last run period of TTF was dedicated to high gradient, long pulse operation [6]. During the 42 days of operation the modules where running for ~90% of the time with gradients between 19 and 22 MV/m in module 3. It could be demonstrated, that the linac can be operated stable even close to the quench limit of individual cavities. Interlock trips can in general be immediately reseted. Even the quench of a cavity does not necessarily lead to a beam interruption.

An important goal of the long pulse operation was to demonstrate the capability of the digital rf-controls to keep the accelerating gradient constant under beam loading. Figure 7 shows the measured energy variation of a full 800 µs long macro pulse.

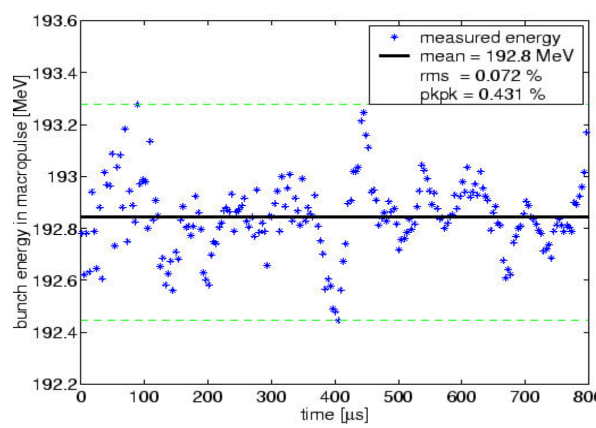

Figure 7: Energy variation over a long macro pulse. The rf-control system is operated with beam loading compensation, the bunch spacing is 444 ns.

The bunch charge was stable to ~10% and the average current was 7 mA. The energy spread of σ_E / E =0.07% is within the specification of TESLA.

Concerning the FEL operation, not only the saturation of the SASE process at short wavelength could be demonstrated, but also the tuneability over a range from 80 to 120 nm and the reliable operation for user operation. A full characterization of the photon beam including coherence and statistical properties complement the measurements [7]. Besides the high brightness FEL users are particularly interested in short radiation pulses in the fs regime. Due to the internal bunch structure only a short fraction of the bunch radiated at TTF and radiation pulses from 30 to 100 fs could be realized. The same internal bunch structure leads to increased effects of coherent synchrotron radiation in the bends of the bunch compressors. Coherent synchrotron radiation in bends represents one of the major limitations on the way to even shorter bunches.

In the next month superstructure tests and high gradient test of module 1* (rebuild from module 1) are scheduled, followed by high gradient tests of modules 3, 4 and 5 (w. o. beam) in spring 2003. In a shut down the linac will be complemented to reach a final beam energy of 1 GeV in order to operate an FEL at wavelength down to 6 nm.

6 TIMELINE

After the presentation of the TDR to the public and the German government in spring 2001 a lively review activity started. Groups of KEK and US-physicists, headed by Fermilab, visited DESY in order to discuss details of the TDR [8]. Furthermore TESLA is reviewed among other linear collider projects in the framework of the Technical Review Committee headed by Greg Loew, as requested by ICFA. The ILC-TRC report will be published in autumn. This fruitful and cooperative work has highlighted several issues where design optimisations are advisable, which will be addressed by the TESLA collaboration. It marks also another step towards the development of a truly international collaboration required to build a linear collider.

The German Science Council, the advisory committee to the German government, evaluated the TESLA proposal together with other large scale facilities proposed in Germany [9]. The science council recommends the TESLA proposal under the condition, that the international organisation proposed for the construction and operation of TESLA will be specified in more detail and that a revised technical project proposal for an X-ray FEL with a decoupled linear accelerator is presented. The aim is to react on this by autumn this year and a decision of the German government is envisaged for 2003.

Meanwhile DESY is compiling relevant information for the Plan Approval Procedure, a formal procedure which all large scale projects in Germany have to pass. It includes environmental impact and safety studies, detailed civil construction engineering, transport access requirement and others.

7 REFERENCES

[1] TESLA Technical Design Report, DESY 2001-11, http://tesla.desy.de/new_pages/TDR_CD/start.html
[2] L. Lilje, High Gradient Superconducting Multi-cell cavities, this conference MO476.
[3] S. Farthoukh, et. al., Evidence for a Strongly Coupled Dipole Mode with Insufficient Damping in TTF First Accelerating Module, PAC 1999.
[4] M. Dohlus, et. al., Higher Order Mode Absorption in TTF Modules in the Frequency Range of the 3rd Dipole Band, TESLA 2002-05.
[5] M. Dohlus, et. al., Resonance Frequencies and Q-factors of Multi-Resonance Complex Electromagnetic Systems, to be published.
[6] H.Weise, Operational Experience with the Test Facilities for TESLA, this conference, TH201.
[7] J. Rossbach, Physics & Experiments with Short-Wavelength, Single-Pass FELs, this conference, TH202.
[8] P. Garbincius, Report on the TESLA Engineering Study Review, http://home.fnal.gov/~peterg/report
[9] http://www.wissenschaftsrat.de/presse/pm_2002.htm